DHANALAKSHMI SRINIVASAN ENGINEERING COLLEGE, PERAMBALUR – 621212

DEPARTMENT OF ELECTRICALAND ELECTRONICS ENGINEERING

EE6009 – POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

TWO MARKS WITH ANSWER

UNIT-1

PART-A

1. List out the major factors influencing the amount of GHG emissions. (M.E-NOV/DEC2016)
    - Industrial revolutions
    - Deforestation
    - Fluorinated gases such as hydro fluorocarbon, per fluorocarbon, sulfur hexafluoride
    - Release of Carbon dioxide
    - Depletion of fossil fuels
2. Give any two environmental aspect of electric energy conversion. (APR/MAY2017) (M.E-NOV/DEC2013)
    - Increased atmospheric pollution
    - Depletion of fossil fuels
    - Reduction in sustainable development
3. What is SOFC? State its limitations. (M.E-NOV/DEC2016)
   A **solid oxide fuel cell** (or **SOFC**) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. Fuel cells are characterized by their electrolyte material; the SOFC has a solid oxide or ceramic electrolyte. Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues.
4. List the various renewable energy resources. (M.E-NOV/DEC2013)
   Biofuel, Biomass, Geothermal, Hydropower, Solar energy, Tidal power, Wave power, Wind power
5. List out the salient features of renewable energy resources. (M.E-NOV/DEC2010)
    - Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries.
    - Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits.
    - Renewable energy facilities generally require less maintenance than traditional generators.
    - Even more importantly, renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so has minimal impact on environment.
6. What is meant by spring and neap tides? (M.E-APR/MAY2013)

   During full or new moons which occur when the Earth, sun, and moon are nearly in alignment average tidal ranges are slightly larger. In this case, the gravitational pull of the sun is "added" to the gravitational pull of the moon on Earth, causing the oceans to bulge a bit more than usual. This means that high tides are a little higher and low tides are a little lower than average. These are called **spring tides**. Seven days after a spring tide, the sun and moon are at right angles to each other. When this happens, the bulge of the ocean caused by the sun partially cancels out the bulge of the ocean caused by the moon. This produces moderate tides known as **neap tides**, meaning that high tides are a little lower and low tides are a little higher than average. Neap tides occur during the first and third quarter moon, when the moon appears "half full."

7. How is a fuel cell characterized? (M.E-APR/MAY2013)

The fuel cell characterization is of particular importance to the fuel cell developers, scientists and researchers. Therefore, it is one of the most important topics of the fuel cell technology. Once the fuel cell is fabricated, it is required to access whether a fuel cell is good or bad from the pool of the developed cells. It is required to know whether the fuel cell is comparatively inferior or superior to the competitive cell either prepared by others or the improvement from the previous cells. In order to distinguish between inferior or superior fuel cell, the characterization techniques are very straight forward by using i-v characteristics of the fuel cell. The fuel cell characterization can be divided into two broad categories,

In-situ characterization: In–situ characterization means the fuel cell is fabricated and now you would like to performance of the fuel cell. You may also be interested to know how much losses are occurring in the fuel cell, quantity of the losses, location of the losses etc. Thus we have to characterize the fuel cell in the ready form. A few major in-situ characterization techniques are

1. Current voltage measurements
2. Current interruption technique
3. Cyclic voltammetry
4. Electrochemical impedance spectroscopy

Ex-situ characterization: Once we know that the performance of the fuel cell is not upto the desired standards then we have to find out the route cause. We need to identify the problematic component(s) as well as the reasons of ill-performance. Thus we need to characterize the component for its properties. Various characterization techniques may be followed depending upon the individual components of the fuel cell. A some of them are shown below,

Electrolyte: Proton conductivity; cross-over etc.

Bipolar plate: Mechanical and chemical strength; flow field design; electrical conductivity etc.

Catalyst: Surface area; selectivity etc.

Gas diffusion layer: Porosity; hydropholicity; hydrophilicity; strength etc.

8. What are fuel cells? (M.E-NOV/DEC2010)

A fuel cell is an electrochemical cell that converts the chemical energy from a fuel into electricity through an electrochemical reaction of hydrogen fuel with oxygen or another oxidizing agent. Fuel cells are different from batteries in requiring a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy comes from chemicals already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied.

9. Justify how fuel cell becomes renewable energy source. (APR/MAY2017)

Fuel cells have the potential to be used for cogeneration of electricity and heat, covering thus the heat and power needs for domestic and other larger scale industrial applications, which is very interesting under the perspective of the steadily increased tendency for decentralized power production. Fuel cell systems are flexible regarding the power output and they can be used for the power production of electrical power in the region from 50 W to 100 MW. Specifically, the power output of small portable systems can be as low as a few watts, whereas in the case of biological fuel cells for medical applications the power output can be lower. They produce zero or very low emissions, especially Green House Gases (GHGs) depending on the fuel used.

10. Mention the use of a fuel cell. (ME-Nov/Dec17)
    - They produce zero or very low emissions, especially Green House Gases (GHGs) depending on the fuel used.
    - Modular in design, offering flexibility in size and efficiencies in manufacturing
    - Can be utilized for combined heat and power purposes, further increasing the efficiency of energy production
11. What are the contributions of GHG Emissions in renewable energy generation?
    The acceleration of GHG emissions indicates a mounting threat of runaway climate change, with potentially disastrous human consequences. The utilization of Renewable energy sources together with improvement of the energy end use efficiency can contribute to the reduction of primary energy consumption, to the mitigation of GHG emissions and thereby to the prevention of dangerous climate change.
12. What is hydrogen energy?
    Hydrogen has been identified as a potential zero emission energy carrier for the future, primarily transport sector. Hydrogen is an energy carrier but not an energy resource, and thus hydrogen must be produced. Hydrogen can be produced from coal, natural gas, propane gas, biomass and water. Some organic substances can be used for hydrogen production and they includes methanol synthesized via synthesis gas from natural gas and coal.
13. Define solar insolation.
    Solar insolation is a measure of solar radiation energy received on a given surface area in a given time. It is commonly expressed as average irradiance in watts per square meter or kilowatt-hours per square meter per day. In the case of photovoltaics it is commonly measured as kilowatt hours per year per kilowatt peak rating.

UNIT-2

PART-A

1. Define reference theory. (M.E-NOV/DEC2013)
   The reference frame theory is a powerful tool for the analysis of electrical machines and it helps in the design of sophisticated control techniques. By using the reference frame theory, it is possible to transform the phase variable machine description to another reference frame. Moreover, this theory reduces the complexity involved in the modeling of electrical machines.
2. Write the significance of reference theory. (APR/MAY2017)

The voltage equations that describe the performance of induction and synchronous machines are functions of the rotor speed, whereupon the coefficients of the differential equations that describe the behavior of these machines are time varying except when the rotor is stalled. A change of variables is often used to reduce the complexity of these differential equations. This general transformation refers machine variables to a frame of reference that rotates at an arbitrary angular velocity. This transformation is set forth because many of its properties can be studied without the complexities of machine equations. By this approach, many of basic concepts and interpretations of this general transformation are readily and concisely established.

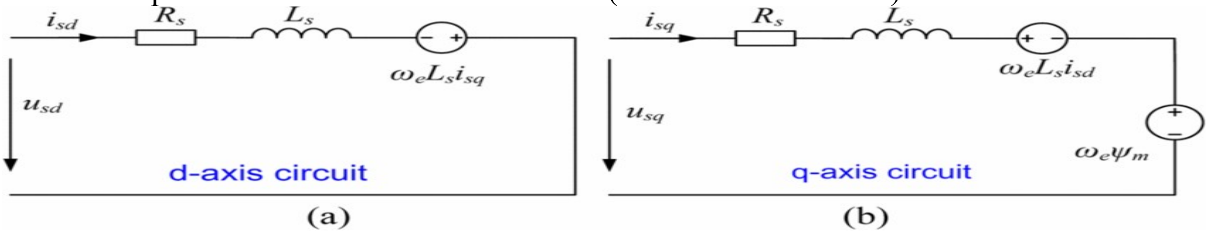
3. Why are induction generators preferred over DC generators in WECS? (M.E-NOV/DEC2016) (M.E-APR/MAY2013)
   - Simple and robust construction.
   - Can run independently.
   - Inexpensive.
   - Minimal maintenance.
   - Inherent overload protection.
   - At high speed, reduces size and weight of machine and filter components.
4. What is the principle of operation of induction generator? (M.E-NOV/DEC2010)

   An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls. An induction generator usually draws its excitation power from an electrical grid; sometimes, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot usually "black start" a de-energized distribution system.

5. Name any four types of generators used in wind energy conversion systems. (APR/MAY2017)

Induction generator, Permanent Magnet synchronous generator, Squirrel cage induction generator, doubly fed induction generator

6. Draw the equivalent circuit model of a PMSG. (M.E-NOV/DEC2016)



7. What are the merits of squirrel cage induction generator for wind energy conversion? (M.E-NOV/DEC2010)

- The low cost and low maintenance requirements of induction generators.
- Another advantage is that it can be on the ground, completely separate from the wind machine. If there is a problem in the converter, it could be switched out of the circuit for repair and the wind machine could continue to run at constant speed.

8. What is meant by DFIG? (M.E-NOV/DEC2013)

DFIG for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed.

9. What are the constructional differences between SCIG and DFIG? (M.E-APR/MAY2013)

SCIG	DFIG
Only stator is connected to electrical source	Both rotor and stator are connected to electrical sources
Rotor is made up of solid conducting bars embedded in the slots of a magnetic core	The rotor has three phase windings which are energized with three phase currents

10. Define tip-speed ratio.

The tip-speed ratio, X, or TSR for wind turbines is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind. The tip-speed ratio is related to efficiency, with the optimum varying with blade design. Higher tip speeds result in higher noise levels and require stronger blades due to large centrifugal forces.

$$\lambda = \frac{Tip\ speed\ of\ blade}{wind\ speed}$$

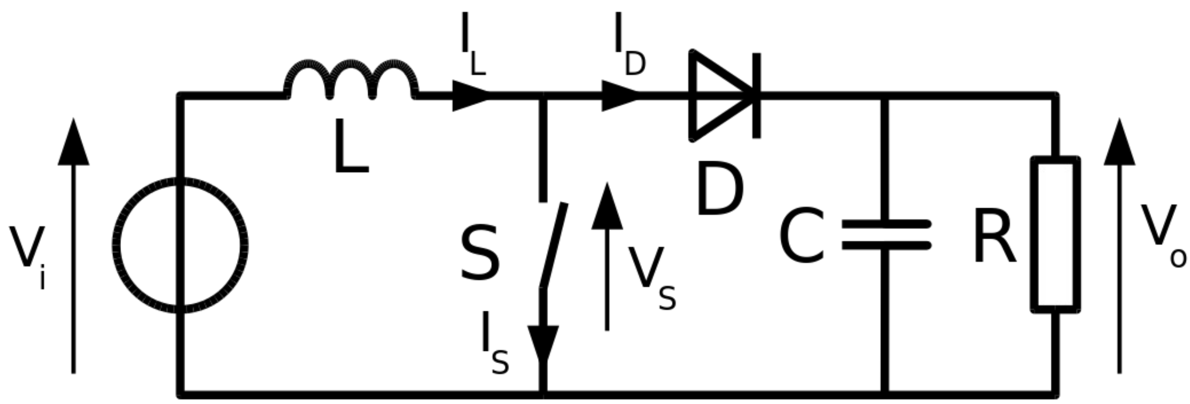
11. What is meant by pitch angle control?
Blade pitch control is a feature of nearly all large modern horizontal-axis wind turbines. While operating, a wind turbine's control system adjusts the blade pitch to keep the rotor speed within operating limits as the wind speed changes. Feathering the blades stops the rotor during emergency shutdowns, or whenever the wind speed exceeds the maximum rated speed. During construction and maintenance of wind turbines, the blades are usually feathered to reduce unwanted rotational torque in the event of wind gusts.

UNIT-3

PART-A

1. What are the advantages of boost and buck converters? (M.E-NOV/DEC2013)
   Advantages of buck converter:
   - It has high efficiency
   - di/dt of the load current is reduced by inductor L
   - This circuit requires only one transistor.

   Advantages of boost converter:
   - Input current is continuous
   - This regulator can step up the output voltage
2. Draw the schematic of boost converter. (M.E-NOV/DEC2010)



3. What is the function of boost converter in solar photovoltaic system? (APR/MAY2017)
   It is connected between PV panel and DC load. The main function of boost converter is to boost (step up) the output voltage of PV panel so that it can drive the load.
4. What are the factors to be considered for the selection of batteries for solar energy conversion system? (M.E-NOV/DEC2016)
   - Battery voltage
   - Battery capacity
   - Battery life cycle
   - State of charge (SOC)
   - Depth of discharge (DOD) (70-80% of DOD)
   - Discharge rate
   - Self discharge
5. What are the advantages of dc link inverters? (M.E-APR/MAY2013)
   - Lossless turn-on and turn-off of all devices

- Switching loss is less
- High efficiency up to 95%

6. What is a grid interactive inverter? State its significance. (M.E-NOV/DEC2016)
    - It acts as an interface that converts dc current produced by the solar cells into utility grade ac current.
    - The inverters must produce good quality sine wave output, must follow the frequency and voltage of the grid, and must extract maximum power from the solar cells with the help of MPPT.
    - The inverter input stage varies the input voltage until the maximum power point on the I-V curve is found.
    - The inverter must monitor all the phases of the grid, and inverter output must be controlled in terms of voltage and frequency variation.
7. What is meant by matrix converters? (APR/MAY2017) (M.E-NOV/DEC2013) (M.E-NOV/DEC2010)
   Matrix converter is capable of direct conversion from AC to AC by using bidirectional fully controlled switches. The matrix converter arranges semiconductor switches into a matrix configuration and controls them to convert an input AC voltage directly into the desired AC voltage.
8. Where is matrix converters used? (M.E-APR/MAY2013)
    - m phase to n phase conversion
    - All silicon motor drives with capability of regeneration
    - Grid interface for non conventional energy sources
    - Variable voltage, variable frequency power supplies
9. What is line commutated inverter?
   The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. The controlled rectifier can provide controllable output dc voltage in a single unit. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the inverter mode of operation and are known as "Line commutated inverter".
10. Define the photo conversion efficiency of the PV cell.
   The photo conversion efficiency of the PV cell is defined as the following:
   $$\eta = \frac{electrical\ power\ output}{solar\ power\ impinging\ the\ cell}$$
   Obviously, the higher the efficiency, the higher the output power we get under a given illumination.
11. What is the inversion mode operation of line commutated inverter?
   The driver circuit has to be changed to shift the firing angle from rectifier operation ($0<\alpha<90^0$) to inverter operation ($90^0<\alpha<180^0$).
12. What is the basic requirement of PV array sizing?

Maintain the energy balance over the specified period. The energy drained during lean times must be made up by the positive balance during the remaining time of the period.

UNIT-4

PART-A

1. Differentiate between fixed and variable speed wind energy conversion systems. (APR/MAY2017) (M.E-NOV/DEC2016) (M.E-NOV/DEC2010)

- For a fixed speed wind turbine, the generator is connected to the grid directly operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency.
- For a variable speed wind turbine the generator is connected to the grid through power electronics equipments. The rotor speed has the possibility to be controlled by those equipments.

2. What is meant by energy payback period? (M.E-APR/MAY2013)

The Energy Pay Back Time is defined by EPBT = E_{input}/E_{saved}, where E_{input} is the energy input during the module life cycle (which includes the energy requirement for manufacturing, installation, energy use during operation, and energy needed for decommissioning) and E_{saved} the annual energy savings due to electricity generated by the solar PV module.

3. What are the issues in connecting the renewable energy systems to the grid? (M.E-NOV/DEC2016)
    - Local issues: capacity, voltage control and stability, harmonics.
    - Large area issues: balance of power, transmission capacity.
4. List out the grid connection issues. (M.E-NOV/DEC2013)
    - Harmonics
    - Frequency and voltage fluctuations
    - Islanding issues
5. What are the major problems associated with grid integration of wind energy system? (APR/MAY2017)

    If the penetration of wind power into the grid is continuously increased, it might reach to a level where economics of the total power production is affected in a negative way. This will limit the penetration of wind power into the grid. The optimum penetration depends on specific circumstances and characteristics of the utility system. For higher power penetration, total electricity production system is to be re-optimized. This may require integration of some more peak load units or storage capacity plants. Also the distance of wind resource from the grid poses another limiting factor as it influences the economics of wind power.
6. Define grid integrated solar system. (M.E-NOV/DEC2013)

A grid-connected photovoltaic power system or grid-connected PV power system is an electricity generating solar PV power system that is connected to the utility grid. A grid-connected PV system consists of solar panels, one or several inverters, a power conditioning unit and grid connection equipment. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution, as they are still very expensive. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load, to the utility grid.

7. What will happen if no load is connected to a solar PV system? (M.E-APR/MAY2013)

   At no load the solar cell will be operating in open circuit condition. If there is internal shunting resistance it will slightly load the solar cell. This shunt resistance must be high enough such that it will not cause an appreciable loss of the photo voltaic power. The terminal open circuit voltage given in data sheet is measured with the shunt is present. Open circuit condition means that the there is no load connected to the cell. Under this condition the photo generated electrical power will be dissipated in the cell causing some temperature rise compared to the maximum operating power condition.

8. List out the issues to be addressed while integrating the solar PV systems with grid. (M.E-NOV/DEC2010)
   - Islanding
   - Variations in frequency
   - Harmonics

9. What is islanding?

   Islanding is the condition in which a distributed generator continues to power a location even though power from the electric utility grid is no longer present. Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered, even though there is no power from the electrical grid. For that reason, distributed generators must detect islanding and immediately stop producing power; this is referred to as anti-islanding.

10. Define Fill Factor

    The Fill Factor (FF) which indicates the quality of PV cell is defined as the ratio of peak power to the product of open circuit voltage and short circuit current.

    $FF= (V_m I_m) / (V_{OC} I_{SC})$

11. What is the role of back to back converter in wind energy conversion system?

    It is an AC/DC/AC converter which is widely used in renewable energy systems. For example, in a variable speed wind energy conversion system the general function of AC/DC/AC converter is to transmit the power generated from wind turbines to the grid. The converter should provide good abilities to transmit power effectively, respond quickly and accurately, and operate stably in potential extreme conditions.

12. What is inrush current?

    The small unavoidable difference between the site and the grid voltages will result in an inrush current to flow between the site and the grid. The inrush current eventually decays to zero at an exponential rate that depends on the internal resistance and inductance.

13. What is the main objective of MPPT converter in grid system?

- Capture the maximum available power from the solar panel whatever the condition of the climate.
- Step up the PV panel voltage to the required level of DC voltage in order to transfer

the captured power from the solar to the grid through inverter.

UNIT-5

PART-A

1. What is need of hybrid systems? (M.E-NOV/DEC2016) (M.E-NOV/DEC2013) (M.E-APR/MAY2013)
    - Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand.
    - Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply.
    - The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people.
    - Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance.
    - Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area.
    - Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.
2. What are the advantages of hybrid renewable energy systems? (APR/MAY2017)
    - Higher total energy efficiency
    - More reliable
    - Operational flexibility
    - Lower emission
3. What are the advantages of PV-Diesel hybrid system? (M.E-NOV/DEC2016)
   The diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption.
   No switching of ac power between different energy sources is required, which simplifies the electrical output interface.

The system load can be met in an optimal way.
Efficiency is high.
Fuel consumption is reduced.

4. Give the range of hybrid systems. (M.E-NOV/DEC2013)
    - Control methods are complex.
    - Power conditioning system design is quite difficult.
5. Name the various types of hybrid energy systems. (M.E-APR/MAY2013)
    - PV-wind hybrid system
    - PV-diesel hybrid system
    - Wind-PV hybrid with diesel
    - Biomass-wind-fuel cell hybrid system.
6. What is the importance of Maximum Power Point Tracking (MPPT) in the operation of a photovoltaic system? (APR/MAY2017)
The daily solar irradiation diagram has abrupt variations during the day. Under these conditions, the MPP of the PV array changes continuously; consequently the PV system's operation point must change to maximize the energy produced. An MPPT technique is therefore used to maintain the PV array's operating point at its maximum power point.
7. What are Hybrid Renewable Energy Systems? (M.E-NOV/DEC2010)
Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area. Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.
8. What are the types of PV-diesel hybrid systems?
    - Series hybrid energy systems
    - Switched hybrid energy systems
    - Parallel hybrid energy systems
9. List the various MPPT techniques
    - Constant voltage method
    - Hill climbing
    - Perturb and observe methods
    - Incremental conductance method
    - Neural network
    - Fuzzy logic control
10. What are the various stages adopted in fuzzy logic control?
    - Fuzzification
    - Rule based table lookup
    - Defuzzificztion

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DEPARTMENT OF ELECTRICALAND ELECTRONICS ENGINEERING

EE6009 – POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

QUESTION BANK - PARTB

UNIT-1

PART-B

1. What are the different types of fuel cells? Explain them with neat diagrams. (M.E-NOV/DEC2016)

Basically fuel cell in common language is a device which converts chemical energy from a fuel into electrical energy. It happens by undergoing a chemical reaction where positively charged hydrogen ions react with oxygen or any other oxidizing agent by an electrochemical process. The fuel cell consists of two electrodes where the reaction takes place; one is positively charged called anode and the negatively charged called cathode.

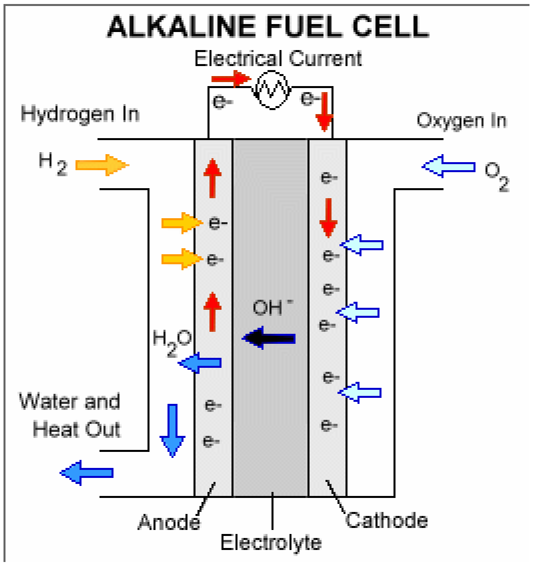
A single fuel cell consists of an electrolyte sandwiched between those two thin electrodes anode and cathode. This electrolyte and a catalyst are needed to fasten the reaction rate and to mobilise the ions to one electrode to the other. The electrons from the anode side of the cell cannot pass through the membrane to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current. The amount of power produced by a fuel cell depends upon several factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure at which the gases are supplied to the cell A single fuel cell generates a tiny amount of direct current (DC) Electricity. Many fuel cells are usually assembled into a stack. Cell or stack, the principles are the same.

On the basis of the electrolyte used the fuels cell can be classified as Follows:-

1. Alkaline Fuel Cell-alkaline solution electrolyte such as KOH.
2. Phosphoric Acid Fuel Cells (PAFC)-electrolyte is phosphoric acid.
3. Solid Proton Exchange Membrane Fuel Cell-electrolyte is polymer electrolyte membrane fuel cells and their electrolyte consists of the proton exchange membrane.
4. Molten Carbonate Fuel Cells-electrolyte as molten carbonate.
5. Solid Oxide Fuel Cells (SOFC)-electrolyte is ceramic ion conducting electrolyte in solid oxide form.
6. Regenerative Fuel Cell

Alkaline Fuel Cells (AFC)

The alkaline fuel cell uses an alkaline electrolyte such as 40% aqueous **potassium hydroxide**. In alkaline fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. It was originally used by NASA on space missions. NASA space shuttles use Alkaline Fuel Cells. Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water onboard spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. AFCs are high-performance fuel cells due to the rate at which chemical reactions take place in the cell. They are also very efficient, reaching efficiencies of 60 percent in space applications. The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO2). In fact, even the small amount of CO2 in the air can affect the cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell. CO2 can combine with KOH to form potassium carbonate which will increase the resistance. The purification process is costly.



Anode Reaction: $2H2 + 4OH^- \longrightarrow 4H2O + 4e^-$
Cathode Reaction: $O_2 + 2H2O + 4e^- \longrightarrow 4OH^-$

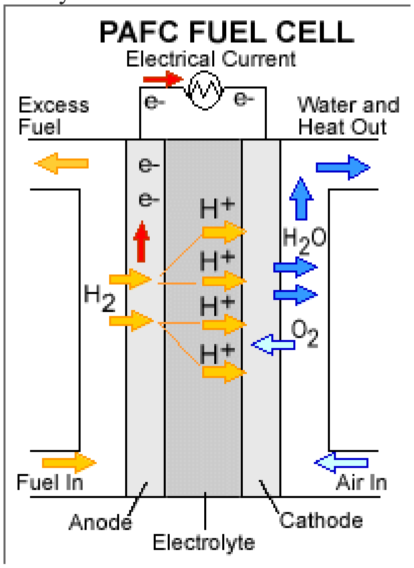
Phosphoric Acid Fuel Cells (PAFC)

A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon and a silicon carbide structure that holds the phosphoric acid electrolyte. In phosphoric acid fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat.

The phosphoric acid fuel cell (PAFC) is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially, with over 200 units currently in use. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

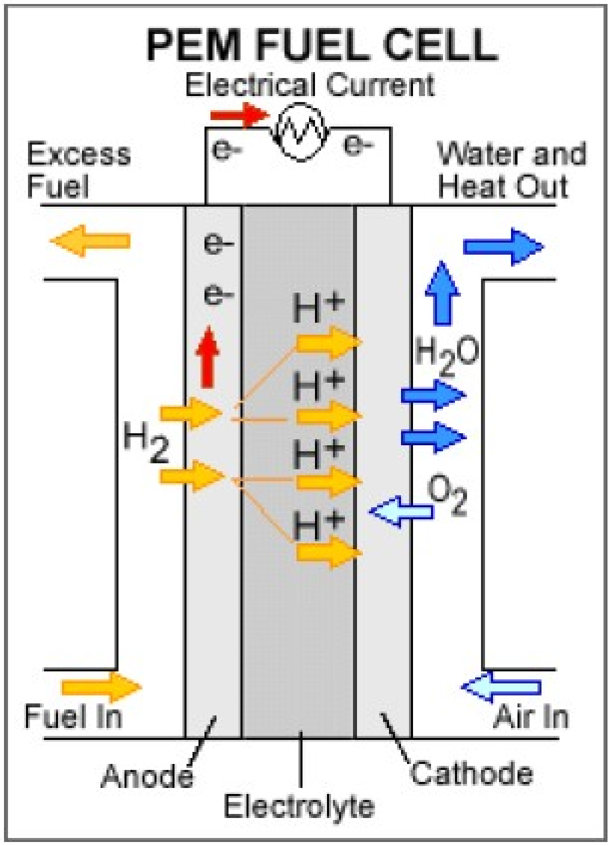
Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $O_2 (g) + 4H^+ + 4e^- \rightarrow 2H_2O$
Overall cell reaction: $2 H_2 + O_2 \rightarrow 2H_2O$

PAFCs are CO2-tolerant and even can tolerate a CO concentration of about 1.5 percent, which broadens the choice of fuels they can use. They have an efficiency of about 70%.



Solid Proton Exchange Membrane Fuel Cell

In polymer electrolyte membrane (PEM) fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat. Polymer electrolyte membrane (PEM) fuel cell uses a polymeric membrane as the electrolyte, with platinum electrodes. These cells operate at relatively low temperatures. These cells are the best candidates for cars, for buildings and smaller applications. Polymer electrolyte membrane (PEM) fuel cells—also called proton exchange membrane fuel cells—deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst.



Anode: $H_2 = 2H^+ + 2e^-$

Cathode: $1/2\ O_2 + 2H^+ + 2e^- = H_2O$

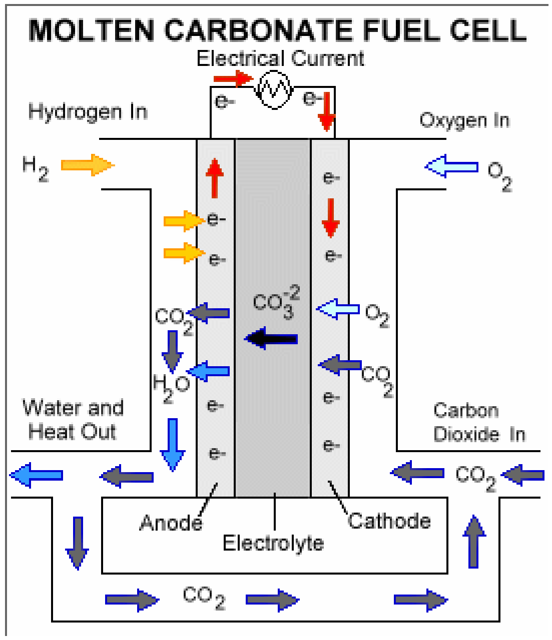
<u>Molten Carbonate Fuel Cells (MCFC):</u>

The molten carbonate fuel cell uses a **molten carbonate salt as the electrolyte.** It has the potential to be fuelled with coal- derived fuel gases, methane or natural gas. These fuel cells can work at up to 60% efficiency In molten carbonate fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications.

Anode Reaction: CO3-2 + H2 → H2O + CO2 + 2e-

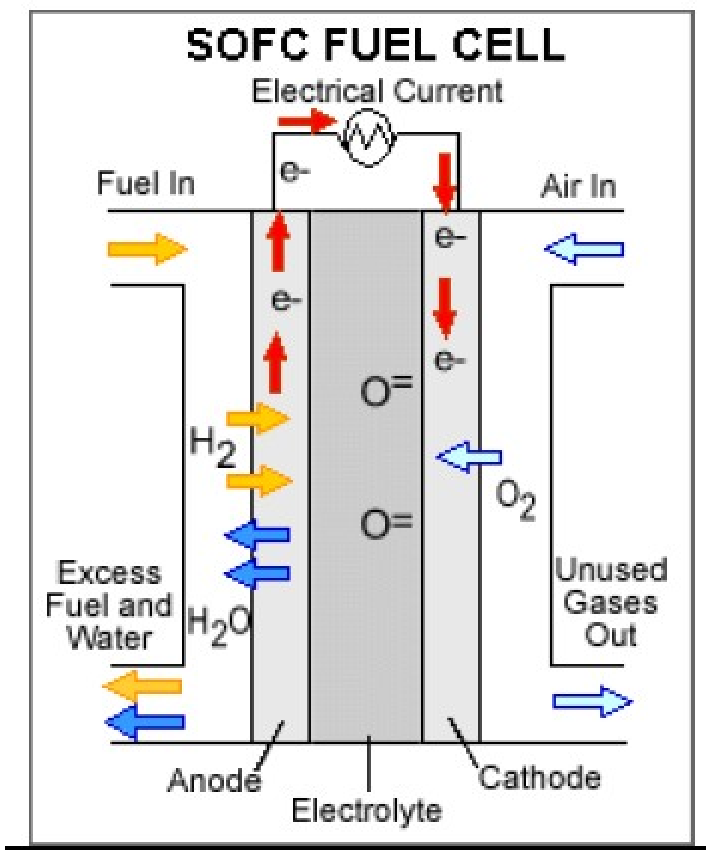
Cathode Reaction: CO2 + ½O2 + 2e- → CO3-2

Overall Cell Reaction: H2 + ½O2 → H2O



Solid Oxide Fuel Cells (SOFC)

They use a solid ceramic electrolyte, such as zirconium oxide stabilised with yttrium oxide, instead of a liquid and operate at 800 to 1,000°C. In solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. Efficiencies of around 60 per cent and are expected to be used for generating electricity and heat in industry and potentially for providing auxiliary power in vehicles. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types.



REGENERATIVE FUEL CELL

If a fuel cell is a device that takes a chemical fuel and consumes it to produce electricity and a waste product, an RFC can be thought of as a device that takes that waste product and electricity to return the original chemical fuel. Indeed any fuel cell chemistry can be run in reverse, as is the nature of oxidation reduction reactions.

When you run a fuel cell in reverse, the anode becomes the cathode and the cathode becomes the anode. The mechanics of an electrolyser are best understood using the hydrogen fuel cell as an example. In a hydrogen fuel cell, the goal is to consume hydrogen and oxygen to generate water and an electric current that can be used to perform work. The oxidation reaction occurs at the anode, breaking down hydrogen H2 gas into positive hydrogen ions and negative electrons. The reduction reaction occurs at the cathode combining hydrogen and oxygen and electrons into water. An external wire between the anode and the cathode completes the circuit, allowing electrons to flow from the anode to the cathode. This current can be used to supply useful work. By contrast, supplying a current and reversing the polarities of the electrodes in the hydrogen fuel cell results in a regenerative hydrogen fuel cell. The electrode that was once the cathode is now the anode; it oxidizes water decomposing it into oxygen gas O2, hydrogen ions and electrons. The electrode that was once the anode is now the cathode; it reduces hydrogen and electrons into hydrogen gas. The external current will have to be supplied from a power source, like a solar cell.

$$H2 + ½O_2 \rightarrow H_2O$$

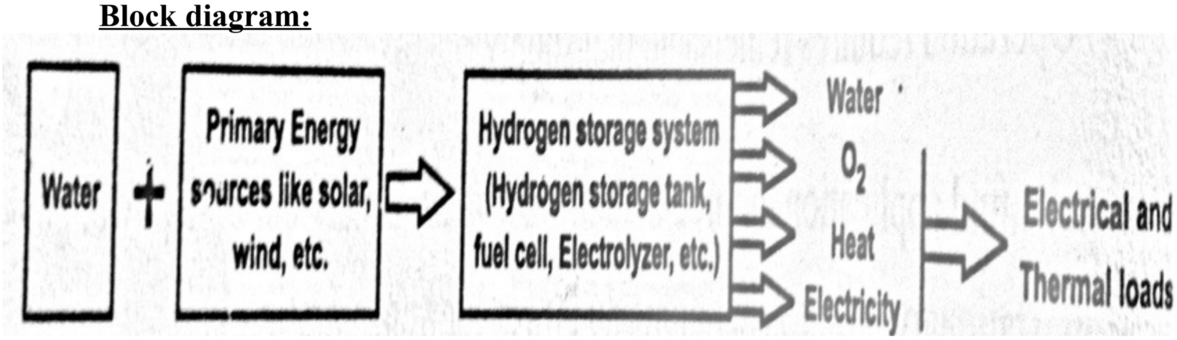
Fuel Cell Efficiency

Since fuel cells use materials that are typically burnt to release their energy, the fuel cell efficiency is described as the ratio of the electrical energy produced to the heat that is produced by burning the fuel. From the basic definition of efficiency: $\eta = W / Qin$

2. What is Hydrogen energy? Explain the operation of hydrogen energy system with a neat schematic. (APR/MAY 2017) (M.E-NOV/DEC 2010)

   Hydrogen has been identified as a potential zero-emission energy carrier for the future, primarily for the transport sector. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, little or no acid rain ingredients and pollution. Hydrogen is an energy carrier but not an energy resource, and thus hydrogen must be produced. It can be produced from coal, natural gas, propane gas, biomass and water. Some organic substances can be used for hydrogen production and they includes methanol synthesized via synthesis gas from natural gas and coal, ethanol made from biological fermentation of crops and biomass etc. For some special applications, hydrogen containing inorganic compounds such as ammonia and hydrogen sulphide have also been considered as source compounds for hydrogen production. The cost of hydrogen production is an important issue. Hydrogen produced by steam reformation costs approximately three times the cost of natural gas per unit of energy produced. Hydrogen storage is an obstacle for the introduction of hydrogen in the transportation sector. There are three options- compressed gas, liquefied gas and hydrogen stored inside pores in solid, porous materials. None of these are satisfactory.

   Block diagram:



Conversion of Hydrogen Energy into Electricity:

Hydrogen gas is an expensive and complex fuel to make because it has to be separated from whatever element it is joined to. It often takes a lot of energy to make hydrogen gas, making it a costly power source. There are a number of ways to separate hydrogen from its companion elements.

Before we look at how hydrogen is converted into electricity, it would be beneficial to know how hydrogen is produced. Hydrogen is produced using two main methods; steam reforming and electrolysis (commonly referred to as water splitting).

Steam reforming

This method produces hydrogen from hydrocarbon fuels such as methane, oil, renewable liquid fuels, gasified biomass, gasified coal and natural gas. A processing device called a reformer is used in this hydrogen production process. The reformer react steam with the hydrocarbon fuels at extremely high temperatures to generate hydrogen. Today, over 90% of hydrogen gas is produced using the steam reforming technique.

Electrolysis

Electrolysis is a method that utilizes direct current (DC) to instigate a chemical reaction. In the production of hydrogen, electrolysis decomposes water and splits it into its main elements, which are hydrogen and oxygen by use of an electric current. The electricity used in the electrolysis process can be derived from fossil fuels such as oil, natural gas, and coal or hydrocarbons.

Fuel Cells:

The most effective way to convert hydrogen into oxygen is using a fuel cell. A fuel cell converts chemical energy into electrical energy. A fuel cell enables hydrogen and oxygen to blend in an electrochemical reaction. The result is production of electricity, water, and heat. Fuel cells mimic batteries since they both convert the energy generated by the electrochemical reaction into useful electric power. Nonetheless, the fuel cell will generate electric power as long as fuel, mainly hydrogen, is available.

Fuel cells represent a potential technology for use a source of electricity and heat for buildings. It's also a promising source of power for electric and hybrid vehicles. Fuel cells function best on pure hydrogen. However, other fuels such as gasoline, methanol, or natural gas can be reformed to generate the needed hydrogen for fuel cells.

With technology moving fast, hydrogen could come on par with electricity as a vital energy carrier. An energy carrier transmits energy to the customer in a ready to use form. Some renewable energy sources such as wind and sun may not be able to generate energy around the clock, but are able to produce hydrogen and electric power and stored for later use.

Issues regarding storage include

- Operating pressure and temperature
- Life span of storage material
- Requirements of hydrogen purity imposed by fuel cell
- Reversibility of hydrogen uptake and release
- Refuelling conditions of rate and time
- Hydrogen delivery pressure
- Overall safety, toxicity and cost

Advantages:

- High energy yield
- Most abundant element
- Produced from many primary energy sources
- Most versatile fuel

Disadvantages:

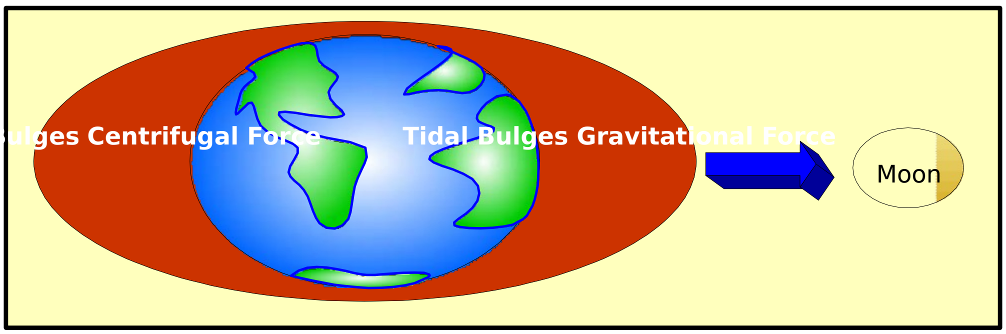
- Low density (large storage area)
- Not found free in nature
- Low ignition energy
- Currently expensive

3. Enumerate the prospects of ocean energy. (M.E-APR/MAY 2013) (M.E-NOV/DEC 2010)

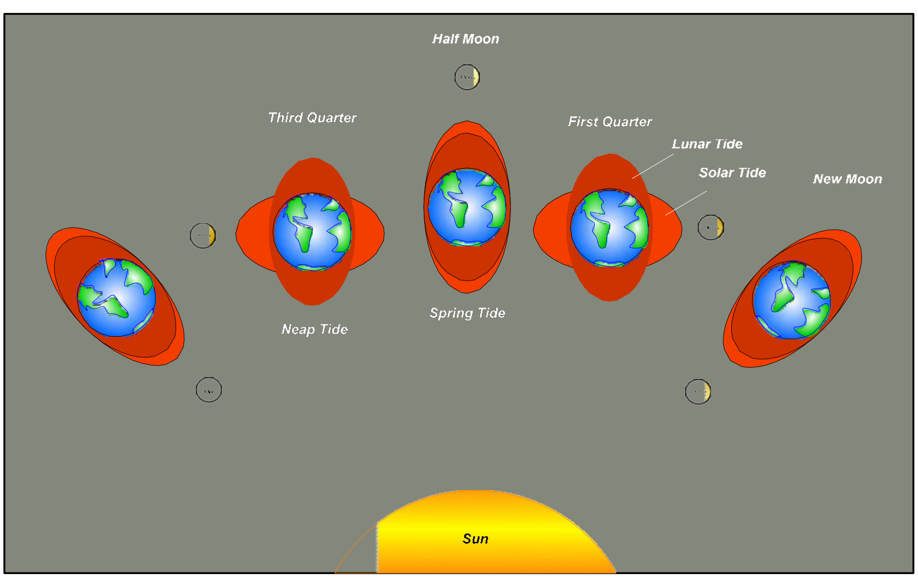
From the oceans we can harvest: thermal energy, from the temperature difference of the warm surface waters and the cool deeper waters, as well as potential and kinetic energy, usually lumped as mechanical energy, from the tides, waves and currents. The technological concept to harvest the thermal energy in the ocean is universally called Ocean Thermal Energy Conversion (OTEC). The basic electric generation systems are: *closed-cycle, open-cycle,* and *hybrid.* Oceans mechanical energy is very different from the oceans thermal energy. Tides are driven primarily by the gravitational pull of the moon, waves are driven primarily by the winds and ocean currents are even more complex driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. For these reasons tides, waves and currents are intermittent sources of energy, while ocean thermal energy is quite constant. The electricity conversion of all three usually involves mechanical devices. This Ocean Energy Resource section is organized in terms of the energy resource. We will discuss in order; tides, currents, thermal and waves.

Tides

The interaction of the sun-moon-earth system causes ones of the strangest phenomena: *tides*. Tides rise and fall is the product of the gravitational and centrifugal forces, of primarily the moon with the earth. The gravitational forces maintain the moon on its positions with respect to the earth, forcing to pull the earth and the moon together see Figure. The centrifugal force acts on the opposite direction pulling the moon away from the earth. These two forces act together to maintain the equilibrium between these two masses. The influence of the sun can be included on the balance of the entire system. The distance plays an important role on the development of the tides. Based on the Newton's laws, the gravitational force is proportional to the square of the distance of two bodies, but the tidal force is proportional to the cube of the distance. For this reason although the moon has a much smaller mass than the sun it is much closer to the earth. The moon effect is 2¼ greater than that of the sun on the generation of tides.



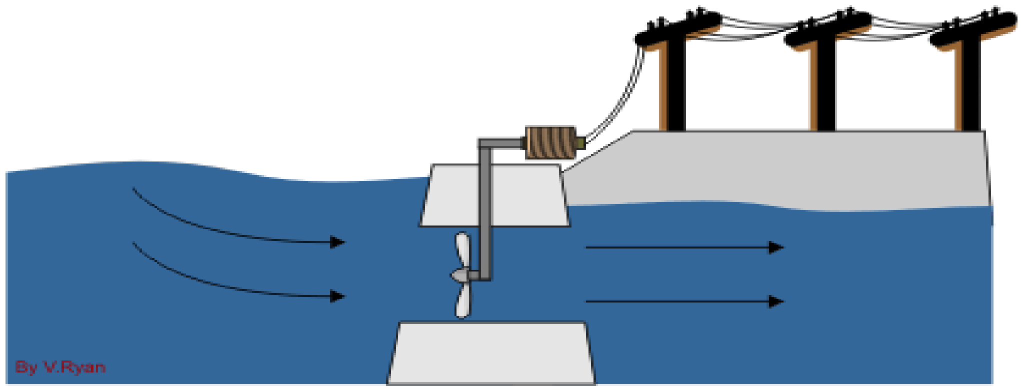
The gravitational force of attraction of the moon causes that the oceans waters bulge on the side of the earth that faces the moon. The centrifugal force produce the same effect but in the opposite side of the earth. On these two sides it can be observe the maximum amplitudes of the tides (high tides) and on the midways of it occur the minimum amplitudes of the tides (low tides). As the earth rotates these two bulges travel at the same rate as the earth's rotation. The moon rotates around the earth with respect to the sun approximately 29.5 days (lunar month) in the same direction that the earth rotates every 24 hours. The rotation of the earth with respect to the moon is approximately 24.84 hours (24 hours and 50 minutes) and is called lunar day. This is the reason of why the tides advance approximately 50 minutes each day. In the same manner that the ocean waters bulges towards the moon, the gravitational force of the sun causes that the ocean waters bulges too but in a lesser degree. Twice a month, when the earth, the moon and the sun are aligned (full and new moon) the tide generating forces of the sun and the moon are combined to produce tide ranges that are greater than average knowing as the *spring tides.* At half moon (first and third quarters) the sun and the moon are 90º with respect to the earth and the tide generating forces tend to produce tidal ranges that are less than the averages knowing as the *neap tides*, see Figure below. Typically the spring tides ranges tend to be twice of the neap tides ranges.



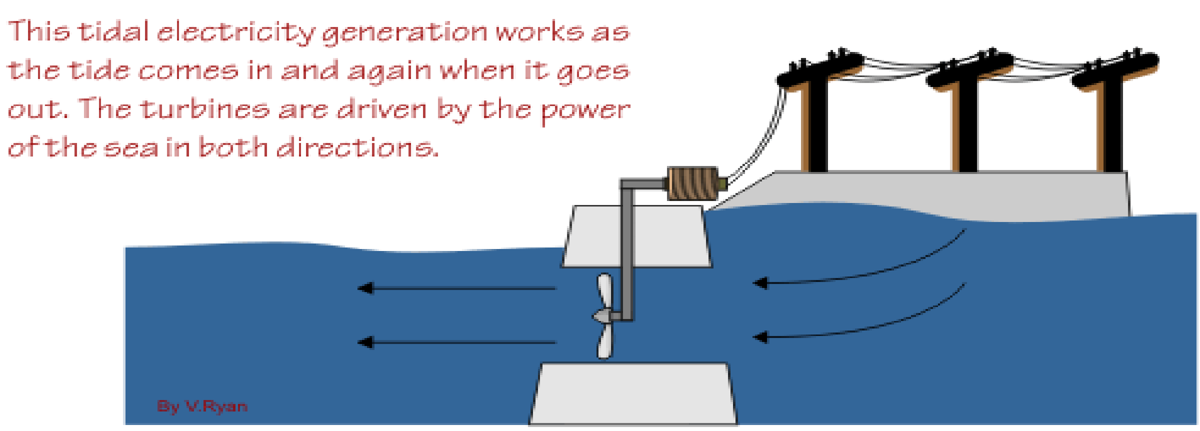
The tidal movements can be reflect and restrict by the interruption of masses of land, the bottom friction can reduce its velocity and the depth, size and shape of the ocean basins, bays and estuaries altered the movements of the tidal bulges and generate different types of tides. There are three types of tides: diurnal, semidiurnal and mixed.

Tidal Energy to Electric Energy Conversion

The technology that is use to produce electricity using the difference between the low and high tides is very similar to the one use on the generation of electricity on the traditional hydroelectric power plants. The use of the tidal energy requires a dam or barrage across a shallow area preferably an estuary, bay or gulf of high tidal range where the difference on the low and high tide have to be at least 5 meters. The tide basins are filled and empty every day with the flood tides when the water level rises and with the ebb tides when the water level falls. On the barrage there are low-head turbines and sluices gates that allow the water to flow from one side of the barrage to inside the tidal basin. This difference on elevation of the water level creates a hydrostatic head that generates electricity. There are different modes to generate electricity using the barrage systems:



TIDE COMING IN



TIDE GOING OUT

Ebb generation - Incoming water (flood tide) is allowed to flow freely to fill the basin until high tide, then the sluices are close and water are retained on one side of the barrage. When the level of the water outside of the barrage decreased (ebb tide) sufficiently to create a hydrostatic head between the open waters and the tide basin, the sluices are open and water flows through the turbines and generate electricity. Once the head is low the sluices gates are open and the basin is filled again.

Flood generation - During the flood tide the sluices gates and low-head turbines are kept closed to allow the water level outside of the barrage to increase. Once a hydrostatic head is created the sluices gates are opened and the water flows through the turbines into the basin. This mode is less efficient than the ebb mode.

Two way generation - This mode permits to generate electricity using both the ebb and the flood tide. The main problem with this type of mode is that the turbines must work both ways, when water enters or exits the basin. This requires more expensive turbines and at this time computer simulations do not indicate that this mode increases significantly the energy production.

Pumping- On the ebb generation the hydrostatic head can be increased reversing the power and turning the turbine-generator into a pump-motor. During the generation the energy that was use is returned.

Double basin- All of the modes discuss above use one tide basin. Using two basins, the turbines are placed between the basins. The main basin will going to use the ebb generation mode to operate and pump water with part of the energy that is generated to and from the second basin to generated electricity continuously. This mode has the disadvantage that is very expensive.

Ocean Currents

Ocean currents are driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. Current can be divided in two types: marine currents and tidal currents. Marine currents are relatively constant and flow in one direction. Tidal currents occurred close to the shore due to gravitational forces. Currents are flowing bodies like wind. Current energy can be calculated using the formula of kinetic energy of flowing bodies, $K_E=0.5*p*v^2$. The kinetic energy of flowing bodies is proportional to the cube of their velocities and their density. Ocean energy can be compared with wind energy because these two types of resources are two forms of flowing bodies. The speed of ocean currents is lower when compared to wind speeds but the water is 832 times denser than air. Also ocean currents can be predicted with years in advanced as these depend of the movements of the sun and moon. Through the world there can be found ocean currents of more than five knots or 2.5m/s
(1 knot=0.50 m/s) and current energy has been estimated greater than 5,000 GW, with power densities of up to 15 kW/m^2.

Currents Energy to Electric Energy Conversion

Technologies to convert ocean currents energy into electricity are under development. Several devices are being tested and are very similar to wind energy technologies, consisting in turbines of horizontal and vertical axis of rotation used underwater. The purpose of these technologies is to capture the ocean currents generated by the flow created by the motion of tides. In the horizontal axis turbines the rotational axis is parallel to the directional of the water flow. In vertical axis systems the rotational axis turbines rotate perpendicular to the water flow.

Ocean Thermal Energy

The large difference between the temperatures of the ocean surface waters, especially on the tropics and the deep seawaters stimulate the presence of thermal gradients. Based on this concept, the Ocean Thermal Energy Conversion (OTEC) has been proposed and is currently under development. OTEC converts the difference between warm surface waters and cold deeper waters (approximately 1000 m below the surface) into energy.

Ocean Thermal Energy Conversion (OTEC)

OTEC offers the advantage of a resource which is available almost equally during the day and night with slightly variations on winter and summer. This renewable source can be combined with other applications that are deriving from it like: mar culture, potable water production and air conditioning refrigerant among others.

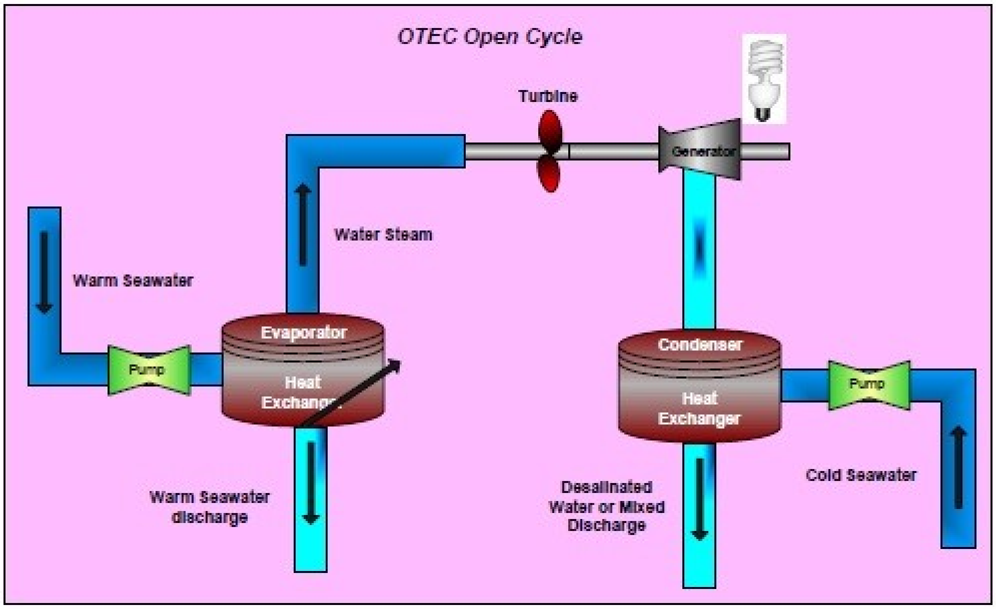
OTEC power plants must be located on areas where the ocean water temperature difference of at least 20º C can be accomplished. But other factors have to taking into account before considered a particular location suitable for an OTEC development. Some of these factors are

- Distance from the thermal resource to the shore (grid interconnection),
- Depth of the cold water location and sea bottom,
- Type of OTEC facility (Shoreline or near-shoreline, platforms or free-floating), Oceans conditions (waves, currents),
- Sea bottom conditions (mooring, floating power conductors installations), Environmental Impacts
- Deep Ocean Water Applications (DOWA) potential, Government's incentives, and others.

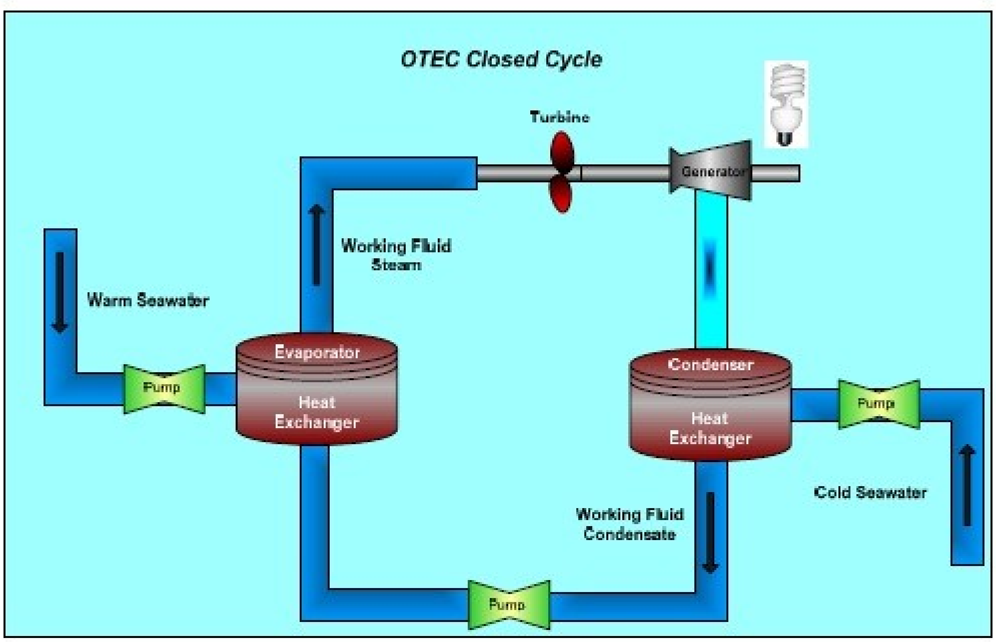
To operate an OTEC plant to generate electricity two working cycles can be used: the OTEC closed cycle proposed by Arsene d'Arsonval and the OTEC open cycle proposed by Georges Claude.

OTEC working cycles

Open Cycle - In the open cycle warm seawater can be use as the working fluid. When the surface seawater is flashed evaporated it is pumped into a vacuum chamber to produce a spray of the liquid. Making the pressure of the chamber less than the saturation pressure of the spray of the water, it starts to boil. The steam that is produce passes through the turbine to generate electricity. The steam later condensates using the cold seawater and is not returned to the evaporator. This condensation process can be done using two methods: spray cold seawater over the steam or in a surface condenser in which the steam and the coldwater do not enter in contact with each other, producing desalinated water. If the condensation is done using the spray method the mixed of steam and cold water is discharged back to the ocean, see Figure below.

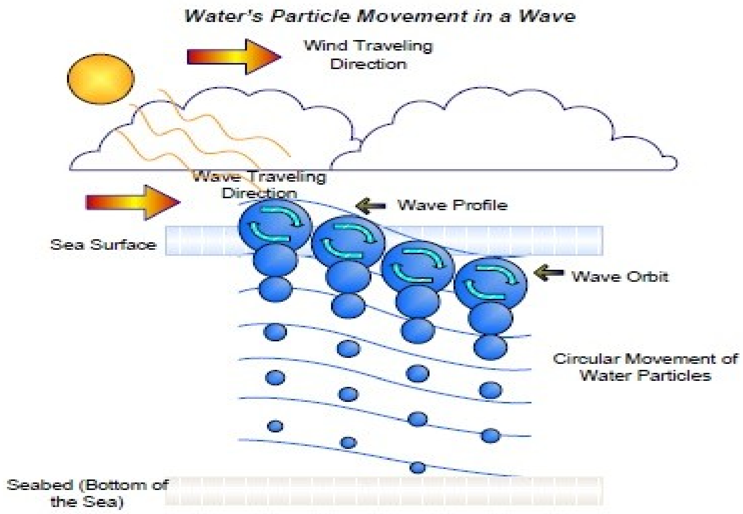


Closed Cycle - In the OTEC closed cycle two working fluids work to complete the cycle. First, it is necessary to use warm seawater to vaporize a second working fluid such as ammonia, propane or a Freon-type refrigerant. This second working fluid will flow through an evaporator (heat exchanger). The high pressure steam that is produced moves a turbine that is connected to a generator that produces electricity. After the steam moves the turbine, it is condensate using the cold seawater that is pumped from the depths and is pumped back to the evaporator to start the cycle. The turbines that are use in the closed cycle are usually smaller than the ones use in the open cycle because the density and operating pressure of the second working fluid are higher, see Figure below

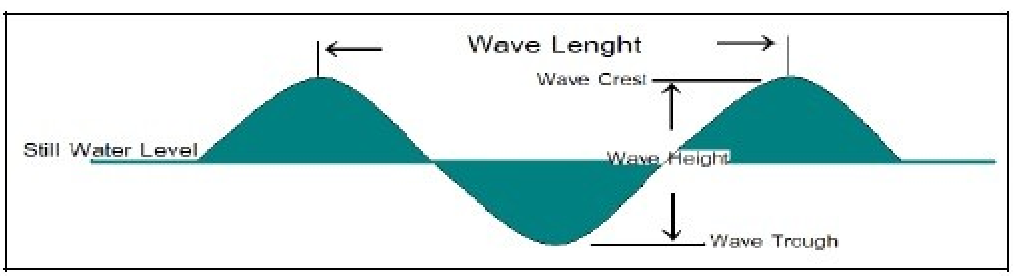


Ocean Waves Energy

Waves can be formed through the presence of many forces that acts on the ocean surface. The gravitational forces like the one that acts between the Earth, the Moon and the Sun and the geological forces that produce subsea earthquakes that can generate tsunamis are some of the forces that act on the formation of ocean waves. But the most common and known form of waves are the ones that are derivative of the solar energy. When the sun heats the earth surface it generates zones with different pressures that produce winds. As those winds blows over the ocean surface the friction that is created between the wind and the water forms the waves, see Figure below. The increase on the speed of the winds cause that the waves increase on height and mass much faster that in depth. The size of the waves will depend on three (3) factors: Strength of the winds, Amount of time that the winds blow, the distance (fetch) over which it blows.



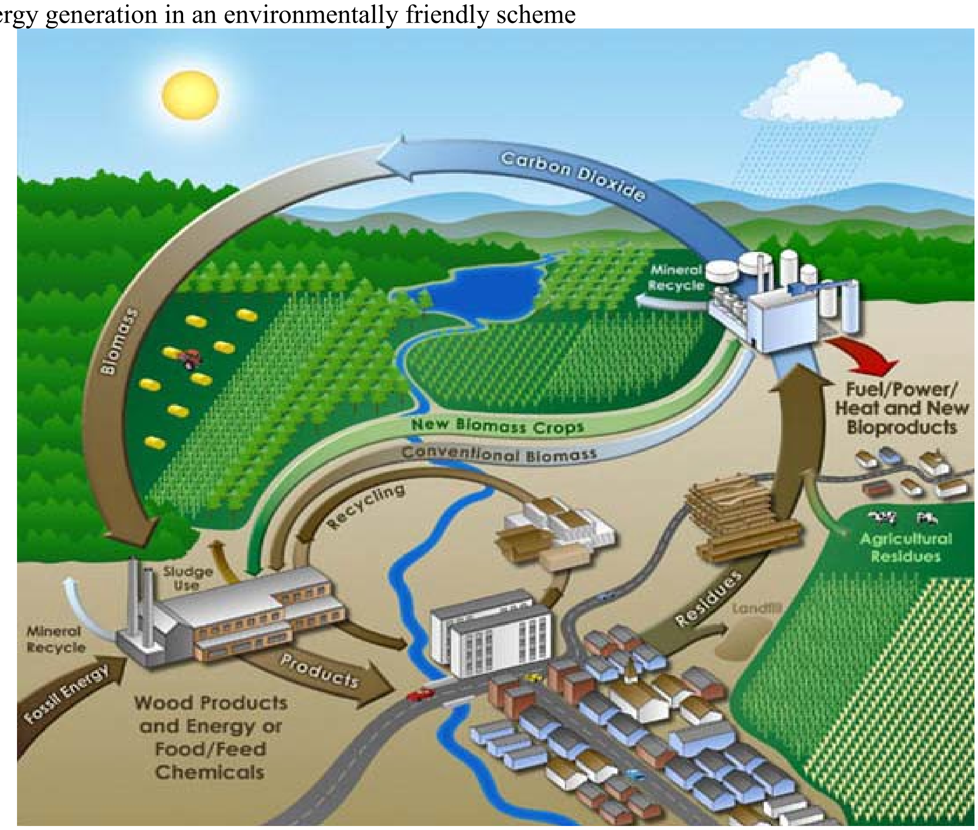
Waves can be characterized by its height (H), its period (T) and its wave length (λ). The wave height is the vertical elevation of the wave crest above the trough; normally it is less than 1/7 of its length. The wave period is the interval of time that it takes for two wave crests to pass a fixed point and the wave length is the horizontal distance between two crests, see below Figure.



Ocean waves vary from location because steady wind causes longer wave duration and with the seasons of the year, because the waves are larger on winter than in summer. Ocean waves can be classified in two types: the *local seas* and the *swells. Local seas* are ocean waves generated by the action of the winds on the location that they blow; their length is ten to twenty times their height. The *swells* are a group of long and short waves that can travel thousands of miles from their point of origin, which normally is a storm in the middle of the ocean. These types of waves suffer little attenuation and arrive at distant coasts with fury.

4. Enumerate the prospects of biomass energy. (M.E-APR/MAY 2013)
   Biomass is a term used to describe all organic matter produced by photosynthesis, existing on the earth's surface. They include all water- and land-based vegetation and trees, and all waste biomass such as municipal solid waste (MSW), municipal bio solids (sewage), and animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes. The world's energy markets have relied heavily on the fossil fuels. Biomass is the only other naturally occurring energy-containing carbon resource that is large enough in quantity to be used as a substitute for fossil fuels. Through the process of photosynthesis, chlorophyll in plants captures the sun's energy by converting carbon dioxide from the air and water from the ground into carbohydrates, i.e., complex compounds composed of carbon, hydrogen, and oxygen. When these carbohydrates are burned, they turn back into carbon dioxide and water and release the sun's energy they contain. In this way, biomass functions as a sort of natural battery for storing solar energy. The exploitation of energy from biomass has played a key role in the evolution of mankind. Until relatively

recently it was the only form of energy which was usefully exploited by humans and is still the main source of energy for more than half the world's population for domestic energy needs. One of the simplest forms of biomass is a basic open fire used to provide heat for cooking, warming water or warming the air in our home. More sophisticated technologies exist for extracting this energy and converting it into useful heat or Power in an efficient way. In the mid-1800s, biomass, principally wood biomass, supplied over 90% of U.S. energy and fuel needs, after which biomass energy usage began to decrease as fossil fuels became the preferred energy resources. This eventuality of fossil fuel and the adverse impact of fossil fuel usage on the environment are expected to be the driving forces that stimulate the transformation of biomass into one of the dominant energy resources. Unlike fossil fuels, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource. Biomass also is the only renewable energy source that releases carbon dioxide in use. However the release is compensated by the fact that the biomass grown uses the carbon dioxide from the atmosphere to store energy during photosynthesis. If the biomass resource is being used sustainably, there are no net carbon emissions over the time frame of a cycle of biomass production. Below Figure shows a biomass energy cycle and the way biomass is utilized for energy generation in an environmentally friendly scheme



METHODS OF EXTRACTING BIOMASS ENERGY

Biomass can be converted to thermal energy, liquid, solidor gaseous fuels and other chemical products through a variety of conversion processes. All of today's capacity is based on mature, direct-combustion technology. Future efficiency improvements will include co-firing of biomass in existing coal-fired boilers and the introduction of high-efficiency gasification, combined-cycle systems, fuel cell systems, and modular systems. Generally, the prominent bio power technologies are comprised of direct combustion, co-firing, gasification, pyrolysis, anaerobic digestion, and fermentation.

1. Direct Combustion

This is perhaps the simplest method of extracting energy from biomass. Industrial biomass combustion facilities can burn many types of biomass fuel, including wood, agricultural residues, wood pulping liquor, municipal solid waste (MSW) and refuse-derived fuel. Biomass is burned to produce steam, the steam turns a turbine and the turbine drives a generator, producing electricity. Because of potential ash build-up (which fouls boilers, reduces efficiency and increases costs), only certain types of biomass materials are used for direct combustion.

2. Gasification

Gasification is a process that exposes a solid fuel to high temperatures and limited oxygen, to produce a gaseous fuel. The gas produced by the process as shown in below Figure is a mix of gases such as carbon monoxide, carbon dioxide, nitrogen, hydrogen, and methane. The gas is then used to drive a high efficiency, combined-cycle gas turbine. Gasification has several advantages over burning solid fuel. One is convenience – one of the resultant gases, methane, can be treated in a similar way as natural gas, and used for the same purposes. Another advantage of gasification is that it produces a fuel that has had many impurities removed and could therefore cause fewer pollution problems when burnt. Under suitable circumstances, it can also produce synthesis gas, a mixture of carbon monoxide and hydrogen which can be used to make hydrocarbon (e.g., methane and methanol) for replacing fossil fuels. Hydrogen itself is a potential fuel without much pollution which can conceivably substitute oil and petroleum in a foreseeable future.

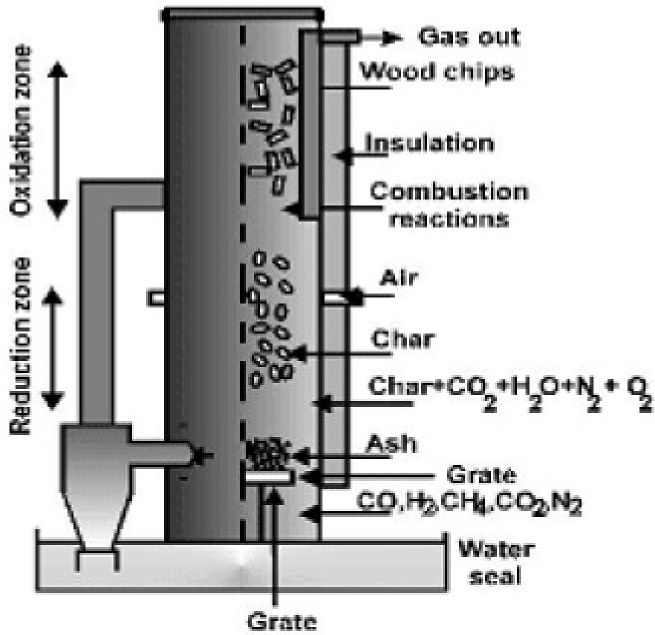


Figure. Gasification Process

3. Pyrolysis

In its simplest form, pyrolysis represents heating the biomass to drive off the volatile matter and leaving behind the Charcoal. This process has doubled the energy density of the original material because charcoal, which is half the weight of the original biomass, contains the same amount of energy, making the fuel more transportable. The charcoal also burns at a much higher temperature than the original biomass, making it more useful for manufacturing processes. More sophisticated pyrolysis techniques are developed recently to collect volatiles that are otherwise lost to the system. The collected volatiles produce a gas which is rich in hydrogen (a potential fuel) and carbon monoxide. These compounds are synthesized into methane, methanol, and other hydrocarbons. The steps involved in this process are illustrated in below Figure. Flash pyrolysis is used to produce bio-crude, a combustible fuel. Heat is used to chemically convert biomass into pyrolysis oil. The oil, which is easier to store and transport than solid biomass material, is then burned like petroleum to generate electricity. Pyrolysis can also convert biomass into phenol oil, a chemical used to make wood adhesives, moulded plastics, and foam insulation.

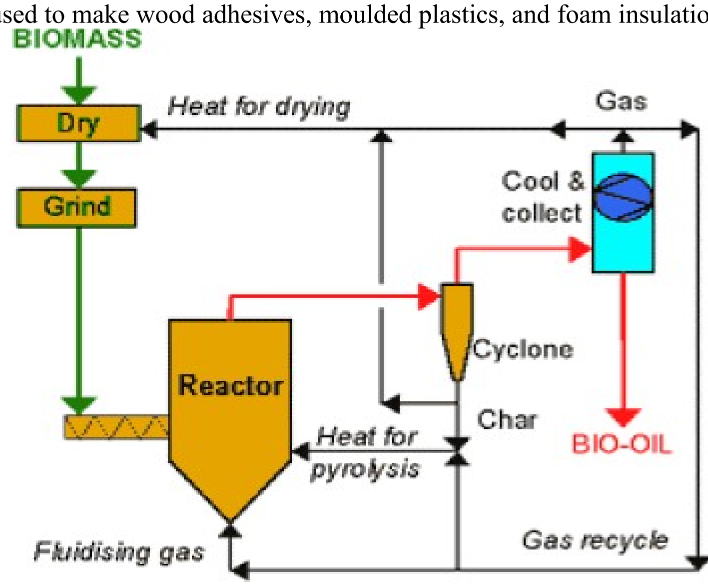


Figure. Pyrolysis process

4. Digestion
Biomass digestion works by utilizing anaerobic bacteria. These microorganisms usually live at the bottom of swamps or in other places where there is no air, consuming dead organic matter to produce methane and hydrogen. We put these bacteria to work for us. By feeding organic matter such as animal dung or human sewage into tanks, called digesters, and adding bacteria, we collect the emitted gas to use as an energy source. This process is a very efficient means of extracting usable energy from such biomass. Usually, up to two thirds of the fuel energy of the animal dung could be recovered. Another related technique is to collect methane gas from landfill sites. A large proportion of household biomass waste, such as kitchen scraps, lawn clipping and pruning, ends up at the local tip. Over a period of several decades, anaerobic bacteria at the bottom of such tips could steadily decompose the organic matter and emit methane. The gas can be extracted and used by capping a landfill site with an impervious layer of Clay and then inserting perforated pipes that would collect the gas and bring it to the surface.

5. Fermentation
For centuries, people have used yeasts and other microorganisms to ferment the sugar of various plants into ethanol. Producing fuel from biomass by fermentation is just an extension of this process, although a wider range of plant material from sugar cane to wood fibre can be used. For instance, the waste from a wheat mill in New South Wales is used to produce ethanol through fermentation. Ethanol is then mixed with diesel to produce diesehol, a product used by trucks and buses in Australia. Technological advances will inevitably improve the method. For example, scientists in Australia and the U.S. have substituted a genetically engineered bacterium for yeast in the fermentation process. The process has vastly increased the efficiency by which waste paper and other forms of wood fiber is fermented into ethanol.

<u>Bio fuels:</u> Biomass is converted into transportation fuels such as ethanol, methanol, biodiesel and additives for reformulated gasoline. Bio fuels are used in pure form or blended with gasoline.

<u>Ethanol:</u> Ethanol, the most widely used bio fuel, is made by fermenting biomass in a process similar to brewing beer. Currently, most of the 1.5 billion gallons of ethanol used in the U.S. each year is made from corn and blended with gasoline to improve vehicle performance and reduce air pollution.

<u>Methanol:</u> Biomass-derived methanol is produced through gasification. The biomass is converted into a synthesis gas (syngas) that is processed into methanol. Most of the 1.2 billion gallons of methanol annually produced in the U.S. are made from natural gas and used as solvent, antifreeze, or to synthesize other chemicals. About 38 percent is used for transportation as a blend or in reformulated gasoline.

<u>Biodiesel:</u> Biodiesel fuel, made from oils and fats found in micro-algae and other plants is substituted for or blended with diesel fuel.

BENEFITS OF BIOMASS ENERGY:
Some of the advantages of using biomass as a source of energy are illustrated below.

1. Biomass energy is an abundant, secure, environmental friendly and renewable source of energy. Biomass does not add carbon dioxide to the atmosphere as it absorbs the same amount of carbon in growing as it releases when consumed as a fuel.
2. One of the major advantages of biomass is that it can be used to generate electricity with the same equipment or in the same power plants that are now burning fossil fuels.
3. Biomass energy is not associated with environmental impacts such as acid rain, mine spoils, open pits, oil spills, radioactive waste disposal or the damming of rivers.
4. Biomass fuels are sustainable. The green plants from which biomass fuels are derived fix carbon dioxide as they grow, so their use does not add to the levels of atmospheric carbon. In addition, using refuse as a fuel avoids polluting landfill disposal.
5. Alcohols and other fuels produced by biomass are efficient, viable, and relatively clean burning.
6. Biomass is easily available and can be grown with relative ease in all parts of the world.

CONSTRAINTS TO BIOMASS ENERGY USE:

1. Biomass is still an expensive source of energy, both in terms of producing biomass and converting it into Alcohols, as a very large quantity of biomass are needed.
2. On a small scale there is most likely a net loss of energy as a lot of energy must be used for growing the plant mass; biomass is difficult to store in the raw form.
3. One of the disadvantages of biomass is that direct combustion of biomass can be harmful to the environment as burning biomass releases carbon dioxide, which contributes to the warming of the atmosphere and possible climatic change. Burning also creates soot and other air pollutants.
4. Over-collecting wood can destroy forests. Soils bared of trees erode easily and do not hold rainfall. Increased runoff can cause flooding downstream.
5. When plant and animal wastes are used as fuel, they cannot be added to the soil as fertilizer. Soil without fertilizer is depleted of nutrients and produces fewer crops.
6. Biomass has less energy than a similar volume of fossil fuels.

5. List out the available renewable energy sources. Explain how solar energy sources plays significant role of electric power generation. (APR/MAY 2017)
   Bio fuel, Biomass, Geothermal, Hydropower, Solar energy, Tidal power, Wave power, Wind power.

Solar energy

Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2.Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc. For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

Units of solar power and solar energy:

In SI units, energy is expressed in Joule. Other units are angley and Calorie where
1 angley = 1 Cal/cm^2.day
1 Cal = 4.186 J
For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of kJ/m^2/day or kJ/m^2/hour. Solar power is expressed in terms of W/m^2 or kW/m^2.

Essential subsystems in a solar energy plant:

1. **Solar collector or concentrator**: It receives solar rays and collects the energy. It may be of following types:
a) Flat plate type without focusing
b) Parabolic trough type with line focusing
c) Paraboloid dish with central focusing
d) Fresnel lens with centre focusing
e) Heliostats with centre receiver focusing
2. **Energy transport medium**: Substances such as water/ steam, liquid metal or gas are used to transport the thermal energy from the collector to the heat exchanger or thermal storage. In solar PV systems energy transport occurs in electrical form.
3. **Energy storage**: Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods. There are three major types of energy storage:
a) Thermal energy storage; b) Battery storage; c) Pumped storage hydro-electric plant.
4. **Energy conversion plant**: Thermal energy collected by solar collectors is used for producing steam, hot water, etc. Solar energy converted to thermal energy is fed to steam thermal or gas-thermal power plant.
5. **Power conditioning, control and protection system**: Load requirements of electrical energy vary with time. The energy supply has certain specifications like voltage, current, frequency, power etc. The power conditioning unit performs several functions such as control, regulation, conditioning, protection, automation, etc.

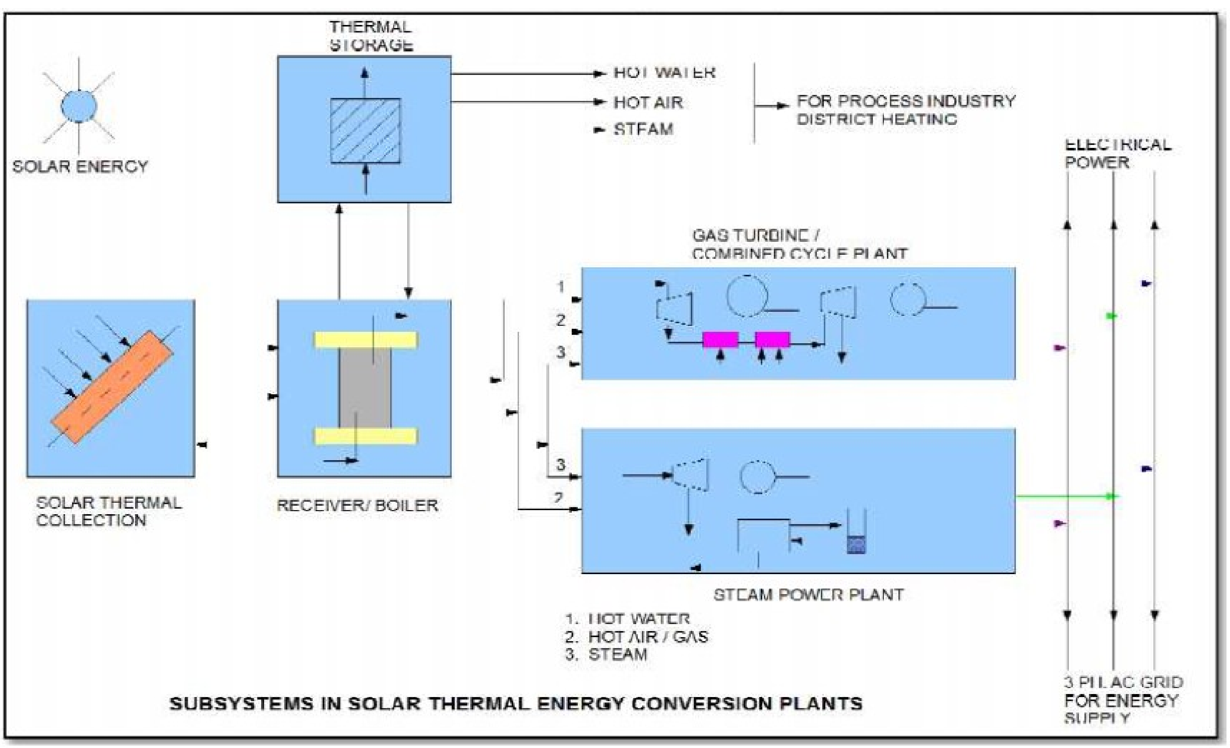


Fig Subsystems in solar thermal energy conversion plants

6. **Alternative or standby power supply**: The backup may be obtained as power from electrical network or standby diesel generator.

Energy from the sun:

The sun radiates about 3.8 x 10^{26} W of power in all the directions. Out of this about 1.7 x10^{17} W is received by earth. The average solar radiation outside the earth's atmosphere is 1.35 kW/m^2 varying from 1.43 kW/m^2 (in January) to 1.33 kW/m^2 (in July).

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

Solar thermal collectors are classified by the United States Energy Information Administration as low-, medium-, or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric power production. However, there is a term that used for both the applications. Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries and Concentrated Solar Power (CSP) when the heat collected is used for power generation. CST and CSP are not replaceable in terms of application. A solar thermal collector system gathers the heat from the solar radiation and gives it to the heat transport fluid. The heat-transport fluid receives the heat from the collector and delivers it to the thermal storage tank, boiler steam generator, heat exchanger etc. Thermal storage system stores heat for a few hours. The heat is released during cloudy hours and at night. Thermal-electric conversion system receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the AC grid. Applications of solar thermal energy systems range from simple solar cooker of 1 kW rating to complex solar central receiver thermal power plant of 200 MW rating.

For producing grid-connected electric power, following two major types of solar energy technologies are commercially viable.

- Concentrated Solar Power (CSP) technology
- Solar Photo Voltaic (PV) technology

Concentrated Solar Power (CSP) technology

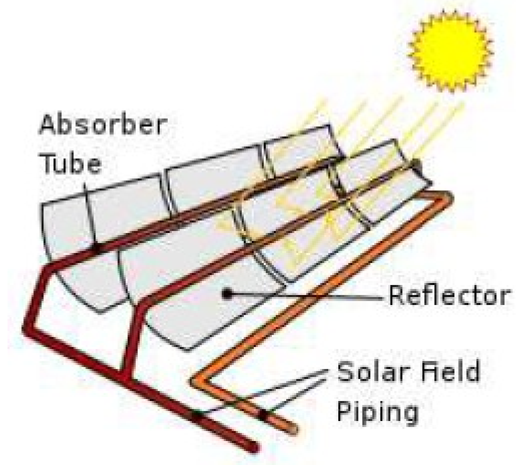
Concentrated solar power plants produce electric power by converting the sun's energy into high temperature heat using various minor configurations. The working fluid in the heat engine that is heated by the concentrated sunlight can be a liquid (water, oil) salts or a gas (air, nitrogen, helium). The amount of power generated by a CSP plant depends on the quality of the reflector design and material and the amount of direct sunlight impinging on the reflector.

Following are the most commonly accepted CSP technologies for solar energy collection

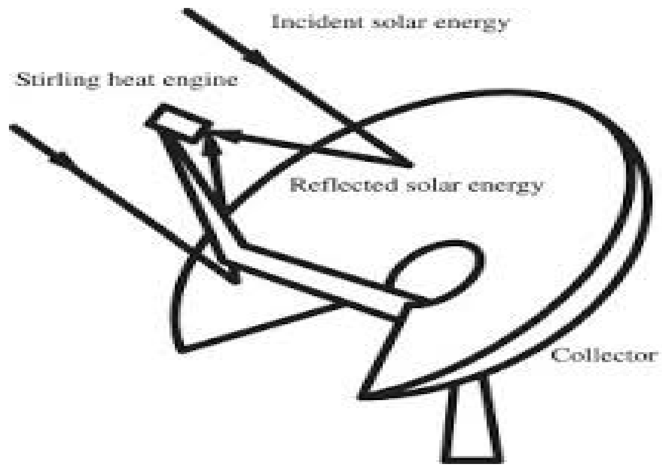
- Parabolic trough
- Parabolic dish
- Power tower
- Fresnel reflector

Parabolic trough

Parabolic trough power plants use a curved, mirrored trough which reflects the direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber or collector) running the length of the trough, positioned at the focal point of the reflectors. The trough is parabolic along one axis and linear in the orthogonal axis. For change of the daily position of the sun perpendicular to the receiver, the trough tilts east to west so that the direct radiation remains focused on the receiver. However, seasonal changes in the in angle of sunlight parallel to the trough does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the trough design does not require tracking on a second axis. The receiver may be enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat loss. A fluid (also called heat transfer fluid) passes through the receiver and becomes very hot. Common fluids are synthetic oil, molten salt and pressurized steam. The fluid containing the heat is transported to a heat engine where about a third of the heat is converted to electricity. Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the Solar Energy Generating Systems (SEGS) system. Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology.



Parabolic dish



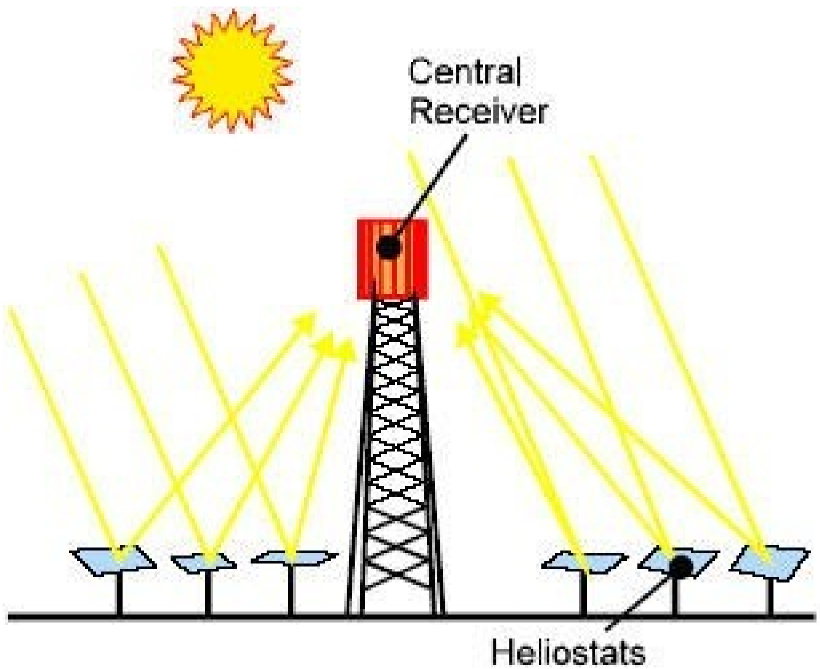
Solar Parabolic dish

With a parabolic dish collector, one or more parabolic dishes concentrate solar energy at a single focal point, similar to the way a reflecting telescope focuses starlight, or a dish antenna focuses radio waves. This geometry may be used in solar furnaces and solar power plants. The shape of a parabola means that incoming light rays which are parallel to the dish's axis will be reflected toward the focus, no matter where on the dish they arrive. Light from the sun arrives at the Earth's surface almost completely parallel, and the dish is aligned with its axis pointing at the sun, allowing almost all incoming radiation to be reflected towards the focal point of the dish. Most losses in such collectors are due to imperfections in the parabolic shape and imperfect reflection. Losses due to atmospheric scattering are generally minimal. However, on a hazy or foggy day, light is diffused in all directions through the atmosphere, which significantly reduces the efficiency of a parabolic dish. In dish stirling power plant designs, a stirling engine coupled to a dynamo, is placed at the focus of the dish. This absorbs the energy focused onto it and converts it into electricity.

Power tower

A power tower is a large tower surrounded by tracking mirrors called heliostats. These mirrors align themselves and focus sunlight on the receiver at the top of tower, collected heat is transferred to a power station below. This design reaches very high temperatures. High temperatures are suitable for electricity generation using conventional methods like steam turbine or a direct high temperature chemical reaction such as liquid salt. By concentrating sunlight, current systems can get better efficiency than simple solar cells. A larger area can be covered by using relatively inexpensive mirrors rather than using expensive solar cells. Concentrated light can be redirected to a suitable location via optical fiber cable for such uses as illuminating buildings. Heat storage for power production during cloudy and overnight conditions can be accomplished, often by underground tank storage of heated fluids. Molten salts have been used to good effect. Other working fluids, such as liquid metals, have also been proposed due to their superior thermal properties.

However, concentrating systems require sun tracking to maintain sunlight focus at the collector. They are unable to provide significant power in diffused light conditions. Solar cells are able to provide some output even if the sky becomes cloudy, but power output from concentrating systems drops drastically in cloudy conditions as diffused light cannot be concentrated.



Fresnel Reflector

A linear Fresnel reflector power plant uses a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. On top of the receiver a small parabolic mirror can be attached for further focusing the light. These systems aim to offer lower overall costs by sharing a receiver between several mirrors (as compared with trough and dish concepts), while still using the simple line-focus geometry with one axis for tracking. This is similar to the trough design (and different from central towers and dishes with dual-axis). The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not need to support the receiver, so they are structurally simpler. When suitable aiming strategies are used (mirrors aimed at different receivers at different times of day), this can allow a denser packing of mirrors on available land area.

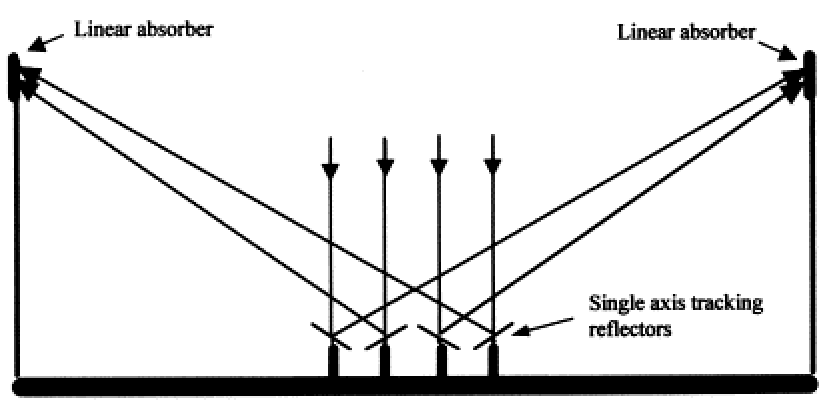
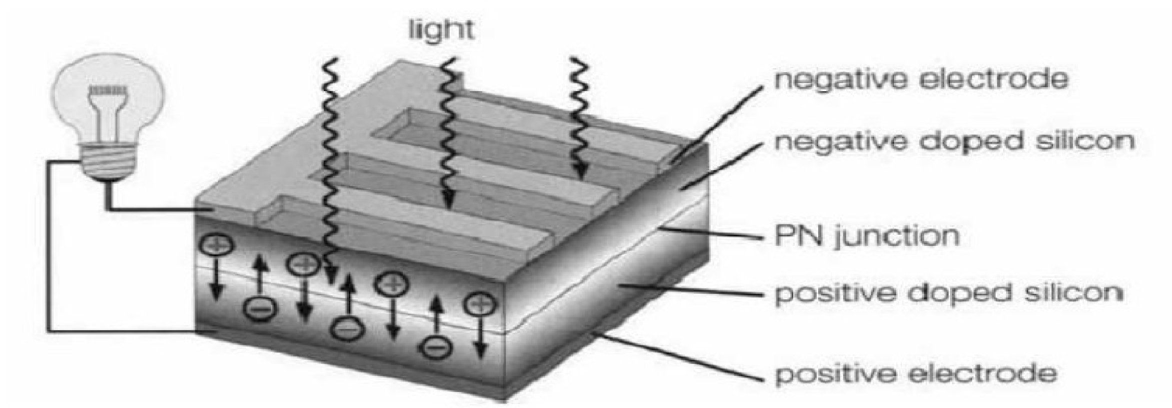


PHOTO VOLTAIC TECHNOLOGY:

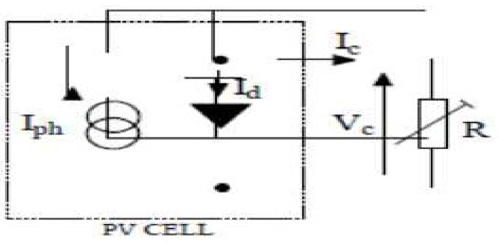
The density of power radiated from the sun (referred to as the ‘‘solar energy constant’’) at the outer atmosphere is 1.373kW/m^2. Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface has a peak density of 1kW/m2 at noon in the tropics. The technology of photovoltaic (PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity. Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Below Figure shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3mm thick mono crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (Iph), which is internally generated in the solar cell, is proportional to the radiation intensity.

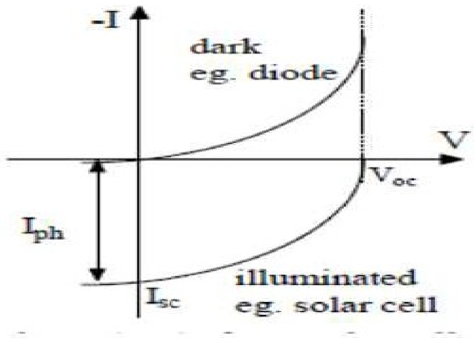


A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Figure below. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (Iph) generated by the solar radiation then flows to the output. The solar cell current has its maximum (Isc). If the load resistance is increased, this results in an increasing voltage across the p n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation:

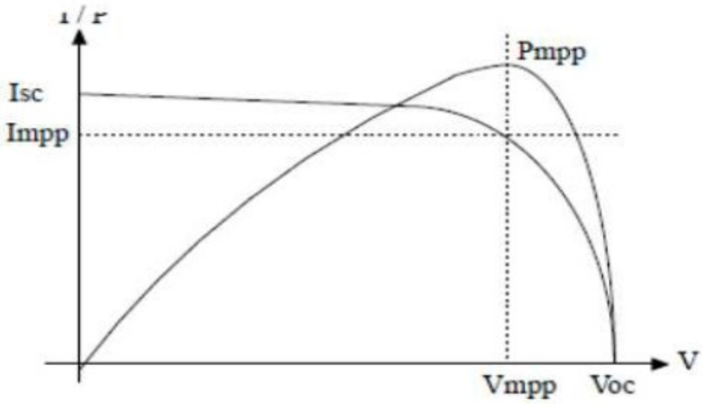
$$I = I_{ph} - I_0 \left(e^{\frac{qv}{kt}} - 1 \right) = I_{ph} - I_d$$

Where q is the electron charge, k is the Boltzmann constant, Iph is photocurrent, I0 is the reverse saturation current, Id is diode current, and T is the solar cell operating temperature (K). The current versus voltage (I-V) of a solar cell is thus equivalent to an ‘‘inverted’’ diode.

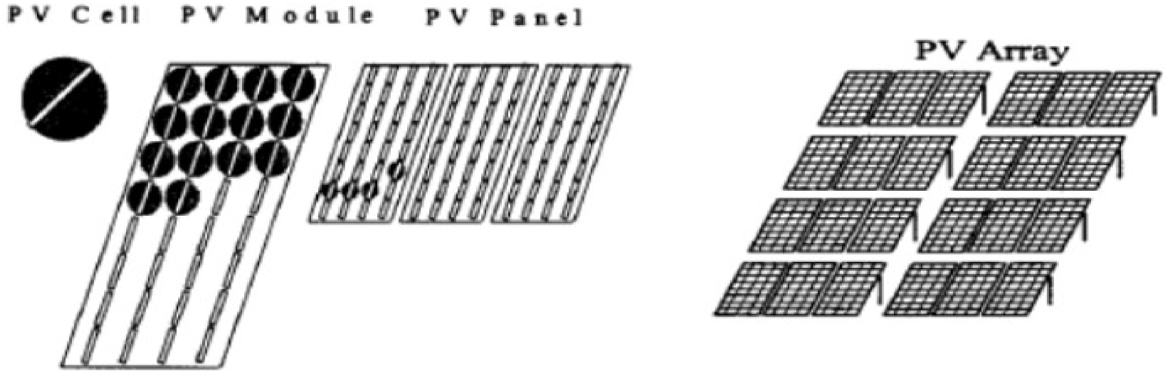




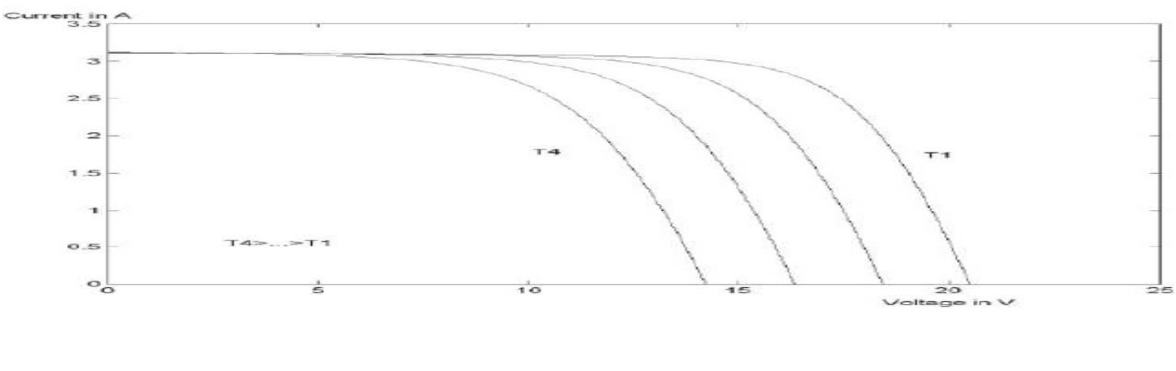
A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Figure below. Two important points on this curve are the open circuit voltage (Voc) and short-circuit current (Isc). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, Voc is typically 0.6–0.7 V, and Isc is typically 20–40mA for every square centimetre of the cell area. To a good approximation, Isc is proportional to the illumination level, whereas Voc is proportional to the logarithm of the illumination level.



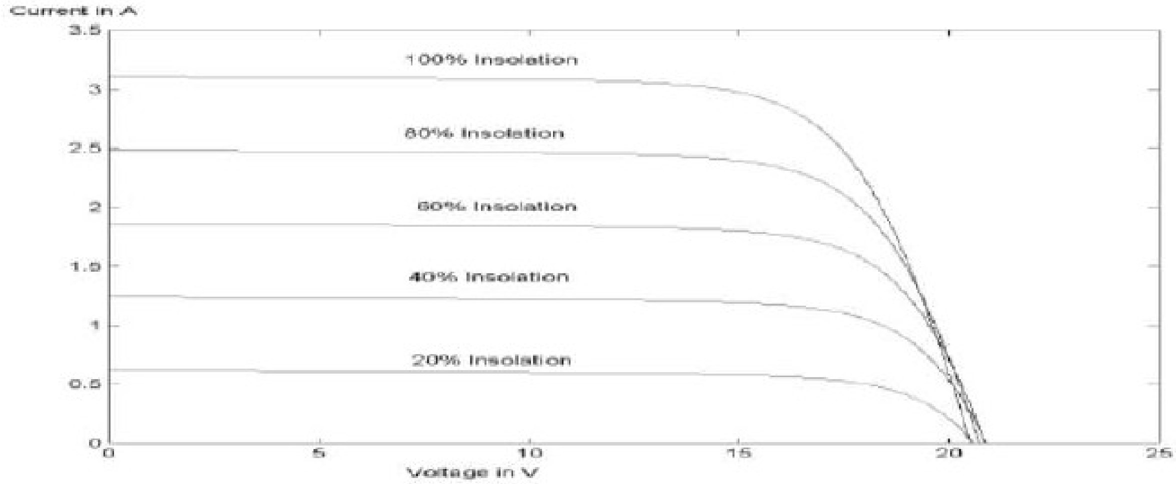
A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (Vmp, Imp). Silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Figure below).



The effect of temperature on the performance of a silicon solar module is illustrated in Figure below. Note that Isc slightly increases linearly with temperature, but Voc and the maximum power Pm decrease with temperature.



Below Figure shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant voltage segment and a constant-current segment. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segments meet.



ARRAY DESIGN

The major factors influencing the electrical design of the solar array are as follows:

- The sun intensity
- The sun angle
- The load matching for maximum power
- The operating temperature

SUN TRACKING:

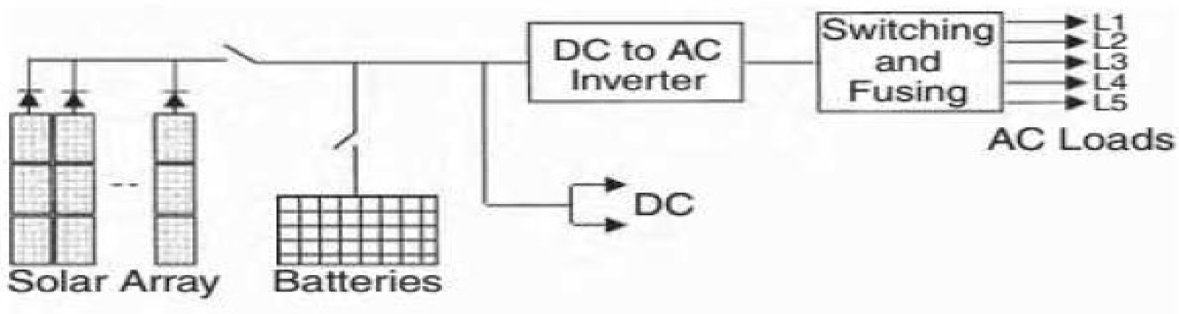
More energy is collected by the end of the day if the PV module is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers:

• One-axis tracker, which follows the sun from east to west during the day.

• Two-axis tracker, which follows the sun from east to west during the day, and from north to south during the seasons of the year.

TYPICAL PV STAND-ALONE SYSTEM

The typical PV stand-alone system consists of a solar array and a battery connected as shown in Figure. The PV array supplies power to the load and charges the battery when there is sunlight. The battery powers the load otherwise. An inverter converts the DC power of the array and the battery into 60 or 50 Hz power. Inverters are available in a wide range of power ratings with efficiencies ranging from 85 to 95%. The array is segmented with isolation diodes for improving reliability. In such a design, if one string of the solar array fails, it does not load or short the remaining strings. Multiple inverters are preferred for reliability. For example, three inverters, each with a 35% rating, are preferred to one with a 105% rating. If one such inverter fails, the remaining two can continue supplying most loads until the failed one is repaired or replaced. The same design approach also extends to using multiple batteries.



PV stand-alone power system with battery.

6. Explain how wind energy sources plays significant role of electric power generation. (APR/MAY 2017)

Wind energy

The wind is a clean, free, and readily available renewable energy source. Each day, around the world, wind turbines are capturing the wind's power and converting it to electricity. This source of power generation plays an increasingly important role in the way we power our world. Wind energy is a commercially available renewable energy source, with state-of-the-art wind plants producing electricity at about $0.05 per kWh. However, even at that production cost, wind-generated electricity is not yet fully cost-competitive with coal-or natural-gas-produced electricity for the bulk electricity market. The wind is a by-product of solar energy. Approximately

2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high-to low-pressure areas. The wind has played an important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore.

SPEED AND POWER RELATIONS

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

$$\text{kinetic energy} = \frac{1}{2} m V^2$$

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

$$\text{power} = \frac{1}{2}(\text{mass flow per second}) V^2$$

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:

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

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

$$\text{specific power of the site} = \frac{1}{2} \rho V^3$$

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.

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 3.2, this is given by the following equation in units of watts:

$$P_o = \frac{1}{2}(\text{mass flow per second}) \left\{ V^2 - V_o{}^2 \right\}$$

where

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

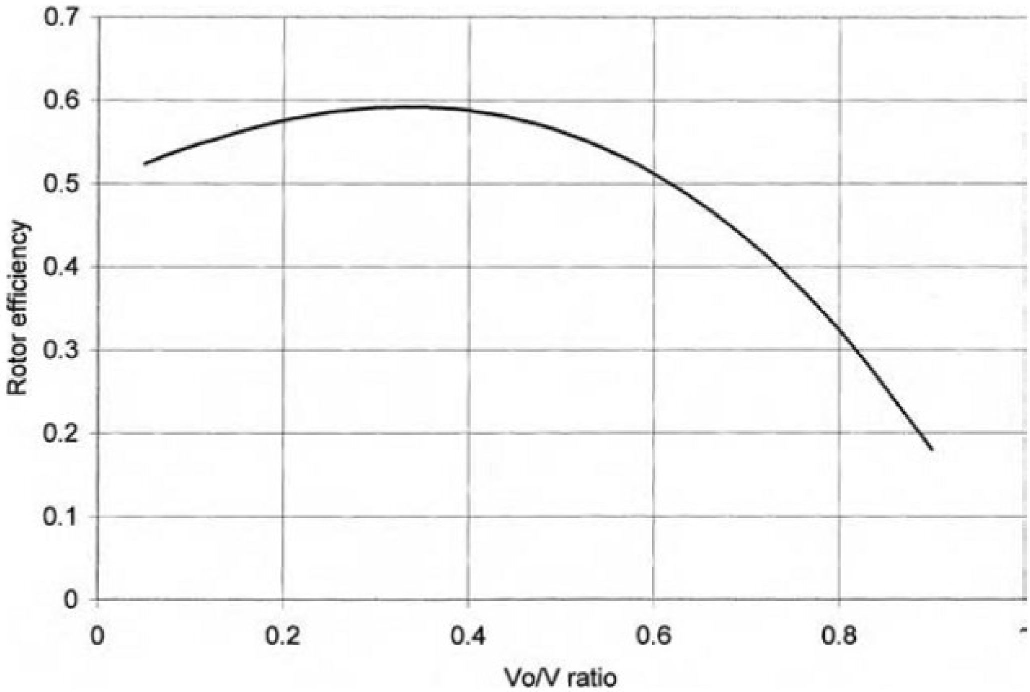
V= upstream wind velocity at the entrance of the rotor blades, and

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

$$\text{mass flow rate} = \rho A \frac{V + V_o}{2}$$

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

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



Rotor efficiency vs. V_o/V ratio has a single maximum.

The preceding expression is algebraically rearranged in the following form:

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

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

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

Where

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

Comparing Equations, we can say that Cp is the fraction of the upstream wind power that is extracted by the rotor blades and fed to the electrical generator. The remaining power is dissipated in the downstream wind. The factor Cp is called the power coefficient of the rotor or the rotor efficiency.

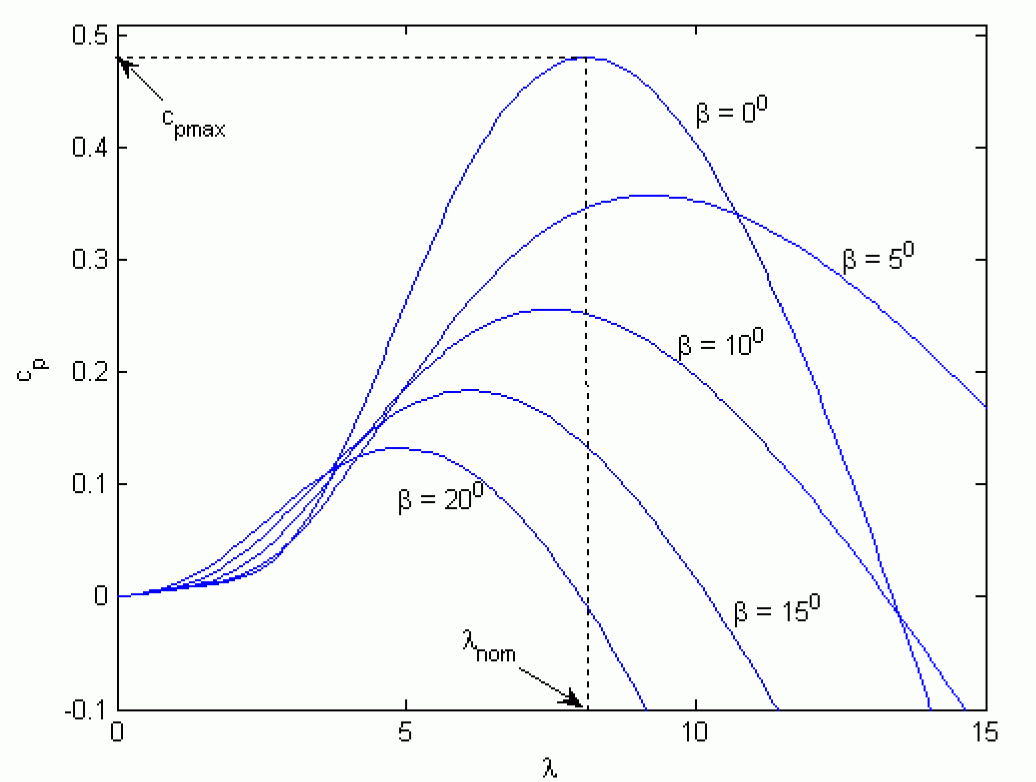


Figure: typical characteristics of wind energy conversion system

Advantages of Wind Energy

- It is a free source of energy
- Produces no water or air pollution
- Wind farms are relatively inexpensive to build
- Land around wind farms can have other uses

Disadvantages of Wind Energy

- Requires constant and significant amounts of wind
- Wind farms require significant amounts of land
- Can have a significant visual impact on landscapes

Wind Turbine Types:

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 horizontal axis configuration 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.

Vertical-axis wind turbines

Vertical-axis wind turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set transverse to the wind (but not necessarily vertically) while 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. VAWTs do not need to be pointed into the wind,[1][2] which removes the need for wind-sensing and orientation mechanisms. Major drawbacks for the early designs (Savonius, Darrieus and giromill) included the significant torque variation or "ripple" during each revolution, and the large bending moments on the blades. Later designs addressed the torque ripple issue by sweeping the blades helically. A VAWT tipped sideways, with the axis perpendicular to the wind streamlines, functions similarly. A more general term that includes this option is "transverse axis wind turbine" or "cross-flow wind turbine." For example, the original Darrieus patent, US Patent 1835018, includes both options. Drag-type VAWTs such as the Savonius rotor typically operate at lower tipspeed ratios than lift-based VAWTs such as Darrieus rotors and cyclo turbines.

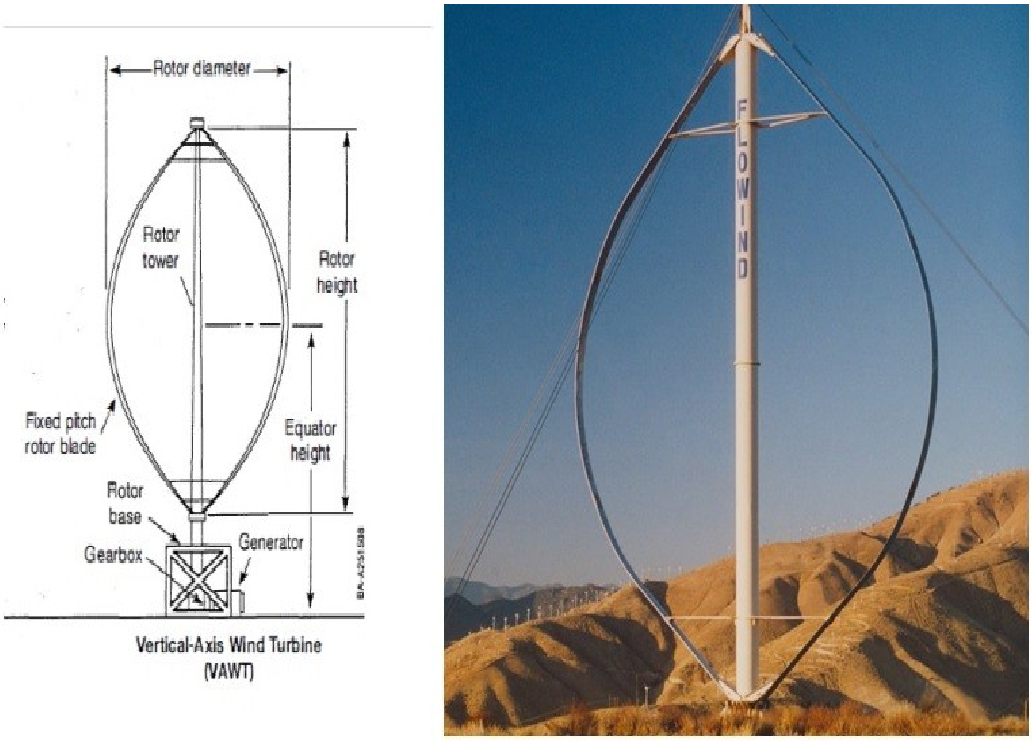


Figure Vertical-axis wind turbines

Advantages

VAWTs offer a number of advantages over traditional horizontal-axis wind turbines (HAWTs):

- They are omni-directional and do not need to track the wind. This means they don't require a complex mechanism and motors to yaw the rotor and pitch the blades.
- Ability to take advantage of turbulent and gusty winds. Such winds are not harvested by HAWTs, and in fact cause accelerated fatigue for HAWTs.
- Wings of the Darrieus type have a constant chord and so are easier to manufacture than the blades of a HAWT, which have a much more complex shape and structure.
- Can be grouped more closely in wind farms, increasing the generated power per unit of land area.
- Can be installed on a wind farm below the existing HAWTs; this will improve the efficiency (power output) of the existing farm.

Disadvantages

One of the major outstanding challenges facing vertical axis wind turbine technology is dynamic stall of the blades as the angle of attack varies rapidly. The blades of a VAWT are fatigue-prone due to the wide variation in applied forces during each rotation. This can be overcome by the use of modern composite materials and improvements in design - including the use of aerodynamic wing tips that cause the spreader wing connections to have a static load. The vertically oriented blades can twist and bend during each turn, causing them to break apart. VAWTs have proven less reliable than HAWTs, although modern designs of VAWTs have overcome many of the issues associated with early designs.

Horizontal-axis wind turbines

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 servomotor. 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. Any solid object produces a wake behind it, leading to fatigue failures, so the turbine is usually positioned upwind of its supporting tower. Downwind machines have been built, because they don't need an additional mechanism for keeping them in line with the wind. In high winds, the blades can also be allowed to bend which reduces their swept area and thus their wind resistance. In upwind designs, turbine blades must be made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

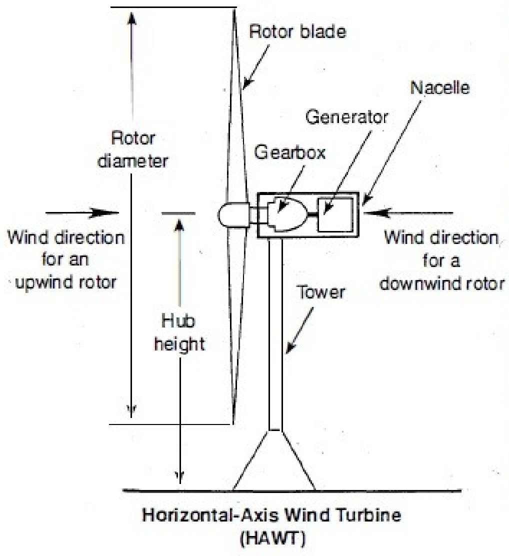


Figure Horizontal-axis wind turbines

Advantages

- Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.

Disadvantages

- Taller masts and blades are more difficult to transport and install. Transportation and installation can now cost 20% of equipment costs.
- Stronger tower construction is required to support the heavy blades, gearbox, and generator.
- Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.
- Mast height can make them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

Components of wind turbine:

- **Rotor:**

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

- **Gearbox**

The gearbox alters the rotational velocity of the shaft to suit the generator

- **Generator**

The generator is a device that produces electricity when mechanical work is given to the system.

- **Control and protection system**

The protection system is like a safety feature that makes sure that the turbine will not be working under dangerous condition. This includes a brake system triggered by the single of higher wind speeds to stop the rotor from movement under excessive wind gusts.

- **Tower**

The tower is the main shaft that connects the rotor to the foundation. It also raises the rotor high in the air where we can find stronger winds.

- **Foundation**

The foundation or the base supports the entire wind turbine and make sure that it is well fixed onto the ground or the roof for small household wind turbines. This is usually consists of a solid concrete assembly around the tower to maintain its structural integrity.

- **Tip Speed Ratio:**

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed.

7. Explain the impacts of renewable energy generation on environment.(APR/MAY 2017) (M.E-NOV/DEC2013)

Introduction

Today, renewable energy provides only a tiny fraction of its potential electricity output worldwide. But numerous studies have repeatedly shown that renewable energy can be rapidly deployed to provide a significant share of future electricity needs, even after accounting for potential constraints In accordance with REN21 Renewable 2010 Global Status Report renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off-grid) energy services:

1. **Power generation**

Renewable energy provides 19% of electricity generation worldwide. Renewable power generators are spread across many countries, and wind power alone already provides a significant share of electricity in some areas: for example, 14% in the U.S. state of Iowa, 40% in the northern German state of Schleswig-Holstein, and 49% in Denmark. Some countries get most of their power from renewable, including Iceland (100%), Norway (98%), Brazil (86%), Austria (62%), New Zealand (65%), and Sweden (54%).

2. Heating

Solar hot water makes an important contribution to renewable heat in many countries, most notably in China, which now has 70% of the global total (180 GWh). Most of these systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50– 60 million households in China. Worldwide, total installed solar water heating systems meet a portion of the water heating needs of over 70 million households. The use of biomass for heating continues to grow as well. In Sweden, national use of biomass energy has surpassed that of oil. Direct geothermal for heating is also growing rapidly.

3. Transport fuels

Renewable bio fuels have contributed to a significant decline in oil consumption in the United States since 2006. The 93 billion litres of bio fuels produced worldwide in 2009 displaced the equivalent of an estimated 68 billion litres of gasoline, equal to about 5% of world gasoline production.

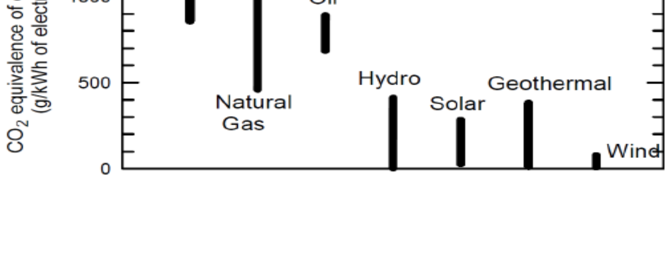
Types of Environmental Impacts

It is important to understand the environmental impacts associated with producing power from renewable sources such as wind, solar, geothermal, biomass, and hydropower. The exact type and intensity of environmental impacts varies depending on the specific technology used, the geographic location, and a number of other factors. Various aspects of the impact of renewable energy sources can be analyzed, including, among others: air and water emissions, waste generations, specially hazardous materials, noise generation, land use, global warming emissions. By understanding the current and potential environmental issues associated with each renewable energy source, we can takes steps to effectively avoid or minimize these impacts as they become a larger portion of our electric supply. A whole series of determinants are favouring the development of the energy sector based on renewable resources: increasing social awareness of the need to limit emissions of harmful substances, legislation, pro-environmental policies of governments, by-laws, support in the form of programmes and financial mechanisms, not to mention the rising costs of energy from conventional sources and the need to ensure energy security. Because the environmental performance of renewable energy systems is greatly improved by: increased efficiency and longer lifetimes, both should be stimulated for the devices and whole systems.

What does it mean: environment?

The Oxford dictionary (Brown, 1993) defines environment as " the set of circumstances or conditions ... in which a person or community lives, works, develops, etc, or a thing exists or operates; the external conditions affecting the life of a plant or animal".

In most countries, industrial development is contingent on the developer obtaining a permit from a regulatory authority which involves assessing the impact the development may have on the environment. Preservation of the environment is not merely a local issue but an international concern. The brief comparison between environmental benefits and costs of the use of different types of RES is presented in the Figure and Table .



Environmental benefits	Environmental costs
1. Energy produced by the renewable energy systems 2. Greenhouse gas savings	1. Production of devices and BOS • Greenhouse gas emissions • Heavy metals emissions • Energy used (Energy pay-back time[1]) 2. Wastes generated by different RES industry

Environmental Impacts of Different Technologies

Environmental Impacts of Wind Power

A wind farm, when installed on agricultural land, has one of the lowest environmental impacts of all energy sources: it occupies less land area per kilowatt-hour (kWh) of electricity generated than any other energy conversion system, apart from rooftop solar energy, and is compatible with grazing and crops; it generates the energy used in its construction in just 3 months of operation, yet its operational lifetime is 20–25 years; greenhouse gas emissions and air pollution produced by its construction are very tiny and declining. There are no emissions or pollution produced by its operation; in substituting for base-load (mostly coal power) wind power produces a net decrease in greenhouse gas emissions and air pollution, and a net increase in biodiversity; modern wind turbines are almost silent and rotate so slowly (in terms of revolutions per minute) that they are rarely a hazard to birds. Modern wind turbine designs have significantly reduced the noise from turbines. Turbine designers are working to minimise noise, as noise reflects lost energy and output. Noise levels at nearby residences are managed through the siting of turbines, the approvals process for wind farms and operational management of the wind farm. The noise limit for wind farms is 35 A-weighted decibels, which is usually around 5 A weighted decibels above a quiet countryside. Alternatively, the limit is 5 A-weighted decibels above the level of background noise (i.e. without wind farm noise), if that is greater than 35 A-weighted decibels. Low frequency sound and infrasound (ie usually beneath the threshold of human hearing) are everywhere in the environment. They are emitted from natural sources such as wind and rivers and artificial sources such as traffic and air conditioning. Modern turbine designs which locate the blades upwind instead of downwind have significantly reduced the level of infrasound. Scientific and health authorities have found the low level of infrasound emitted by wind turbines pose no health risks. Wind turbines may create shadow flicker on nearby residences when the sun passes behind the turbine. However, this can easily be avoided by locating the wind farm to avoid unacceptable shadow flicker, or turning the turbine off for the few minutes of the day when the sun is at the angle that causes flicker. Shadow flicker is considered in the NSW development assessment process to ensure potential impacts are addressed. Many energy policy studies have noted how wind turbines present direct and indirect hazards to birds, other avian species, and bats [5], [6]. Birds can directly smash into moving or even stationary turbine blades, crash into towers and nacelles, and collide with local distribution lines. These risks are exacerbated when turbines are placed on ridges and upwind slopes or built close to migration routes. Some species, such as bats, face additional risks from the rapid reduction in air pressure near turbine blades, which can cause internal haemorrhaging. For fossil-fuelled power stations, the most significant fatalities come from climate change, which is altering weather patterns and destroying habitats that birds depend on. For nuclear power plants, the risk is almost equally spread across hazardous pollution at uranium mine sites and collisions with draft cooling structures.

Environmental Impacts of Solar Power

Photovoltaic's is now a proven technology which is inherently safe, as opposed to some dangerous electricity generating technologies. Over its estimated life a photovoltaic module will produce much more electricity than was used in its production. A 100 W module will prevent the emission of over two tonnes of CO2. Photovoltaic systems make no noise and cause no pollution while in operation. PV cell technologies that have relatively lower environmental risks compared to other types of electric sources. However, chemicals used in PV cells could be released to air, surface water, and groundwater in the manufacturing facility, the installation site, and the disposal or recycling facility. The production of photovoltaic devices involves the use of a variety of chemicals and materials. The amounts and types of chemicals used will vary depending upon the type of cell being produced. Based on a review of the chemical information reported, it appears that most of the chemicals used by the manufacturing companies are not released in reportable quantities. The releases of chemicals to the air from the photovoltaic facilities were reported as both air stack emissions and fugitive air emissions. The chemicals released in the largest quantities in air stack emissions included 1, 1, 1-trichloroethane, acetone, ammonia, isopropyl alcohol, and methanol. The scale of the system plays a significant role in the level of environmental impact. Depending on their location, larger utility-scale solar facilities can raise concerns about land degradation and habitat loss and impacts from utility-scale solar systems can be minimized by siting them at lower-quality locations such as abandoned mining land, or existing transportation and transmission corridors. Solar PV cells do not use water for generating electricity. However, as in all manufacturing processes, some water is used to manufacture solar PV components. Concentrating solar thermal plants (CSP), like all thermal electric plants, require water for cooling. Water use depends on the plant design, plant location, and the type of cooling system.

Environmental Impacts of Geothermal Energy

Geothermal power is a relatively benign source of energy. For the most part, the impacts of development are positive. Worldwide geothermal energy utilization increases yearly because it is an attractive alternative to burning imported and domestic fossil fuels. Electricity generation from geothermal resources involves much lower greenhouse gas (GHG) emission rates than that from fossil fuels. According to the International Atomic Energy Agency (IAEA), replacing one kilowatt-hour (kWh) of fossil power with a kilowatt-hour of geothermal power reduces the estimated global warming impact by approximately 95%. However, geothermal development could have certain negative impacts if appropriate mitigation actions and monitoring plants are not in place. Any large-scale construction and drilling operation will produce visual impacts on the landscape, create noise and wastes and affect local economies. Some countries have strict environmental regulations regarding some of the impacts associated with geothermal development, and others do not. Environmental issues usually addressed during the development of geothermal fields include air quality, water quality, waste disposal, geologic hazards, noise, biological resources and land use issues. The protection of groundwater is important during the drilling phase. The groundwater is to be managed sustainably. It is part of the ecosystem, is a habitat for animals and plants, and has a role in the livelihood of local residents. The main visual impact during the construction phase is the presence of a drilling rig, but once a project is in the production phase the rig is not required and the energy centre footprint is very small. Because of low emissions, the geothermal power plants also meet the most stringent clean air standards. It should be noted that all geothermal plants have to meet various national and local environmental standards and regulations, although emissions are not routinely measured below a certain threshold, and emissions from geothermal plants typically fall below this threshold. The list of barriers resulting from environmental regulations can be rather long. Environmental regulations should include groundwater protection incl. pressure issues, soil protection but also protocol on micro-seismicity, and surface issues. For work safety, construction and traffic, any legislation applicable for similar activities in mining, drilling, construction, etc. should be applied.

Environmental Impacts of Biomass

Biomass power plants share some similarities with fossil fuel power plants: both involve the combustion of a feedstock to generate electricity. Thus, biomass plants raise similar, but not identical, concerns about air emissions and water use as fossil fuel plants. Biomass power plants, like coal- and natural gas-fired power plants, require water for cooling. Land use impacts from biomass power production are driven primarily by the type of feedstock: either a waste stream or an energy crop that is grown specifically for generating electricity. There are global warming emissions associated with growing and harvesting biomass feedstock, transporting feedstock to the power plant, and burning or gasifying the feedstock. Transportation and combustion emissions are roughly equivalent for all types of biomass. However, global warming emissions from the sourcing of biomass feedstock vary widely. It was once commonly thought that biomass had net zero global warming emissions, because the growing biomass absorbed an equal amount of carbon as the amount released through combustion, but now it is understood that some biomass feedstock sources are associated with substantial global warming emissions. Beneficial biomass resources include energy crops that do not compete with food crops for land, portions of crop residues such as wheat straw or corn Stover, sustainably-harvested wood and forest residues, and clean municipal and industrial wastes.

Environmental Impacts of Hydroelectric Power

Although hydropower has no air quality impacts, construction and operation of hydropower dams can significantly affect natural river systems as well as fish and wildlife populations. Assessment of the environmental impacts of a specific hydropower facility requires case-by-case review. Negative impact of dams are as follows: in flat basins large dams cause flooding of large tracts of land, destroying local animals and habitats; people have to be displaced causing change in life style and customs - about 40 to 80 million people have been displaced physically by dams worldwide; large amounts of plant life are submerged and decay an aerobically; the migratory pattern of river animals like salmon and trout are affected; dams restrict sediments that are responsible for the fertile lands downstream; salt water intrusion into the deltas means that the saline water cannot be used for irrigation; large dams are breeding grounds for mosquitoes and cause the spread of disease; dams serve as a heat sink, and the water is hotter than the normal river water - this warm water when released into the river downstream can affect animal life.

8. Describe the consequences of green house effect. (M.E-APR/MAY 2013)

Life on earth is made possible by energy from the sun, which arrives mainly in the form of visible light. About 30 percent of the sunlight is scattered back into space by outer atmosphere and the balance 70 percent reaches the earth's surface, which reflects it in form of infrared radiation. The escape of slow moving infrared radiation is delayed by the green house gases. A thicker blanket of greenhouse gases traps more infrared radiation and increase the earth's temperature.

Greenhouse gases makeup only 1 percent of the atmosphere, but they act as a blanket around the earth, or like a glass roof of a greenhouse and keep the earth 30 degrees warmer than it would be otherwise - without greenhouse gases, earth would be too cold to live. Human activities that are responsible for making the greenhouse layer thicker are emissions of carbon dioxide from the combustion of coal, oil and natural gas; by additional methane and nitrous oxide from farming activities and changes in land use; and by several man made gases that have a long life in the atmosphere.

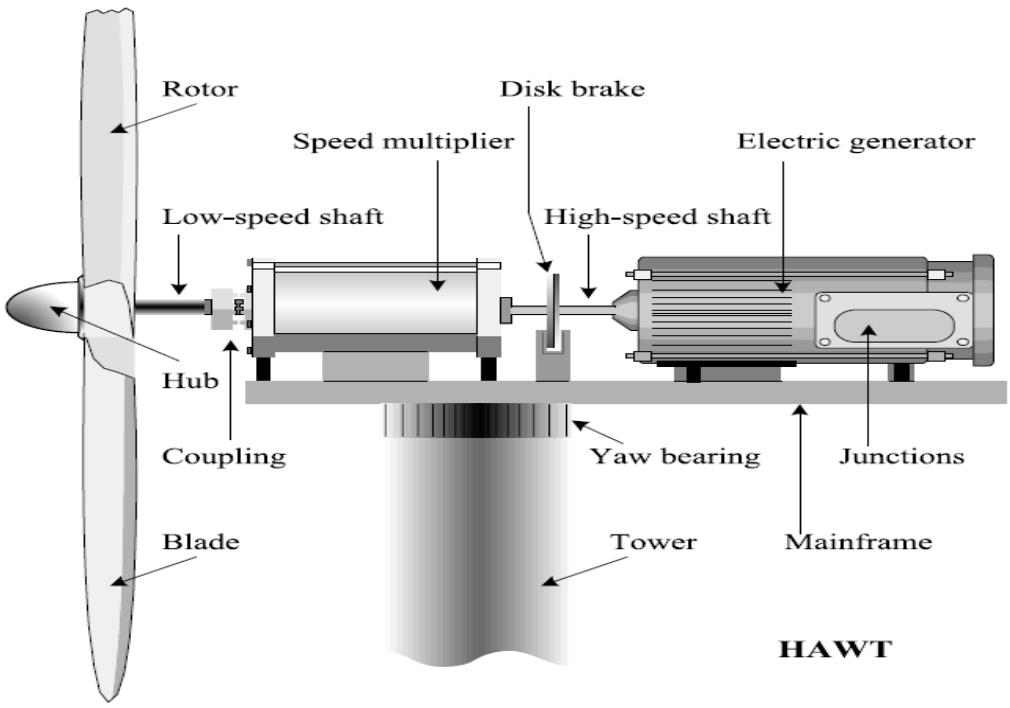
The increase in greenhouse gases is happening at an alarming rate. If greenhouse gases emissions continue to grow at current rates, it is almost certain that the atmospheric levels of carbon dioxide will increase twice or thrice from pre-industrial levels during the 21st century.

Even a small increase in earth's temperature will be accompanied by changes in climate such as cloud cover, precipitation, wind patterns and duration of seasons. In an already highly crowded and stressed earth, millions of people depend on weather patterns, such as monsoon rains, to continue as they have in the past. Even minimum changes will be disruptive and difficult. Carbon dioxide is responsible for 60 percent of the "enhanced greenhouse effect". Humans are burning coal, oil and natural gas at a rate that is much faster than the rate at which these fossil fuels were created. This is releasing the carbon stored in the fuels into the atmosphere and upsetting the carbon cycle (a precise balanced system by which carbon is exchanged between the air, the oceans and land vegetation taking place over millions of years). Currently, carbon dioxide levels in the atmospheric are rising by over 10 percent every 20 years.

9. Explain wind energy conversion system with neat schematic. (M.E-NOV/DEC 2010)

WECS Technology

A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows. The extraction device, named *wind turbine rotor* turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power. Several wind turbine concepts have been proposed over the years. A historical survey of wind turbine technology is beyond the scope here, but someone interested can find that in Ackermann (2005). There are two basic configurations, namely *vertical axis wind turbines* (VAWT) and, *horizontal axis wind turbines* (HAWT). Today, the vast majority of manufactured wind turbines are horizontal axis, with either two or three blades. HAWT is comprised of the tower and the nacelle, mounted on the top of the tower (Figure). Except for the energy conversion chain elements, the nacelle contains some control subsystems and some auxiliary elements (*e.g.*, cooling and braking systems, *etc.*).



The energy conversion chain is organised into four subsystems:

- aerodynamic subsystem, consisting mainly of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades;
- drive train, generally composed of: low-speed shaft – coupled with the turbine
- hub, speed multiplier and high-speed shaft – driving the electrical generator;
- electromagnetic subsystem, consisting mainly of the electric generator;
- Electric subsystem, including the elements for grid connection and local grid.

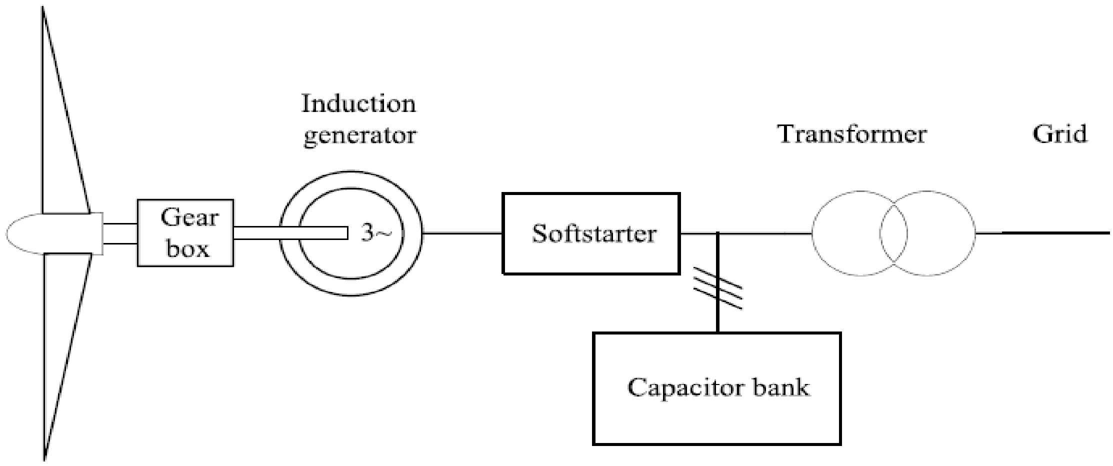
All wind turbines have a mechanism that moves the nacelle such that the blades mare perpendicular to the wind direction. This mechanism could be a tail vane (small wind turbines) or an electric yaw device (medium and large wind turbines). Concerning the power conversion chain, it involves naturally some loss of power. Because of the nonzero wind velocity behind the wind turbine rotor one can easily understand that its efficiency is less than unity. Also, depending on the operating regime, both the motion transmission and the electrical power generation involve losses by friction and by Joule effect respectively. Being directly coupled one with the other, the energy conversion chain elements dynamically interact, mutually influencing their operation.

Power Generation System

The electrical power generation structure contains both electromagnetic and electrical subsystems. Besides the electrical generator and power electronics converter it generally contains an electrical transformer to ensure the grid voltage compatibility. However, its configuration depends on the electrical machine type and on its grid interface.

Fixed-speed WECS

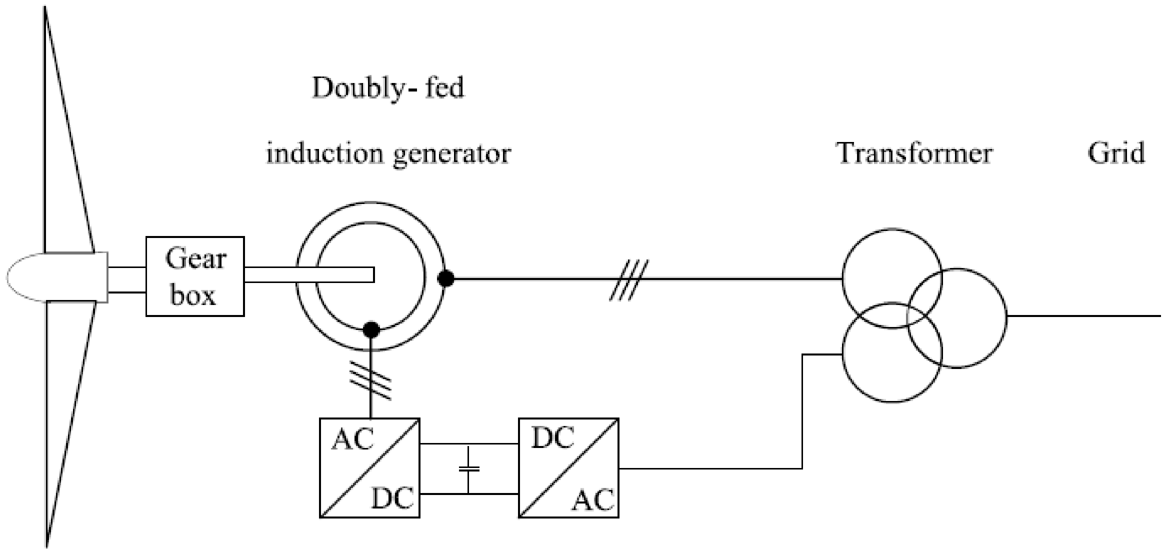
Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below . This WECS configuration is also known as the "*Danish concept*" because it was developed and widely used in Denmark.



Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important. SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection. SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles). Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

Variable-speed WECS

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. The doubly-fed-induction-generator (DFIG)-based WECS (Figure below), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry.

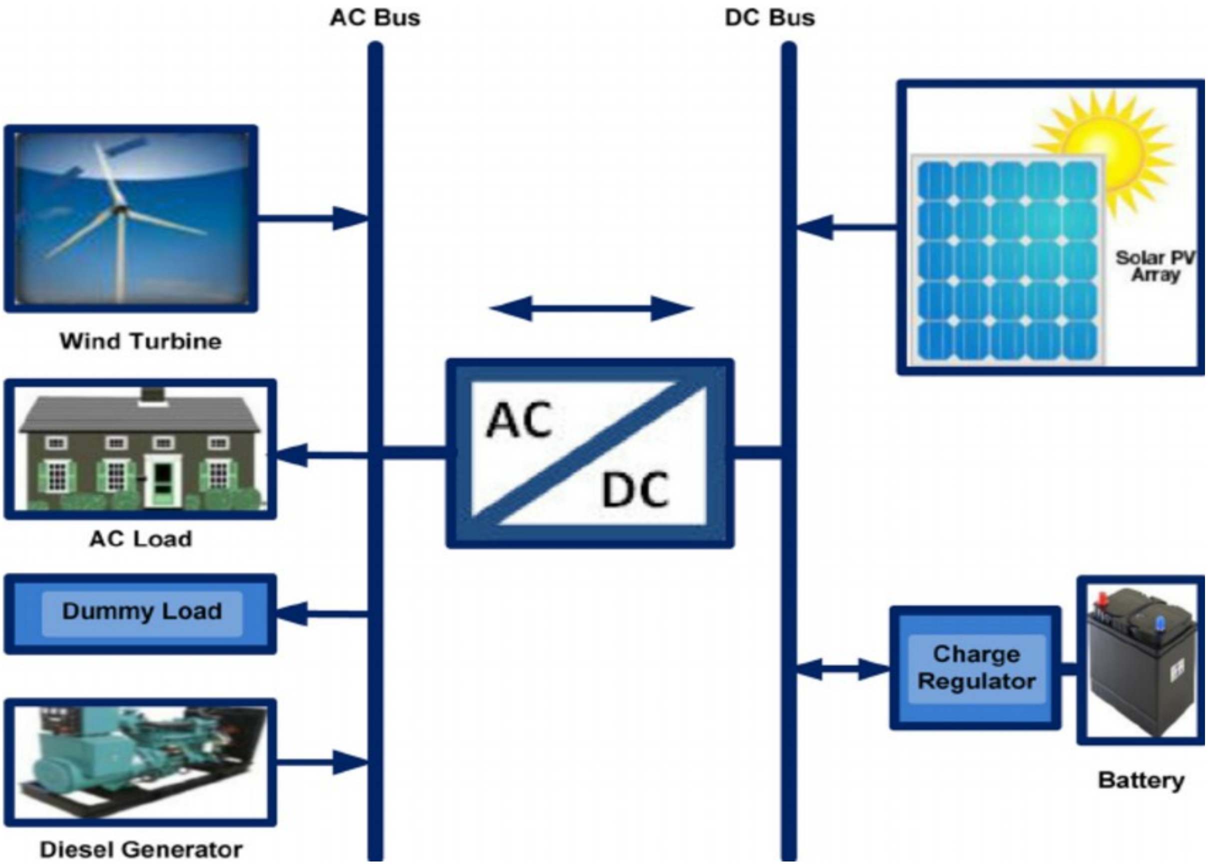


The DFIG is a WRIG with the stator windings connected directly to the three phases, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter. Thus, the term “doubly-fed” comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behaviour being governed by the power electronics converter and its controllers. The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor. The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip (Lu. The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of 40% around the synchronous speed is used. DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

10. Explain in detail about Hybrid Renewable Energy Systems.

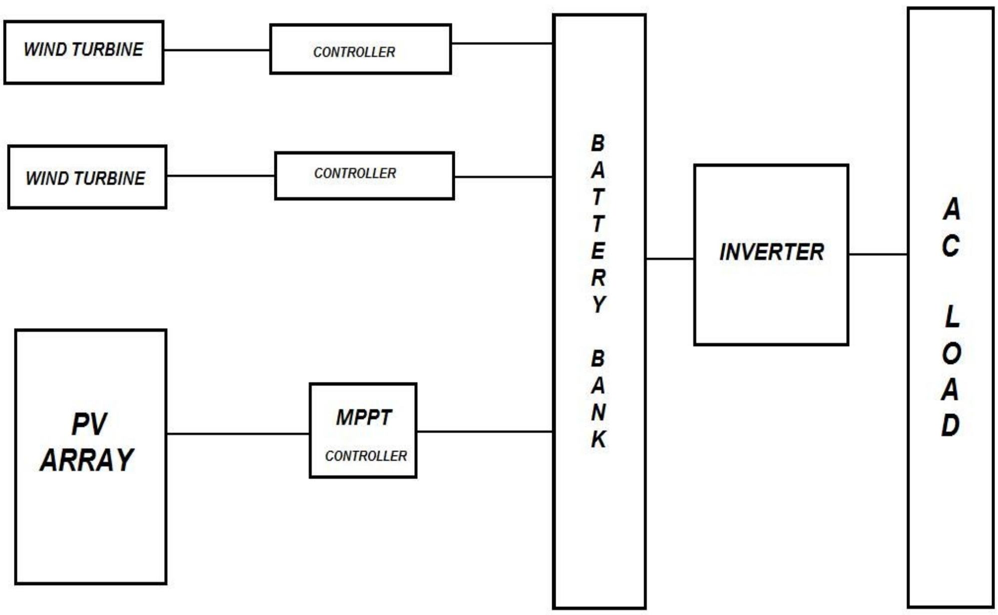
Introduction

Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand. Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply. The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people. Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance. Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area. An example of PV-wind diesel generator HRES is shown in figure below.



Wind- solar Hybrid Renewable energy system

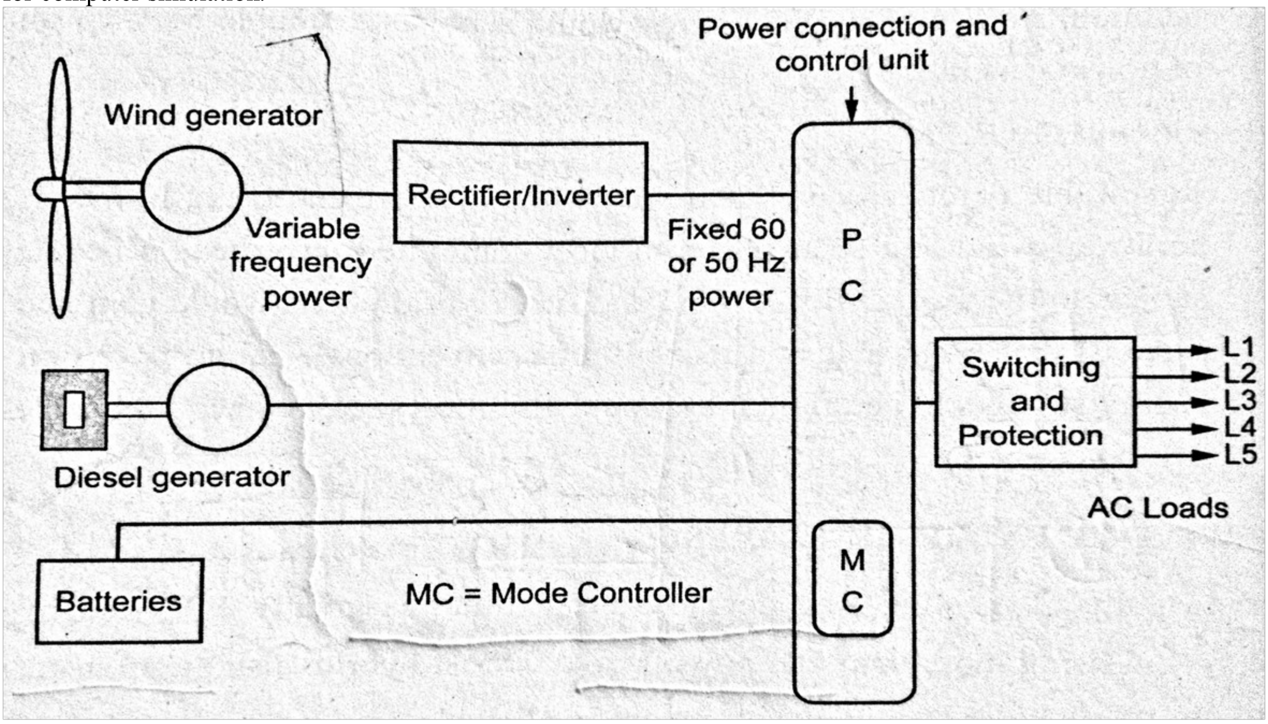
Another example of a hybrid energy system is a photovoltaic array coupled with a wind turbine. This would create more output from the wind turbine during the winter, whereas during the summer, the solar panels would produce their peak output. Hybrid energy systems often yield greater economic and environmental returns than wind, solar, geothermal or trigeneration stand-alone systems by themselves.



Wind-PV hybrid with Diesel

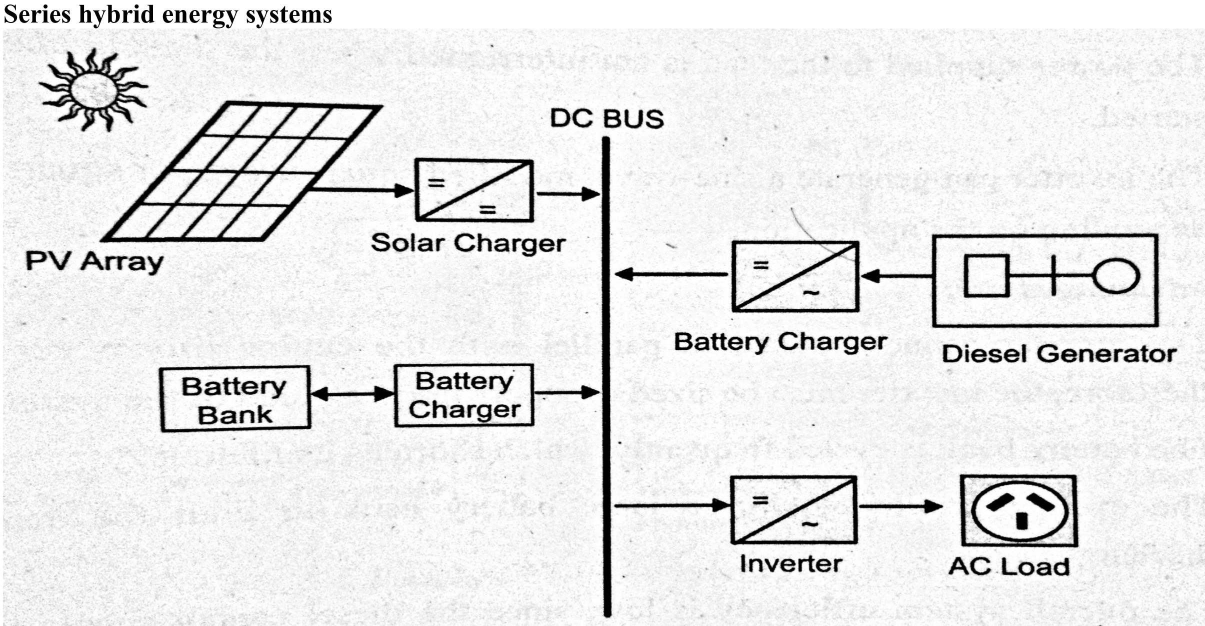
The certainty of meeting load demands at all times is greatly enhanced by the hybrid system using more than one power source. Most hybrids use diesel generator with PV or wind, since diesel provides more predictable power on demand. In some hybrids, batteries are used in addition to the diesel generator. The batteries meet the daily load fluctuation, and the diesel generator takes care of long term fluctuations. Below figure is a schematic layout of wind/diesel/battery hybrid system. The power connection and control unit (PCCU) provides a central place to make organised connections of most system components.

In addition, the PCCU houses the following components
Battery charge and discharge regulators
Transfer switches and protection circuit breakers
Power flow meters
Mode controller
The below figure is a commercially available PCCU for hybrid power system. The transient analysis of integrated wind-PV-diesel requires an extensive model that takes the necessary input data and event definitions for computer simulation.



TYPES OF PV-DIESEL HYBRID SYSTEMS
Series hybrid energy systems
Switched hybrid energy systems
Parallel hybrid energy systems

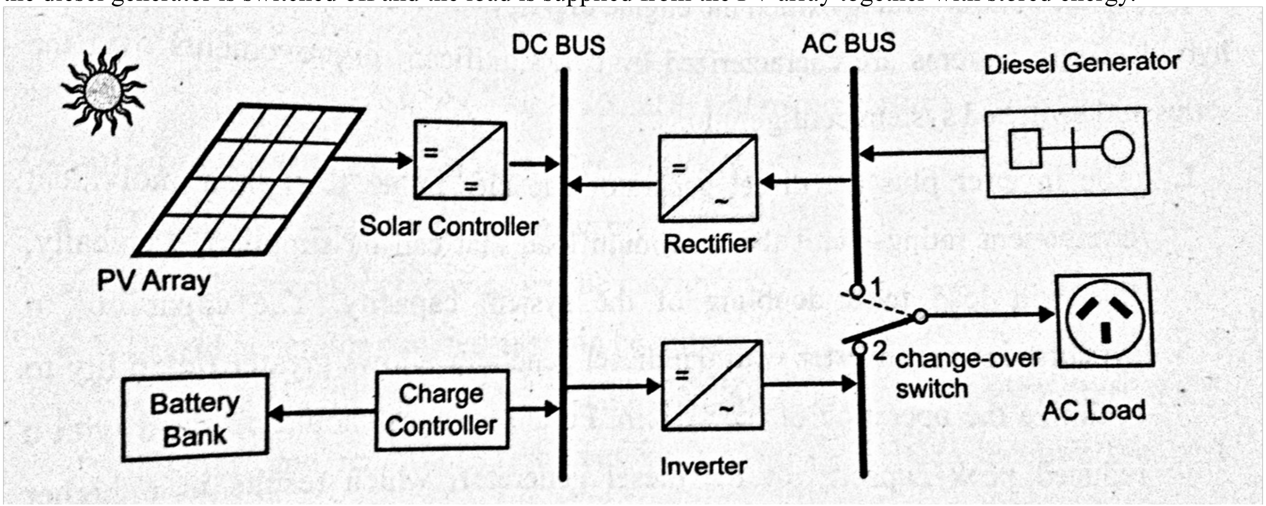
Series hybrid energy systems



The above figure shows a series PV-diesel hybrid system. to ensure reliable operation of series hybrid energy systems, both the diesel generator and inverter have to be sized to meet peak loads. AC power delivered to the load is converted from dc to regulated ac by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to ac before being supplied to the load, which leads to significant conversion losses. The solar controller prevents overcharging of the battery bank from PV generator when PV power exceeds the load demand and batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of engine-driven generator.

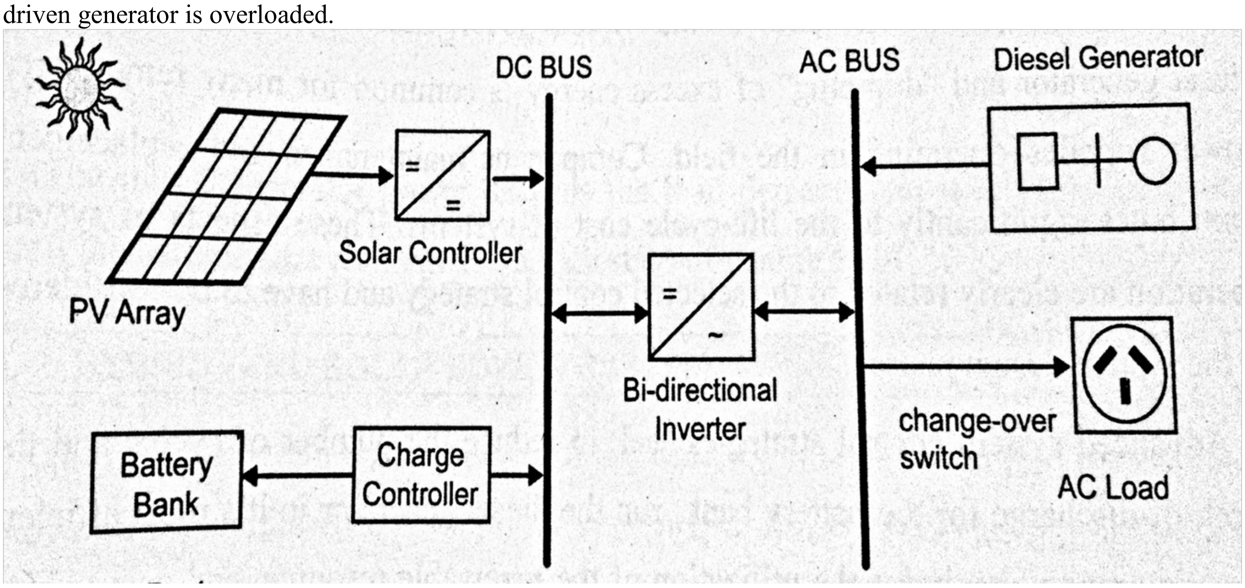
Switched hybrid energy systems

It allows operation with either engine driven generator or the inverter as the ac source, yet no parallel operation of the main generation sources is possible. The diesel generator and renewable energy source can charge the battery bank. The main advantage is that the load can be supplied directly by the engine driven generator, which results in a high overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy.



Parallel hybrid energy systems

The another configuration called parallel one allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronizing the inverter with alternator output waveform. Such a configuration is represented in the below figure. The bidirectional inverter can charge the battery bank when excess energy is available from engine driven generator, as well as a DC-AC converter. The bidirectional inverter may provide peak saving as part of control strategy when engine driven generator is overloaded.



Advantages of Hybrid Renewable Energy Systems:

- Higher total energy efficiency
- More reliable
- Operational flexibility
- Lower emission

Disadvantages of Hybrid Renewable Energy Systems:

Most of us already know how a solar/wind/biomass power generating system works, all these generating systems have some or the other drawbacks, like Solar panels are too costly and the production cost of power by using them is generally higher than the conventional process, it is not available in the night or cloudy days. Similarly Wind turbines can’t operate in high or low wind speeds and Biomass plant collapses at low temperatures.

UNIT-2

PART-B

1. Draw the schematic of double fed induction generator and explain its construction and principle of operation in detail. (M.E-NOV/DEC2016)

Double Fed Induction Generator (DFIG)

Wound rotor induction generators (WRIGs) are provided with three phase windings on the rotor and on the stator. They may be supplied with energy at both rotor and stator terminals. This is why they are called doubly fed induction generators (DFIGs) or double output induction generators (DOIGs). Both motoring and generating operation modes are feasible, provided the power electronics converter that supplies the rotor circuits via slip-rings and brushes is capable of handling power in both directions. As a generator, the WRIG provides constant (or controlled) voltage *Vs* and frequency *f*1 power through the stator, while the rotor is supplied through a static power converter at variable voltage *Vr* and frequency *f*2. The rotor circuit may absorb or deliver electric power. As the number of poles of both stator and rotor windings is the same, at steady state, according to the frequency theorem, the speed ω_m is as follows:

$$\omega_m = \omega_1 \pm \omega_2; \quad \omega_m = \Omega_R \cdot p_1$$

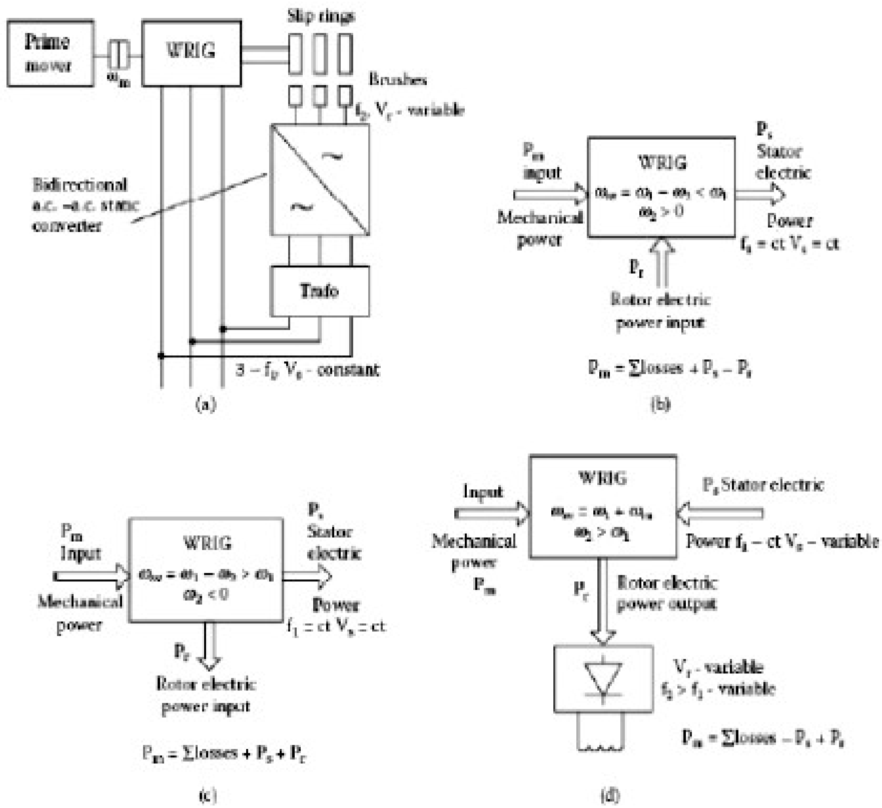
where

p_1 is the number of pole pairs

Ω_R is the mechanical rotor speed

The sign is positive (+) in above Equation when the phase sequence in the rotor is the same as in the stator and $\omega_m<\omega_1$, that is sub synchronous operation. The negative (-) sign in the above equation corresponds to an inverse phase sequence in the rotor when $\omega_m>\omega_1$ that is, super synchronous operation. For constant frequency output, the rotor frequency ω_2 has to be modified in step with the speed variation. This way, variable speed at constant frequency (and voltage) may be maintained by controlling the voltage, frequency, and phase sequence in the rotor circuit. It may be argued that the WRIG works as a synchronous generator (SG) with three-phase alternating current (AC) excitation at slip frequency $\omega_2=\omega_1-\omega_m$. However as ω_1 not equal to ω_m, the stator induces voltages in the rotor circuits even at steady state, which is not the case in conventional SGs. Additional power components thus occur. The main operational modes of WRIG are depicted in Figure a through Figure d (basic configuration shown in Figure a). The first two modes (Figure b and Figure) refer to the already defined sub synchronous and super synchronous generations. For motoring, the reverse is true for the rotor circuit; also, the stator absorbs active power for motoring. The slip *S* is defined as follows:

$$S=\frac{\omega_2}{\omega_1} \quad \begin{matrix} >0;\ \textit{subsynchronous operation} \\ <0;\ \textit{supersynchronous operation} \end{matrix}$$



The main output active power is delivered through the stator, but in super synchronous operation, a good part, about slip stator powers (SPs), is delivered through the rotor circuit. With limited speed variation range, say from *Smax* to *-Smax*, the rotor-side static converter rating — for zero reactive power capability on the rotor side — would be P_{conv}= S $|S_{max}|$ P max With *Smax* typically equal to ±0.2 to 0.25, the static power converter ratings and costs would correspond to 20 to 25% of the stator delivered output power. At maximum speed, the WRIG will deliver increased electric power, *Pmax*

$$P_{max} = P_s + P_{rmax} = P_s + |S_{max}| P_s$$

With the WRIG designed at *Ps* for $\omega m = \omega$ 1 speed. The increased power is delivered at higher than rated speed:

$$\omega_{max} = \omega_1 (1 + |S_{max}|)$$

Consequently, the WRIG is designed electrically for *Ps at ωm* = *ω*1, but mechanically at *wm max* and *Pmax*. The capability of a WRIG to deliver power at variable speed but at constant voltage and frequency represents an asset in providing more flexibility in power onversion and also better stability in frequency and voltage control in the power systems to which such generators are connected. The reactive power delivery by WRIG depends heavily on the capacity of the rotor-side converter to provide it. When the converter works at unity power delivered on the source side, the reactive power in the machine has to come from the rotor-side converter. However, such a capability is paid for by the increased ratings of the rotor-side converter. As this means increased converter costs, in general, the WRIG is adequate for working at unity power factor at full load on the stator side. Large reactive power releases to the power system are still to be provided by existing SGs or from WRIGs working at synchronism (*S* = 0, ω2 = 0) with the back-toback pulse-width modulated (PWM) voltage converters connected to the rotor controlled adequately for the scope. Wind and small hydro energy conversion in units of 1 megawatt (MW) and more per unit require variable speed to tap the maximum of energy reserves and to improve efficiency and stability limits. High-power units in pump-storage hydro- (400 MW) and even thermo power plants with WRIGs provide for extra flexibility for the ever-more stressed distributed power systems of the near future. Even existing (old) SGs may be retrofitted into WRIGs by changing the rotor and its static power converter control. The WRIGs may also be used to generate power solely on the rotor side for rectifier loads (Figured). To control the direct voltage (or direct current [DC]) in the load, the stator voltage is controlled, at constant frequency ω_1 by a low-cost alternating current (AC) three-phase voltage changer. As the speed increases, the stator voltage has to be reduced to keep constant the current in the DC load connected to the rotor. If the machine has a large number of poles ($2p1$ = 6, 8, 12), the stator AC excitation input power becomes rather low, as most of the output electric power comes from the shaft (through motion). Such a configuration is adequate for brushless exciters needed for synchronous motors (SMs) or for generators, where field current is needed from zero speed, that is, when full-power converters are used in the stator of the respective SMs or SGs. With $2p1 = 8$, $n = 1500$ rpm, and $f1 = 50$ Hz, the frequency of the rotor output $f2 = f1 + np1 = 50 + (1500/60)* 4 = 150$ Hz. Such a frequency is practical with standard iron core laminations and reduces the contents in harmonics of the output rectified load current.

Steady state Equations

The emf self induced by stator winding with rotor winding open is as follows:

$$E_1 = \pi\sqrt{2} f_1 W_1 K_{W1} \phi_{1m}; \quad (RMS)$$

$$K_{W1} = K_{d1} \cdot K_{y1}$$

The flux per pole ϕ_{1m} is

$$\phi_{1m} = \frac{2}{\pi} B_{g1m} \tau l_i$$

where

l_i is the stack length

τ is the pole pitch

D_b is the stator bore diameter

B_{g1m} is the airgap fundamental flux density peak value:

$$B_{g1m} = \frac{\mu_0 F_{1m}}{K_C g (1 + K_s)}$$

F_{1m} is the amplitude of stator mmf fundamental per pole

From Equation 1.17, with $\nu = 1$,

$$F_{1m} = \frac{3 W_1 K_{W1} I_0 \sqrt{2}}{\pi p_1}$$

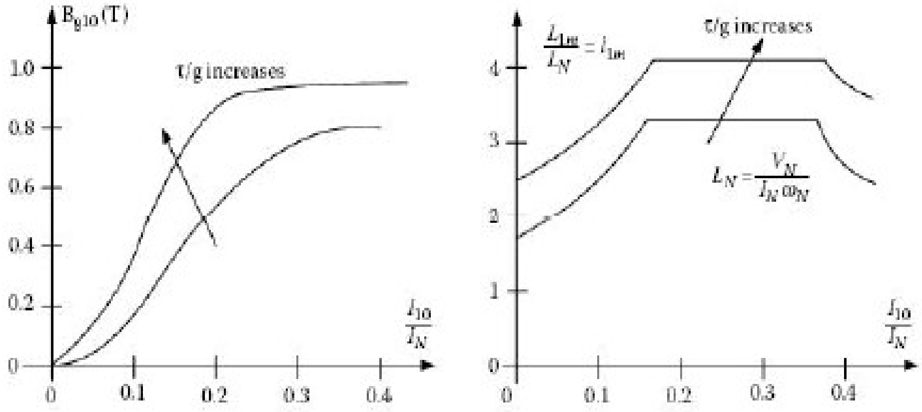


FIGURE Typical airgap flux density (B_{g10}) and magnetization inductance (in per unit [P.U.]) vs. P.U. stator current.

But the same emf E_1 may be expressed as

$$E_1 = \omega_1 L_{1m} \cdot I_{10}$$

So, the main flux, magnetization (cyclic) inductance of the stator — with all three phases active and symmetric — L_{1m} is as follows

$$L_{1m} = \frac{6\mu_0 (W_1 K_{W1})^2 \tau l_i}{\pi^2 p_1 K_C g(1+K_s)}$$

The Carter coefficient $K_C > 1$ accounts for both stator and rotor slot openings ($K_C \approx K_{C1} K_{C2}$). The saturation factor K_S, which accounts for the iron core magnetic reluctance, varies with stator mmf (or current for a given machine), and so does magnetic inductance L_{1m} (Figure).

Besides L_{1m}, the stator is characterized by the phase resistance R_s and leakage inductance L_{sl} [2]. The same stator current induces an emf E_{2s} in the rotor open-circuit windings. With the rotor at speed ω_r — slip $S = (\omega_1 - \omega_r)/\omega_1$ — E_{2s} has the frequency $f_2 = Sf_1$:

$$E_{2s}(t) = E_{2s}\sqrt{2}\cos\omega_2 t$$

$$E_{2s} = \pi\sqrt{2} S f_1 W_2 K_{W2} \phi_{10}$$

Consequently,

$$\frac{E_{2s}}{E_1} = S\frac{W_2 K_{W2}}{W_1 K_{W1}} = S \cdot K_{21}$$

This rotor emf at frequency Sf_1 in the rotor circuit is characterized by phase resistance R_r^r and leakage inductance L^r_{rl}. Also, the rotor is supplied by a system of phase voltages at the same frequency ω_2 and at a prescribed phase.

The stator and rotor equations for steady-state/phase may be written in complex numbers at frequency ω_1 in the stator and ω_2 in the rotor:

$$(R_s + j\omega_1 L_{sl})\underline{I}_s - \underline{V}_s = \underline{E}_1 \quad at \quad \omega_1$$

$$(R_r^r + jS\omega_1 L_{rl})\underline{I}_r^r - \underline{V}_r^r = \underline{E}_{2s} \quad at \quad \omega_2$$

$$(R_r + jS\omega_1 L_{rl})\underline{I}_r - \underline{V}_r = \frac{E_{2s}}{K_{rr}}; \quad E_{2s} = SE_1 K_{rr}$$

$$R_r = R_r^r / K_{rs}^2 \quad L_{rl} = L_{rl}^r / K_{rs}^2$$

$$\underline{V}_r = \underline{V}_R^r / K_{rs} \quad \underline{I}_r = \underline{I}_r^r \cdot K_{rs}$$

The division of Equation 1.31 by slip S yields the following:

$$\left(\frac{R_r}{S} + j\omega_1 L_{rl}\right)\underline{I}_r - \frac{\underline{V}_r}{S} = \frac{S\underline{E}_1}{S}$$

But, Equation 1.31 may also be interpreted as being "converted" to frequency ω_1, as E_1 is at ω_1 ($E_{2s}/S - E_1$):

$$\left(\frac{R_r}{S} + j\omega_1 L_{rl}\right)\underline{I}_r - \frac{\underline{V}_r}{S} = \underline{E}_1; \quad \text{at } \omega_1$$

In Equation 1.33, the rotor voltage V_r and current I_r vary with the frequency ω_1 and, thus, are written (in fact) in stator coordinates. A "rotation transformation" has been operated this way. Also, all variables are reduced to the stator. Physically, this would mean that Equation 1.33 refers to a rotor at standstill, which may produce or absorb active power to cover the losses and delivers in motoring the mechanical power of the actual machine it represents.

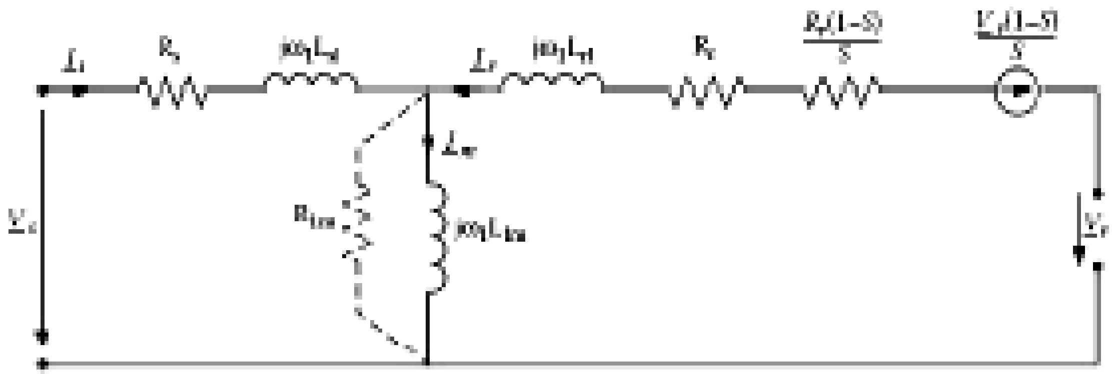
Finally, the emf E_1 may now be conceived to be produced by both I_s and I_r (at the same frequency ω_1), both acting upon the magnetization inductance L_{1m} as the rotor circuit is reduced to the stator:

$$\underline{E}_1 = -j\omega_1 L_{1m}(\underline{I}_s + \underline{I}_r) = -j\omega_1 L_{1m}\underline{I}_m$$

Equivalent circuit:

The equivalent circuit is shown in the below figure

$$p_{cos} = 3R_s I_s^2; \quad p_{cor} = 3R_r I_r^2; \quad p_{Fe} = 3R_{1m}(S\omega_1)I_m^2$$



- The resistance R_{1m} that represents the core losses depends slightly on slip frequency $\omega_2 = S\omega_1$, as non-negligible core losses also occur in the rotor core for $Sf_1 > 5$ Hz.
- The active power balance equations are straightforward, from Figure , as the difference between input electrical powers P_s and P_r and the losses represents the mechanical power P_m:

$$P_m = \left[3\frac{R_r I_r^2}{S} - 3\frac{\mathrm{Re}(\underline{I}_r^* \underline{V}_r)}{S}\right](1-S) = T_e \frac{\omega_1}{p_1}(1-S) = P_{elm}(1-S)$$

$$\Sigma_p = p_{con} + p_{cor} + p_{mec} + P_{Fe}$$

P_{elm} is the electromagnetic (through airgap) power.

$$P_s + P_r' = 3\mathrm{Re}(\underline{V}_s \underline{I}_s^*) + 3\mathrm{Re}(\underline{V}_r \underline{I}_r^*) = P_m + \Sigma p$$

T_e is the electromagnetic torque. The sign of mechanical power for given motion direction is used to discriminate between motoring and generating. The positive sign (+) of P_m is considered here for motoring

The motor/generator operation mode is determined by two factors: the sign of slip S and the sign and relative value of the active power input (or extracted) electrically from the rotor P_r (Table 1.1). So, the WRIG may operate as a generator or a motor both subsynchronously ($\omega_r < \omega_1$) and supersynchronously ($\omega_r > \omega_1$). The power signs in Table 1.1 may be portrayed as in Figure

If all the losses are neglected,

$$P_m = -P_r\frac{(1-S)}{S} = P_s + P_r$$

Consequently,

$$P_r = -SP_s$$

The higher the slip, the larger the electric power absorption or delivery through the rotor. Also, it should be noted that in supersynchronous operation, both stator and rotor electric powers add up to convert the mechanical power. This way, up to a point, oversizing, in terms of torque capability, is not required when operation at $S = -S_{max}$ occurs with the machine delivering $P_1(1+|S_{max}|)$ total electric power.

Reactive power flow is similar. From the equivalent circuit,

$$Q_s + Q_r = 3Imag(\underline{V}_s \underline{I}_s^*) + 3Imag\left(\frac{\underline{V}_r \underline{I}_r^*}{S}\right) = 3\omega_1(L_{sl} I_s^2 + L_{rl} I_r^2 + L_m I_m^2)$$

TABLE 1.1 Operation Modes

S	$0 < S < 1$ Subsynchronous ($\omega_r < \omega_1$)		$S < 0$ Supersynchronous ($\omega_r > \omega_1$)	
Operation Mode	Motoring	Generating	Motoring	Generating
P_m	>0	<0	>0	<0
P_s	>0	<0	>0	<0
P_r	<0	>0	>0	<0

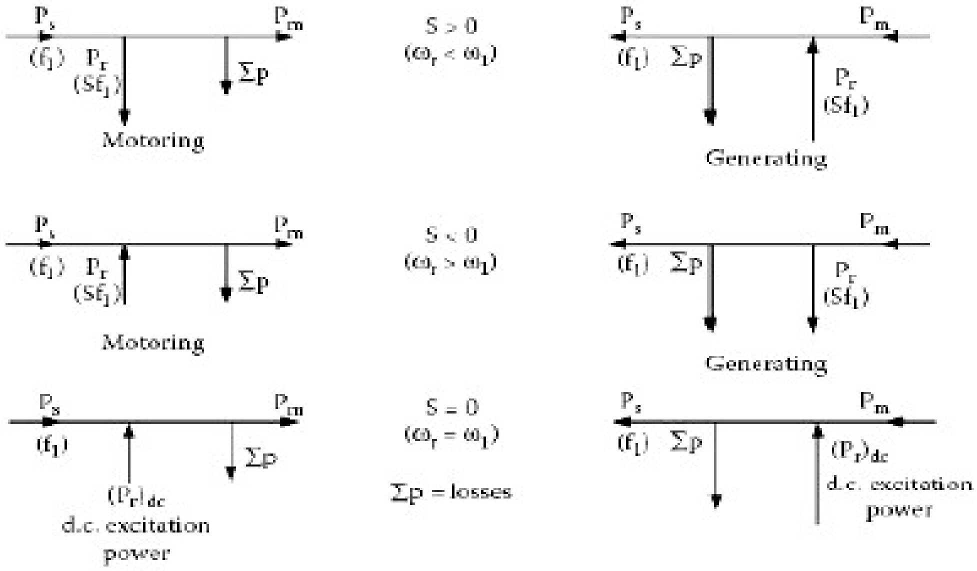


FIGURE Operation modes of wound rotor induction generator (WRIG) at $S > 0$, $S < 0$, and $S = 0$.

So, the reactive power required to magnetize the machine may be delivered by the rotor or by the stator or by both. The presence of *S* in Equation is justified by the fact that machine magnetization is perceived in the stator at stator frequency ω1. As the static power converter rating depends on its rated apparent power rather than active power, it seems to be practical to magnetize the machine from the stator. In this case, however, the WRIG absorbs reactive power through the stator from the power grids or from a capacitive-resistive load. In stand-alone operation mode, however, the WRIG has to provide for the reactive power required by the load up to the rated lagging power factor conditions. If the stator operates at unity power factor, the rotor-side static power Converter has to deliver reactive power extracted either from inside itself (from the capacitor in the DC link) or from the power grid that supplies it. As magnetization is achieved with lowest kVAR in DC, when active power is not needed, the machine may be operated at synchronism to fully contribute to the voltage stability and control in the power system. To further understand the active and reactive power flows in the WRIG, phasor diagrams are used.

2. Explain the operation of SCIG in detail with proper analysis.(APR/MAY2017)(M.E-NOV/DEC2013) (M.E-NOV/DEC2010)

Squirrel Cage Induction Generator

Three-phase induction machines have three windings in the stator and three windings more in the rotor, although, these can be real or imaginary. As it is known, all electrical machines can be described as motor and generator as well, consequently, they can be described with the same set of equations. It is appropriate to remember that these equations govern the operation of the electrical machines. These equations are divided in two groups, Voltage equations and Torque equations in machine variables and other which are expressed in the axes of the reference variables. With the goal of simplifying these equations, to consider the following hypothesis:

Symmetric and balanced three-phase induction machine, with a single winding rotor

- (Squirrel cage simple) and constant gap.
- Material is assumed to be linear, that is to say, the iron saturation is discarded.
- The iron magnetic permeability is assumed to be infinite in front of the air permeability, which means that the magnetic flux density is radial to the gap.
- All kind of losses in the iron are neglected.
- Both the stator windings as the rotor windings represent distributed windings which always generate a sinusoidal magnetic field distribution in the gap.

All hypothesis that we have explained before, using the induction motor's illustration, guide us to the following system of equations which describe the dynamic behaviour of the induction machine.

$$\left\{ \begin{array}{c} v_s^{abc} \\ v_r^{abc} \end{array} \right\} = \left[\begin{array}{cc} r_s^{abc} & 0 \\ 0 & r_r^{abc} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\} + \frac{d}{dt} \left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\}$$

with

v_s^{abc}	stator winding's voltage vector
v_r^{abc}	rotor winding's voltage vector
i_s^{abc}	stator winding's current vector
i_r^{abc}	rotor winding's current vector
λ_s^{abc}	stator winding's concatenated flows vector
λ_r^{abc}	rotor winding's concatenated flows vector

The relationship between concatenated flows, rotor and stator's current is given by

$$\left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\} = \left[\begin{array}{cc} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\}$$

where each term represents a 3-dimensional matrix or a three-dimensional vector. Then, the

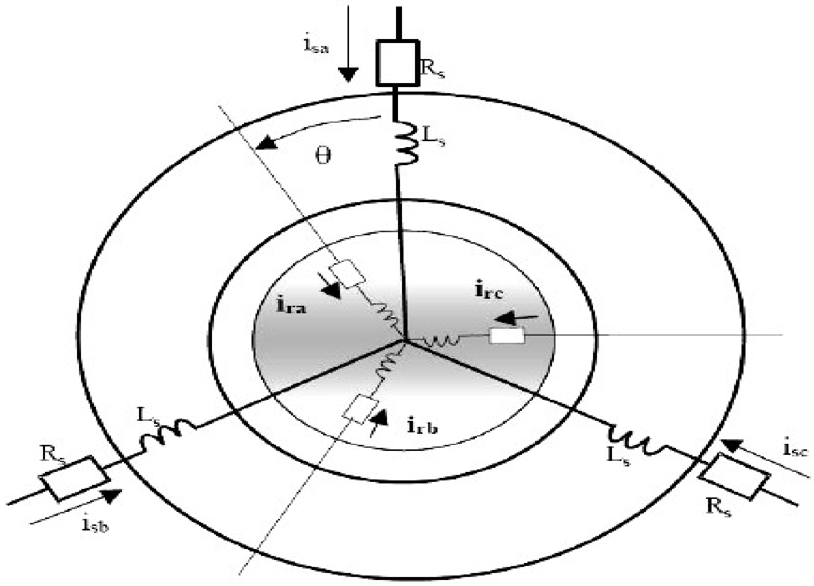


Figure : Induction machine's schematic illustration

vectors can be written as

$$v_s = \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix}, v_r = \begin{pmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{pmatrix}, i_s = \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix}, i_r = \begin{pmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{pmatrix}$$

and impedance matrices as

$$r_s^{abc} = \left[\begin{array}{ccc} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{array} \right]$$

$$r_r^{abc} = \left[\begin{array}{ccc} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{array} \right]$$

$$L_{ss}^{abc} = \left[\begin{array}{ccc} L_{ls} + L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ls} + L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ls} + L_{ss} \end{array} \right]$$

$$L_{sr}^{abc} = \{L_{rs}^{abc}\}^t = L_{sr} \begin{bmatrix} cos(\theta_r) & cos(\theta_r + \frac{2\pi}{3}) & cos(\theta_r - \frac{2\pi}{3}) \\ cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r) & cos(\theta_r + \frac{2\pi}{3}) \\ cos(\theta_r + \frac{2\pi}{3}) & cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r) \end{bmatrix}$$

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr} + L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{lr} + L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{lr} + L_{rr} \end{bmatrix}$$

with:

ω_r	generator's shaft's orientation angle from electric system
r_s	resistance of the stator windings
r_r	resistance of the rotor windings
L_{ss}	self-inductance of the stator windings without the winding owing the dispersion flow
L_{rr}	self-inductance of the rotor windings without the winding owing the dispersion flow
L_{sm}	coupling inductances between stator windings
L_{rm}	coupling inductances between rotor windings
L_{sr}	maximum value reached by coupling inductances between stator and rotor windings
L_{ls}	dispersion inductance of the stator windings
L_{lr}	dispersion inductance of the rotor windings

The electromechanical conversion theory provides the following equation:

$$\Gamma_r = \frac{1}{2}[i]^t \frac{\delta[L(\theta_r)]}{\delta(\theta_r)}[i]$$

where

Γ_r	Torque on the rotor shaft
$L(\theta_r)$	Induction machine's coupling inductance matrix. $L(\theta_r) = \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}$

Usually the induction machines are designed with number of poles over 1. Theoretically, this could be understood as a ideal multiplier with a transmission ratio P between shaft's mechanical angle (θm) and electrical system's angle.

$$\Gamma_m = \frac{P}{2}[i]^t \frac{\delta[L(\theta_r)]}{\delta(\theta_r)}[i]$$

Without the loss of generality we may suppose the number of poles is exactly one. However, we want to remark the results obtained generalize to the situation of multiple poles. The equation expresses the torque developed by the induction machine at any time, depending on the instantaneous currents circulating by each one of the six windings, and the separation angle between the stator winding 1 and the rotor winding 1. This equation is obtained by the electrical system energy balance.Developing the equation it is easily simplified due to Lss and Lrr are not θr dependent. Then the derivative of this constant vanishes. So the new equation can be written as

$$\Gamma_r = \frac{1}{2} \begin{Bmatrix} i_s^{abc} \\ i_r^{abc} \end{Bmatrix}^t \begin{bmatrix} 0 & N_{sr} \\ N_{rs} & 0 \end{bmatrix} \begin{Bmatrix} i_s^{abc} \\ i_r^{abc} \end{Bmatrix}$$

where

$$N_{sr}^{abc} = \{N_{rs}^{abc}\}^t = -L_{sr} \begin{bmatrix} sin(\theta_r) & sin(\theta_r + \frac{2\pi}{3}) & sin(\theta_r - \frac{2\pi}{3}) \\ sin(\theta_r - \frac{2\pi}{3}) & sin(\theta_r) & sin(\theta_r + \frac{2\pi}{3}) \\ sin(\theta_r + \frac{2\pi}{3}) & sin(\theta_r - \frac{2\pi}{3}) & sin(\theta_r) \end{bmatrix}$$

The generator which we will be the studied object is a SCIG (Squirrel Cage Induction Generator), this type of generator is known also as Short-Circuit Induction Generator, owing to rotor windings are then connected in short circuit. So, the only part of the generator connected to the grid will be the stator. Because of this connection to the rotor windings, we are able to get the next simplification $Vr^{abc} = 0$. Then, the equation described before could be written as follows:

$$\left\{ \begin{array}{c} v_s^{abc} \\ 0^{abc} \end{array} \right\} = \left[\begin{array}{cc} r_s^{abc} & 0 \\ 0 & r_r^{abc} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\} + \frac{d}{dt} \left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\}$$

State space of SCIG generator

The dynamic behavior of the machine can be studied by means of a dynamic linear system. Although, most adequate mathematical expression to realize the system simulation is the state space, we are able to obtain our goal with just the few next steps:

First, it is necessary to put on the different side of the equal sign derivative variables and non-derivative.

$$\begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \frac{d}{dt} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} = \left\{ \begin{array}{c} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{array} \right\} - \begin{bmatrix} r_s & L_s\dot{\theta} & 0 & M\dot{\theta} \\ -L_s\dot{\theta} & r_s & -M\dot{\theta} & 0 \\ 0 & M(\dot{\theta}-\dot{\theta}_r) & r_r & L_r(\dot{\theta}-\dot{\theta}_r) \\ -M(\dot{\theta}-\dot{\theta}_r) & 0 & -L_r(\dot{\theta}-\dot{\theta}_r) & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\}$$

Second, we have to determine the inverse of the matrix which is with the derivative. It is needed because of $A^{-1} * A = I$.

$$\begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix}^{-1} = \frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix}$$

Third, to leave only the derivative variables without multiplying constants, we should multiply the inverse in both sides.

$$\frac{d}{dt} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} = -\frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix} \begin{bmatrix} r_s & L_s\dot{\theta} & 0 & M\dot{\theta} \\ -L_s\dot{\theta} & r_s & -M\dot{\theta} & 0 \\ 0 & M(\dot{\theta}-\dot{\theta}_r) & r_r & L_r(\dot{\theta}-\dot{\theta}_r) \\ -M(\dot{\theta}-\dot{\theta}_r) & 0 & -L_r(\dot{\theta}-\dot{\theta}_r) & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} + \frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix} \left\{ \begin{array}{c} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{array} \right\}$$

Finally, we have to multiply the matrices and discard unnecessary elements of the system. Then, we get the following equation:

$$\underbrace{\frac{d}{dt}\begin{Bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{Bmatrix}}_{X} =$$

$$\underbrace{-\frac{1}{L_sL_r - M^2}\begin{bmatrix} L_r r_s & M^2\dot{\theta}_r + (L_sL_r - M^2)\dot{\theta} & -M r_r & M L_r \dot{\theta}_r \\ -M^2\dot{\theta}_r - (L_sL_r - M^2)\dot{\theta} & L_r r_s & -M L_r \dot{\theta}_r & -M r_r \\ -M r_s & -M L_s \dot{\theta}_r & L_s r_r & (L_sL_r - M^2)\dot{\theta} - L_sL_r\dot{\theta}_r \\ M L_s \dot{\theta}_r & -M r_s & -(L_sL_r - M^2)\dot{\theta} - L_sL_r\dot{\theta}_r & L_s r_r \end{bmatrix}}_{A}\underbrace{\begin{Bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{Bmatrix}}_{X}$$

$$+\underbrace{\frac{1}{L_sL_r - M^2}\begin{bmatrix} L_r & 0 \\ 0 & L_r \\ -M & 0 \\ 0 & -M \end{bmatrix}}_{B}\underbrace{\begin{Bmatrix} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{Bmatrix}}_{U}$$

$$\frac{di_{s0}}{dt} = \frac{r_s}{L_{ss} + 2L_{sm} + L_{ls}} i_{s0} - \frac{1}{L_{ss} + 2L_{sm} + L_{ls}} v_{s0}$$

$$\frac{di_{r0}}{dt} = \frac{r_r}{L_{rr} + 2L_{rm} + L_{lr}} i_{r0} - \frac{1}{L_{rr} + 2L_{rm} + L_{lr}} v_{r0}$$

3. Draw the equivalent circuit and show the steady state analysis of permanent magnet synchronous generator (PMSG). Explain the merits and demerits of PMSG for wind energy conversion system. (APR/MAY2017)(M.E-NOV/DEC2013)(M.E-APR/MAY2013)(M.E-NOV/DEC2010)

Permanent magnet synchronous generator (PMSG)

By permanent magnet (PM) synchronous generators (SGs), we mean here radial or axial airgap PM brushless generators with distributed ($q > 1$) or concentrated ($q \leq 1$) windings and rectangular or sinusoidal current control with surface PM or interior PM (IPM) rotors. A PMSG's output voltage amplitude and frequency are proportional to speed. In constant speed prime mover applications, PMSGs might perform voltage self-regulation by proper design; that is, inset or interior PM pole rotors. Small speed variation (10 to 15%) may be acceptable for diode rectified loads with series capacitors and voltage self-regulation. However, most applications require operation at variable speed, and, in this case, constant output voltage vs. load, be it direct current (DC) or alternating current (AC), requires full static power conversion and close-loop control.

Classification of PMSG

PMSGs are classified as

- Radial or axial flux machines
- Longitudinal or transversal flux machines
- Inner rotor or outer rotor machines
- Interior (inset) magnet or exterior (surface mounted) magnet machines

<u>Longitudinal or transversal flux machines:</u>

In transversal flux machines, the plane of flux path is perpendicular to the direction of rotor motion. One attractive property of transversal flux machines is that the current loading and magnetic loading can be adjusted independently.

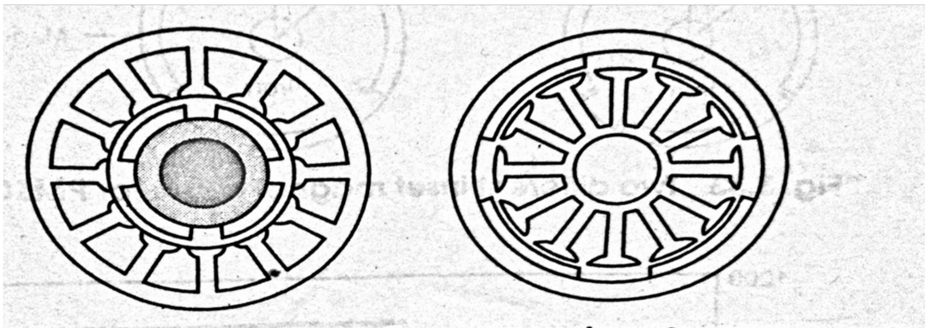
<u>Inner rotor or outer rotor machines:</u>

<u>outer rotor machines:</u>

The rotor surrounds the stator in outer rotor machines. In these machines, the magnets are usually located on the inner circumference of the rotor. The rotor has higher radius compared with the stator and it can be equipped with higher number of poles for the same pole pitch.

<u>Inner rotor machines:</u>

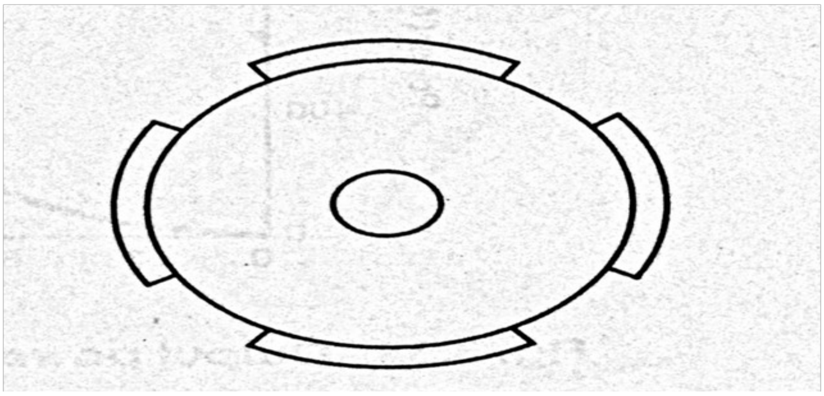
In small machines, the main contributions to the losses are copper losses and therefore the stator winding has the highest temperature rise in the active material of the machine. Hence it is more beneficial to put the stator winding, rather than the magnets, closer to the housing, where the cooling properties are good. This causes less temperature rise for same amount of losses.



1 Inner rotor PMSG (left) and an outer rotor PMSG (right)

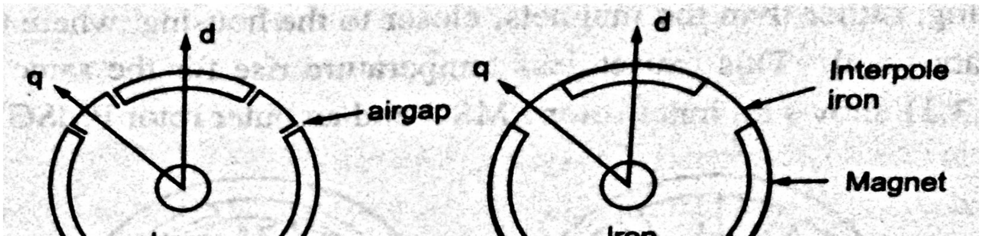
Exterior (surface mounted) magnet machines:

Here the magnets are mounted on the surface of rotor. The magnets are glued and/or bandaged to the rotor surface in order to withstand centrifugal force. Usually, the magnets are oriented or magnetized in radial direction and the direct and quadrature axis reactances are almost equal.



Interior (inset) magnet machines:

In this, the rotor core is modified with iron inter poles. Inter poles cause saliency and the inductances in direct and quadrature directions are different. The magnets are radially magnetised but flux leakage is high which results in low power factor. So, this topology is not common in use.



A typical cylindrical rotor configuration is shown in Figure below. For IPM pole rotors, the magnetic reluctance along the direct (*d*) axis is larger than for the transverse (*q*) axis; thus, $L_d < L_q$ — that is, inverse saliency, in contrast to electromagnetically excited pole rotors for standard synchronous machines. The d axis falls along PM field axis in the airgap. The rotor may be internal or external to the stator, in cylindrical rotor configurations. Interior rotors require a carbon fiber mechanical shield (retainer) against centrifugal forces for high-speed applications (above 50 to 80 m/sec peripheral speed). In contrast, external rotors do not need such a retainer, but the yoke has to withstand high centrifugal forces in high-speed rotors.

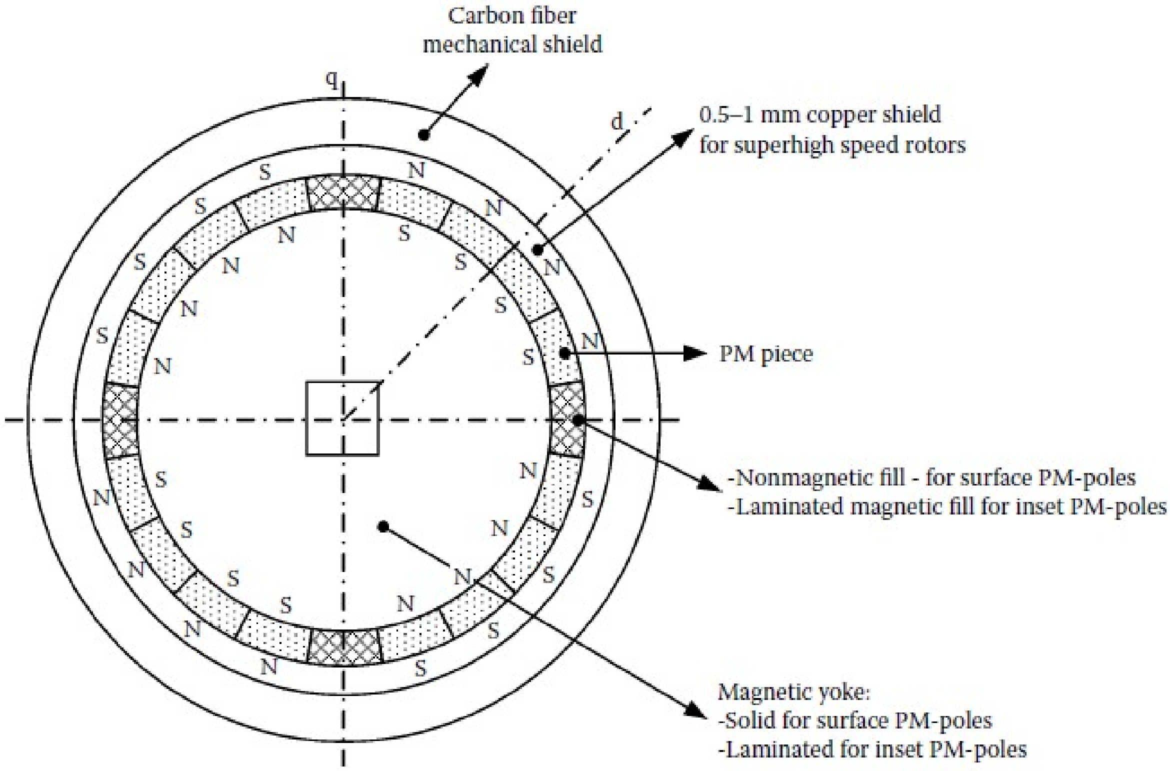


FIGURE Four-pole surface permanent magnet (PM) and inset PM pole rotor configurations.

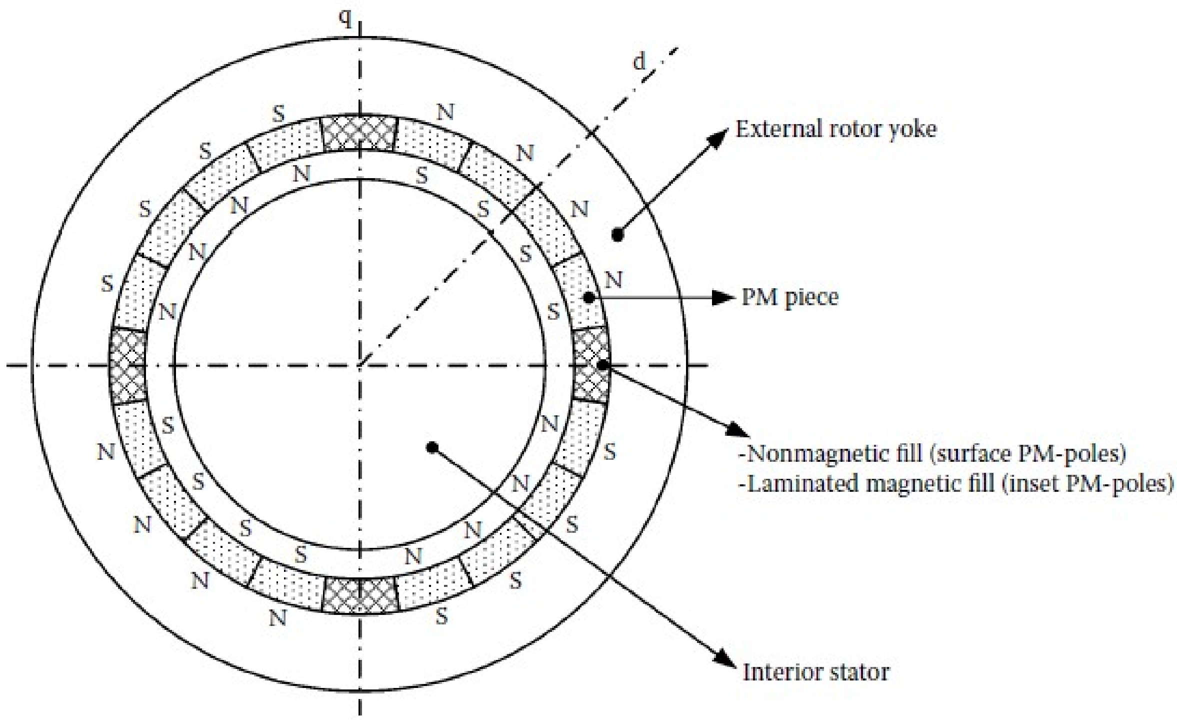


FIGURE Four-pole cylindrical external rotor.

Operating modes of PMSG:

Three operating modes:

- Silent mode
- Variable speed operation mode
- Constant speed mode

Silent mode:

A turbine is silent in two cases: wind speed is below a cut-in level or above the cut-off speed. If the speed is below its cut-in level it produces insufficient torque to move the turbine. At the same time winds above cut-off level may damage the turbine, which must be stopped in such conditions.

Variable speed operation mode:

A turbine operates at variable speed in the wind velocity range from cut-in to rated wind speed. Rated wind speed differs by turbine types, but often has the value of 12m/s.

Constant speed mode:

It takes place above rated wind speed. Turbine output power remains constant at this mode.

The Circuit Model

The Phase Coordinate Model

In essence, the circuit model of a PMSG starts with the phase voltage equations in stator coordinates:

$$i_a R_s - V_a = -\frac{d\Psi_a}{dt}$$

$$i_b R_s - V_b = -\frac{d\Psi_b}{dt}$$

$$i_c R_s - V_c = -\frac{d\Psi_c}{dt}$$

$$\begin{vmatrix}\Psi_a\\ \Psi_b\\ \Psi_c\end{vmatrix} = \begin{vmatrix} L_l + L_{aa}(\theta_{er}) & L_{ab}(\theta_{er}) & L_{ac}(\theta_{er})\\ L_{ab}(\theta_{er}) & L_l + L_{bb}(\theta_{er}) & L_{bc}(\theta_{er})\\ L_{ac}(\theta_{er}) & L_{bc}(\theta_{er}) & L_l + L_{cc}(\theta_{er})\end{vmatrix} \cdot \begin{vmatrix} i_a\\ i_b\\ i_c\end{vmatrix} + \begin{vmatrix}\Psi_{PMa}(\theta_{er})\\ \Psi_{PMb}(\theta_{er})\\ \Psi_{PMc}(\theta_{er})\end{vmatrix}$$

where θ_{er} is the rotor PM axis angle to stator phase a axis/electrical angle.

The self-inductance and mutual inductance of the stator depend sinusoidally on θ_{er} only for IPM rotors, in distributed winding IPM rotor machines. For surface PM pole rotors, stator inductances are independent of θ_{er}. However, the presence of slot openings introduces an additional dependence of stator inductances on $N_s\ \theta_{er}$ for IPM rotors. For concentrated windings, the stator self-inductance and mutual inductance perform in a similar way, with respect to rotor pole configurations, but their values tend to be larger than for distributed windings and equivalent machine geometries. However, the end-turn leakage inductances are notably smaller for concentrated windings.

The trapezoidal distribution may be considered this way:

$$\Psi_{PMa}(\theta_{er}) = \Psi_{PM1}(\theta_{er}) + \Psi_{PM2}(2\theta_{er} - \gamma_2) + \Psi_{PM3}(3\theta_{er} - \gamma_3) + \ldots\ldots$$

The even harmonics occur only with PM pole shifting, adopted to reduce cogging torque. Also, space subharmonics may occur. They have to be avoided for practical designs.

For surface PM pole rotors, the general expressions of E_{aa}, E_{ab}, E_{ac}, and Ψ_{PMa} developed earlier may be used to calculate L_{aah}, L_{abh}, L_{ach}, Ψ_{PMa}, $(i_b = i_c = 0)$:

$$L_{aah} = \frac{E_{aa}}{\omega_1 i_a};\ L_{abh} = \frac{E_{ab}}{\omega_1 i_a};\ \ L_{ach} = \frac{E_{ac}}{\omega_1 i_a};\ \ \Psi_{PMa} = \frac{|E_{PMa}|}{\omega_1}$$

The instantaneous interaction torque expression, in the absence of magnetic saturation, is as follows:

$$T_e = -\frac{\partial W_m}{\partial \theta_{er}}$$

$$W_m = \frac{1}{2}L_{aah}i_a^2 + \frac{1}{2}L_{bbh}i_b^2 + \frac{1}{2}L_{cch}i_c^2 + L_{abh}i_a i_b + L_{bch}i_b i_c + L_{cah}i_c i_a$$
$$+ \Psi_{PMa}(\theta_{er})i_a + \Psi_{PMb}(\theta_{er})i_b + \Psi_{PMc}(\theta_{er})i_c$$

The d-q model of PMSG:

The *d–q* model is based on the assumption that the stator self-inductance and mutual inductance are either constant or vary sinusoidally with the rotor position. In general, the PM flux linkages in the stator phases also vary sinusoidally, but with Eventual harmonics in may be treated in the *d–q* model also, and they are expected to create time pulsations in the torque with sinusoidal currents at speed and frequency.

$$|L_{abc}(\theta_{er})| = \begin{vmatrix} L_{sl} + L_0 + L_2\cos 2\theta_{er} & M_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) & M_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) \\ M_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) & L_{sl} + L_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) & M_0 + L_2\cos 2\theta_{er} \\ M_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) & M_0 + L_2\cos 2\theta_{er} & L_{sl} + L_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) \end{vmatrix}$$

$$M = -\frac{L_0}{2} \text{ for distributed windings}$$

For PM machines, $L_2 < 0$, as they have the PMs placed along axis *d* and exhibit "inverse saliency," in contrast to standard synchronous machine excitation:

$$\begin{vmatrix} \Psi_{PMa}(\theta_{er}) \\ \Psi_{PMb}(\theta_{er}) \\ \Psi_{PMc}(\theta_{er}) \end{vmatrix} = \begin{vmatrix} \Psi_{PM1}\cos\theta_{er} + \cdots\cdots \\ \Psi_{PM1}\cos\left(\theta_{er} - \frac{2\pi}{3}\right) + \cdots\cdots \\ \Psi_{PM1}\cos\left(\theta_{er} + \frac{2\pi}{3}\right) + \cdots\cdots \end{vmatrix}$$

The matrix form of the phase coordinates model is as follows:

$$\left|i_{a,b,c}\right|\left|R_s\right| - \left|V_{a,b,c}\right| = -\frac{d\left|\Psi_{a,b,c}\right|}{dt}$$

$$\Psi_{a,b,c} = \left|L_{a,b,c}(\theta_{er})\right|\left|i_{a,b,c}\right| + \Psi_{PMa,b,c}(\theta_{er})$$

The Park transformation $P(\theta_{er})$ is used to derive the d–q model:

$$\left|P(\theta_{er})\right| = \frac{2}{3}\begin{vmatrix} \cos(-\theta_{er}) & \cos\left(-\theta_{er} + \frac{2\pi}{3}\right) & \cos\left(-\theta_{er} - \frac{2\pi}{3}\right) \\ \sin(-\theta_{er}) & \sin\left(-\theta_{er} + \frac{2\pi}{3}\right) & \sin\left(-\theta_{er} - \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix}$$

The Park transformation from stator to rotor coordinates is, in Equation 10.38, valid for the trigonometric motion direction and axis q in front of axis d by 90° (electrical degrees) (Figure 10.23):

$$\begin{vmatrix} i_d \\ i_q \\ i_0 \end{vmatrix} = \left|P(\theta_{er})\right|\begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}$$

The same transformation is valid for Ψ_{dq0}, V_{dq0}.

Finally, for sinusoidal $\Psi_{PMa,b,c}(\theta_{er})$ distributions,

$$i_d R_s - V_d = -L_d \frac{di_d}{dt} + \omega_r L_q i_q$$

$$i_q R_s - V_q = -L_q \frac{di_q}{dt} - \omega_r (L_d i_d + \Psi_{PM1})$$

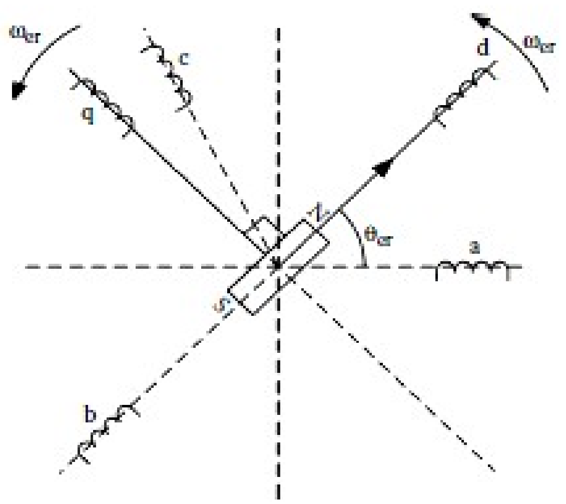


FIGURE Three-phase to d–q transformation.

with

$$\overline{\Psi}_s = \Psi_d + j\Psi_q \qquad \Psi_d = \Psi_{PM1} + L_d i_d \qquad \Psi_q = L_q i_q$$

$$\overline{V}_s = V_d + jV_q \qquad \bar{i}_s = i_d + ji_q$$

The so-called space-vector (or complex variable) model of a PMSG is obtained:

$$\bar{i}_s R_s - \overline{V}_s = -\frac{d\overline{\Psi}_s}{dt} - j\omega_r \overline{\Psi}_s$$

The torque is obtained from power balance in Equation 10.37:

$$T_e = p_1 \frac{P_e}{\omega_r} = \frac{3}{2} p_1 \mathrm{Re}(j\overline{\Psi}_s \vec{i}_s) = \frac{3}{2} p_1 (\Psi_d i_q - \Psi_q i_d) = \frac{3}{2} p_1 (\Psi_{PM1} + (L_d - L_q) i_d) i_q$$

Also,

$$L_d = L_s + \frac{3}{2}(L_0 - |L_2|) \qquad L_q = L_s + \frac{3}{2}(L_0 + |L_2|)$$

The winding losses P_{copper} are as follows:

$$P_{copper} = \frac{3}{2} R_s \left(i_d^2 + i_q^2\right)$$

4. Explain with a neat diagram the operation of an induction generator.(M.E-APR/MAY2013)

INDUCTION GENERATOR

The electric power in industry is consumed primarily by induction machines working as motors driving mechanical loads. For this reason, the induction machine, invented by Nikola Tesla and financed by George Westinghouse in the late 1880s, represents a well-established technology. The primary advantage of the induction machine is the rugged brushless construction that does not need a separate DC field power. The disadvantages of both the DC machine and the synchronous machine are eliminated in the induction machine, resulting in low capital cost, low maintenance, and better transient performance. For these reasons, the induction generator is extensively used in small and large wind farms and small hydroelectric power plants. The machine is available in numerous power ratings up to several megawatts capacity, and even larger. For economy and reliability, many wind power systems use induction machines as electrical generators.

CONSTRUCTION OF INDUCTION GENERATOR

In the electromagnetic structure of the induction generator, the stator is made of numerous coils wound in three groups (phases), and is supplied with three-phase current. The three coils are physically spread around the stator periphery and carry currents, which are out of time phase. This combination produces a rotating magnetic field, which is a key feature in the working of the induction machine. The angular speed of the rotating magnetic field is called the *synchronous speed*. It is denoted by Ns and is given by the following in rpm

$$N_s = \frac{120f}{p}$$

Where f = frequency of the stator excitation
p= Number of magnetic poles.

The stator coils are embedded in slots in a high-permeability magnetic core to produce the required magnetic field intensity with a small exciting current. The rotor, however, has a completely different structure. It is made of solid conducting bars, also embedded in slots in a magnetic core. The bars are connected together at both ends by two conducting end rings (see Figure). Because of its resemblance, the rotor is called a *squirrel cage rotor*, or the *cage rotor*, for short, and the motor is called the *squirrel cage induction motor.*

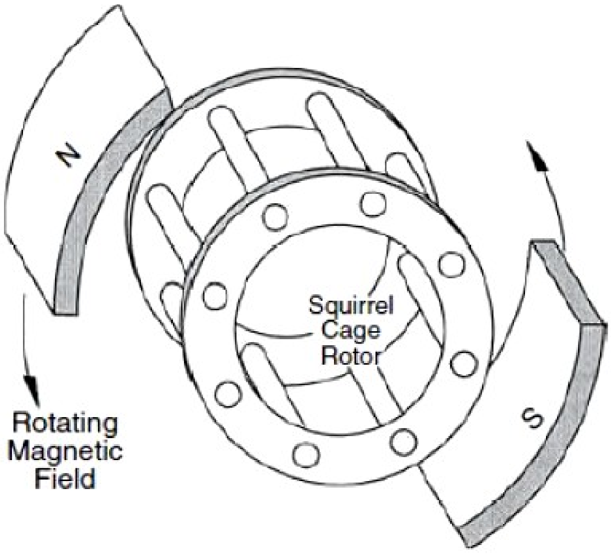


FIGURE Squirrel cage rotor of the induction machine under rotating magnetic field.

WORKING PRINCIPLE

The stator magnetic field is rotating at the synchronous speed determined by Equation below. This field is conceptually represented by the rotating magnets in figure above. The relative speed between the rotating field and the rotor induces the voltage in each closed loop of the rotor conductors linking the stator flux. The magnitude of the induced voltage is given by Faraday's law of electromagnetic induction, namely:

$$e = -\frac{d\phi}{dt}$$

Where φ=the magnetic flux of the stator linking the rotor loop.
This voltage in turn sets up the circulating current in the rotor. The electromagnetic interaction of the rotor current and stator flux produces the torque. The magnitude of this torque is given by the following:

$$T = k\Phi I_2 \cos \phi_2$$

where
k = constant of proportionality
Φ = magnitude of the stator flux wave
I_2 = magnitude of induced current in the rotor loops
ϕ_2 = phase angle by which the rotor current lags the rotor voltage

The rotor accelerates under this torque. If the rotor were on frictionless bearings in a vacuum with no mechanical load attached, it would be completely free to rotate with zero resistance. Under this condition, the rotor would attain the same speed as the stator field, namely, the synchronous speed. At this speed, the current induced in the rotor is zero, no torque is produced, and none is required. Under these conditions, the rotor finds Equilibrium and will continue to run at the synchronous speed. If the rotor is now attached to a mechanical load such as a fan, it will slow down. The stator flux, which always rotates at a constant synchronous speed, will have a relative speed with respect to the rotor. As a result, electromagnetically induced voltage, current, and torque are produced in the rotor. The torque produced must equal that needed to drive the load at this speed. The machine works as a motor in this condition. If we attach the rotor to a wind turbine and drive it faster than its synchronous speed via a step-up gear, the induced current and the torque in the rotor reverse the direction. The machine now works as the generator, converting the mechanical power of the turbine into electric power, which is delivered to the load connected to the stator terminals. If the machine were connected to a grid, it would feed power into the grid. Thus, the induction machine can work as an electrical generator only at speeds higher than the synchronous speed. The generator operation, for this reason, is often called the *super synchronous operation* of the induction machine. As described in the preceding text, an induction machine needs no electrical connection between the stator and the rotor. Its operation is entirely based on electromagnetic induction; hence, the name. The absence of rubbing electrical contacts and simplicity of its construction make the induction generator a very robust, reliable, and low-cost machine. For this reason, it is widely used in numerous industrial applications. Engineers familiar with the theory and operation of the electrical transformer would see the working principle of the induction machine can be seen as the transformer with shorted secondary coil. The high-voltage coil on the stator is excited, and the low voltage coil on the rotor is shorted on itself. The electrical or mechanical power from one to the other can flow in either direction. The theory and operation of the transformer, therefore, holds true when modified to account for the relative motion between the stator and the rotor. This motion is expressed in terms of the slip of the rotor relative to the synchronously rotating magnetic field.

ROTOR SPEED AND SLIP

The slip of the rotor is defined as the ratio of the speed of rotating magnetic field sweeping past the rotor and the synchronous speed of the stator magnetic field as follows:

$$s = \frac{N_s - N_r}{N_s}$$

where

s = slip of the rotor in a fraction of the synchronous speed

N_s = synchronous speed = $60\, f/p$

N_r = rotor speed

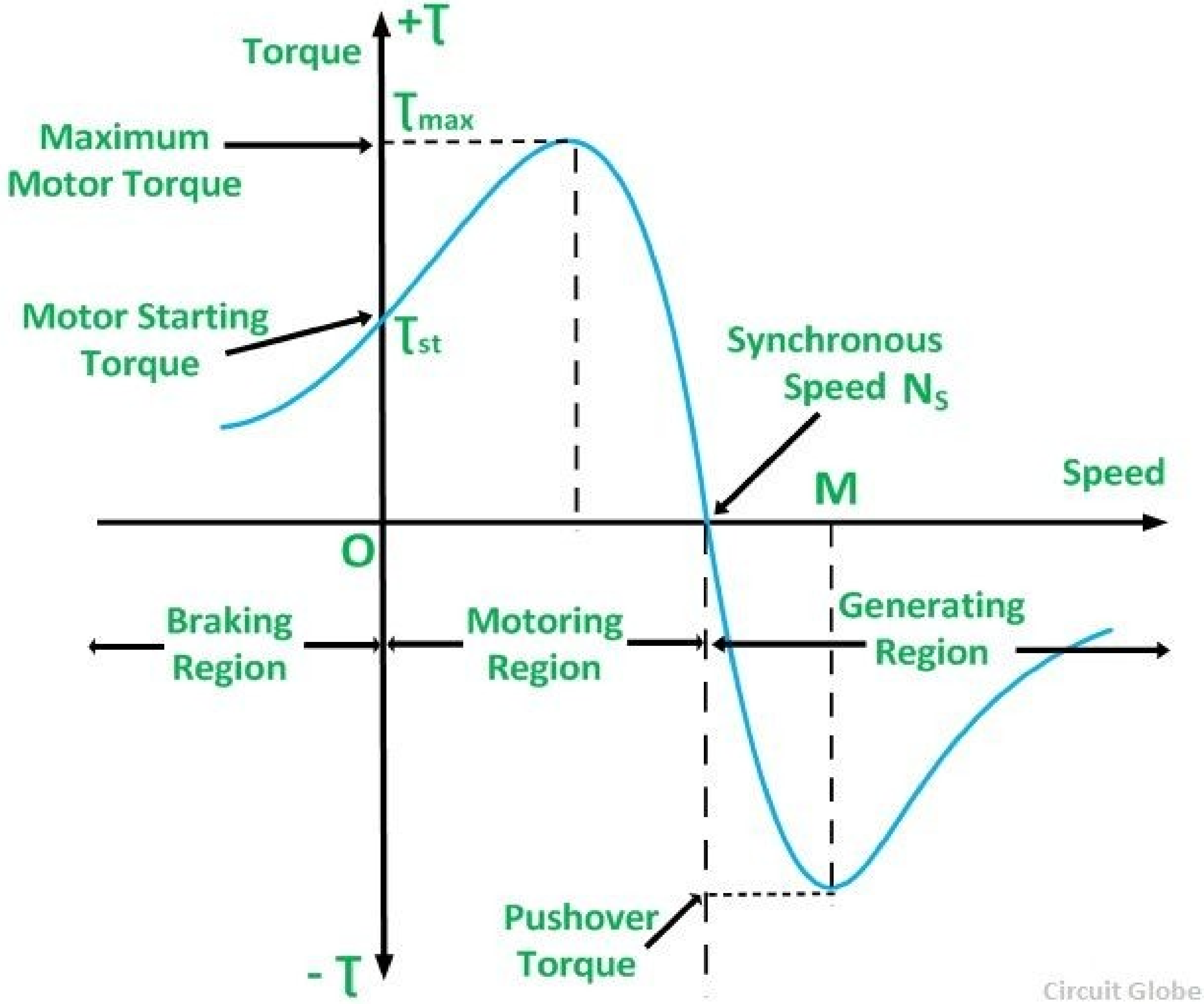
The slip is positive in the motoring mode and negative in the generating mode. In both modes, a higher rotor slip induces a proportionally higher current in the rotor, which results in greater electromechanical power conversion. In both modes, the value of slip is generally a few to several percent. Higher slips, however, result in greater electrical loss, which must be effectively dissipated from the rotor to keep the operating temperature within the allowable limit. The heat is removed from the machine by the fan blades attached to one end ring of the rotor. The fan is enclosed in a shroud at the end. The forced air travels axially along the machine exterior, which has fins to increase the dissipation area. The induction generator feeding a 60-Hz grid must run at a speed higher than 3600 rpm in a 2-pole design, 1800 rpm in a 4-pole design, and 1200 rpm in a 6- pole design. The wind turbine speed, on the other hand, varies from a few hundred rpm in kW range machines to a few tens of rpm in MW-range machines. The wind turbine, therefore, must interface the generator via a mechanical gear. As this somewhat degrades efficiency and reliability, many small stand-alone plants operate with custom-designed generators operating at lower speeds without any mechanical gear. Under the steady-state operation at slip "*s*," the induction generator has the following operating speeds in rpm:

Stator flux wave speed	N_s
Rotor mechanical speed	$N_r = (1 - s)N_s$
Stator flux speed with respect to rotor	sN_s
Rotor flux speed with respect to stator	$N_r + sN_s = N_s$

Thus, the squirrel cage induction machine is essentially a constant-speed machine, which runs slightly slipping behind the rotating magnetic field of the three phase stator current. The rotor slip varies with the power converted, and the rotor speed variations are within a few percent. It always consumes reactive power — undesirable when connected to a weak grid — which is often compensated by capacitors to achieve the systems power factor closed to one. Changing the machine speed is difficult. It can be designed to run at two different but fixed speeds by changing the number of poles of the stator winding. The voltage usually generated in the induction generator is 690-V AC. It is not economical to transfer power at such a low voltage over a long distance. Therefore, the machine voltage is stepped up to a higher value between 10,000 V and 30,000 V via a step-up transformer to reduce the power losses in the lines.

CHARACTERISTICS OF INDUCTION GENERATOR:

The characteristics of induction generator is shown in the below figure.



5. Explain the operating principle of squirrel cage induction generator coupled with wind turbine. (APR/MAY2017)

Fixed Speed Wind Energy Conversion Systems

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below. This WECS configuration is also known as the "Danish concept" because it was developed and widely used in Denmark.

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the Wind speed cubed, the associated electromagnetic variations are important.

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection.

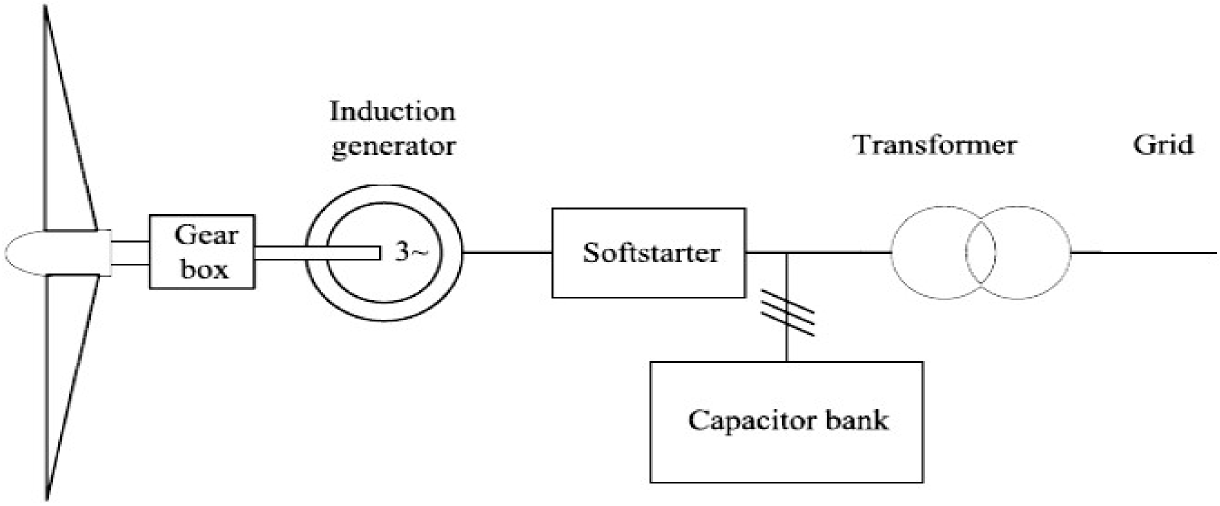


Fig General structure of a fixed-speed WECS

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).

Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

UNIT-3

PART-B

1. Draw the schematic diagram of standalone solar photovoltaic system. What are the main components used in it? Explain their functions.(APR/MAY2017)(M.E-NOV/DEC2010)

Photovoltaic (PV) Systems

Photovoltaic (PV) systems convert sunlight to electric current. You are already familiar with some simple PV applications in today's society, such as calculators and wrist watches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. Many road and traffic signs along highways are now powered by PV.

PV systems produce some electric current any time the sun is shining, but more power is produced when the sunlight is more intense and strikes the PV modules directly. While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun's heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules.

PV allows you to produce electricity—without noise or air pollution—from a clean, renewable resource. A PV system never runs out of fuel, and it won't increase oil imports.

Block Diagram of Solar Photovoltaic System

Generally there are two types of Solar Photovoltaic System they are

1. Autonomous Solar Photovoltaic system or Stand alone Solar Photovoltaic system.
2. Grid Connected PV system.

a) Without Battery.

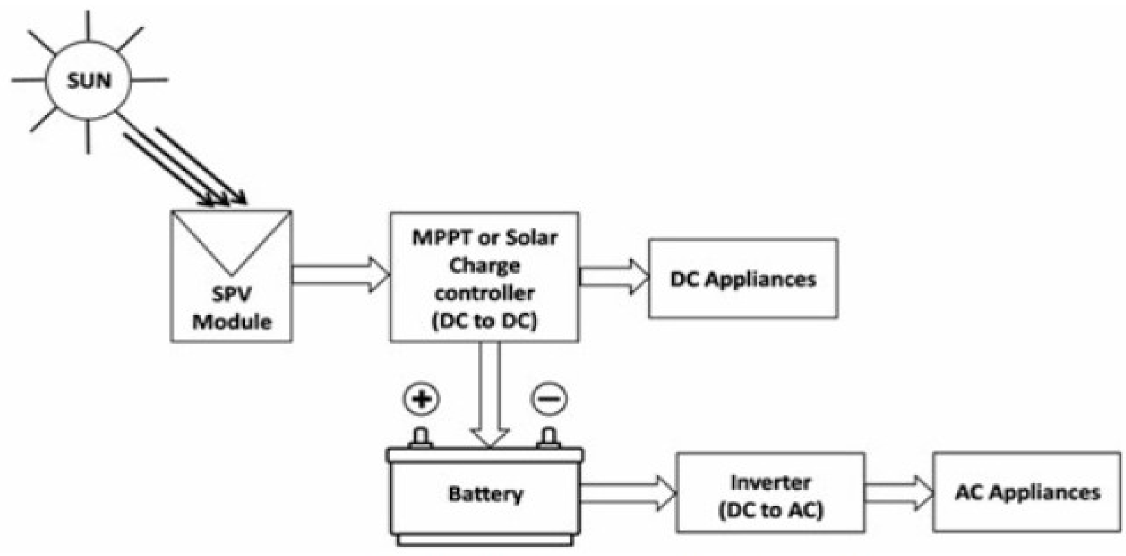
b) With Battery.

Autonomous PV system (or) Stand alone Solar Photovoltaic System (SPV)

A Standalone SPV system is the one which is not connected to the power grid. Standalone PV systems usually have a provision for energy storage. This system has battery support to supply the load requirements during the night hours or even when sunshine is not adequate (Cloudy conditions) during the day.

Block Diagram

Figure shows the block diagram of Standalone SPV system. Power is generated when sun light falls on the SPV module. This power is given to the MPPT or Charge controller block. The function of this block is to control the variation in the output of the SPV module and make it suitable for use at the output according to the supply required by a load. There are two types of the loads: AC and DC. DC components are directly connected to the MPPT or Charge controller block, where as the AC appliances are connected through the Battery and inverter.

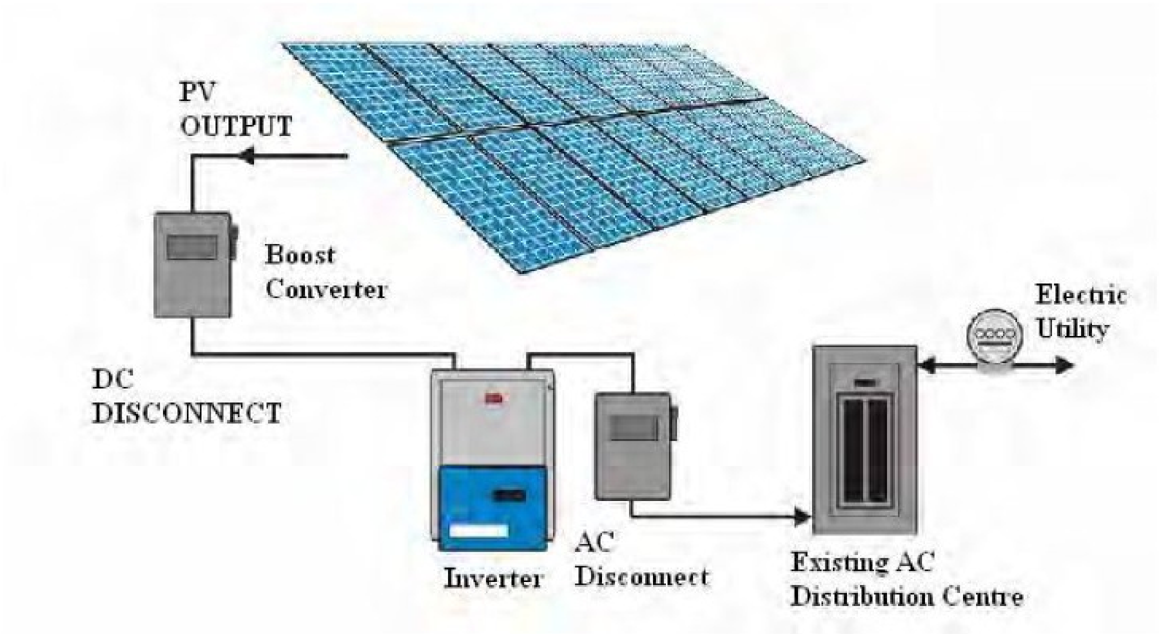


Simple Block Diagram of Standalone SPV system

In this way, a Standalone system is connected depending upon whether only AC load is present or both AC and DC load are present.

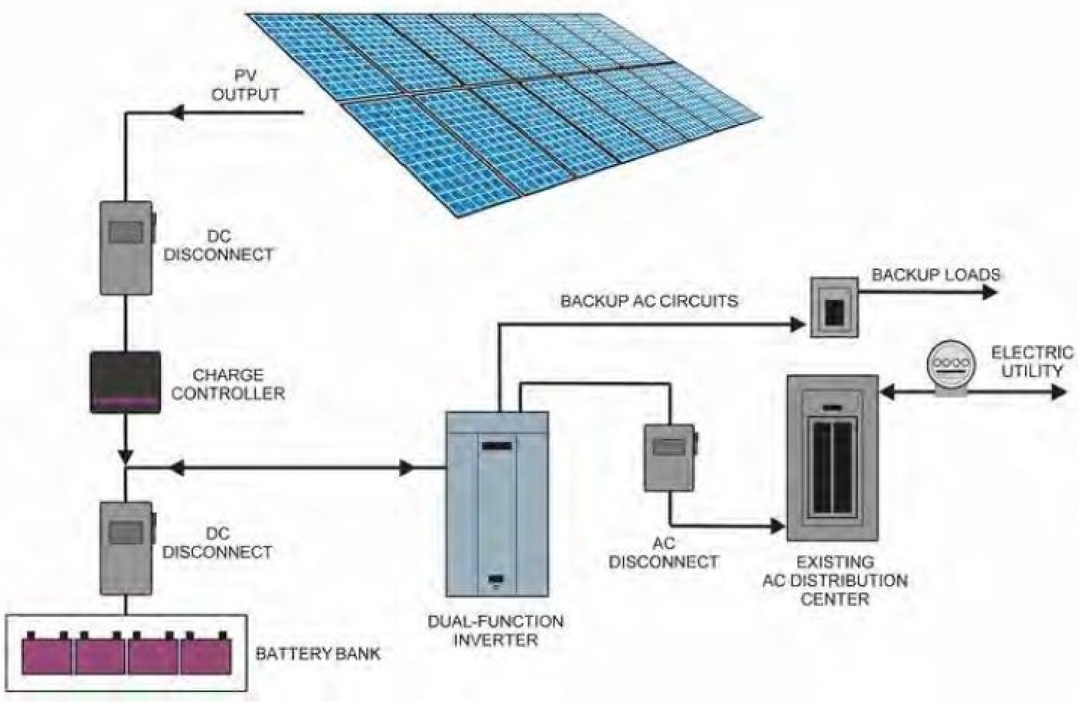
Typical Grid Tied System (Battery less)

There are no batteries to store excess power generated-the electric utility essentially stores it for you through a system called "net-metering." DC (direct current) generated by the PV panels is converted into AC (alternating current) power by the inverter (exactly the same high quality AC current delivered to your site by the utility-provided power grid). Output from the inverter is connected to your existing distribution panel (breaker panel) which feeds the rest of your site. While the system is generating electricity, power needs are provided by the PV system (up to its capacity), reducing or eliminating the power you would have drawn from the utility grid at that time. During periods when your grid-tie system is generating even more energy than your site requires, any excess is fed back into the grid for others to use and the electric utility company "buys" it from you at the retail rate. They provide credits to your account for all the power that is pushed back into the grid through the meter. And your meter will literally run backwards! When your site needs to draw more energy than it is producing (Say, during cloudy conditions or at night), electricity is provided by the power grid in the normal manner and is first paid for by your accumulated credits.



Typical Grid Tied System with Battery Backup

The "Grid-Tie With Battery Backup" PV system incorporates one or more special AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may power a refrigerator, selected lights, computers or servers... any devices the owner deems essential. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits when the grid is down. The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them.

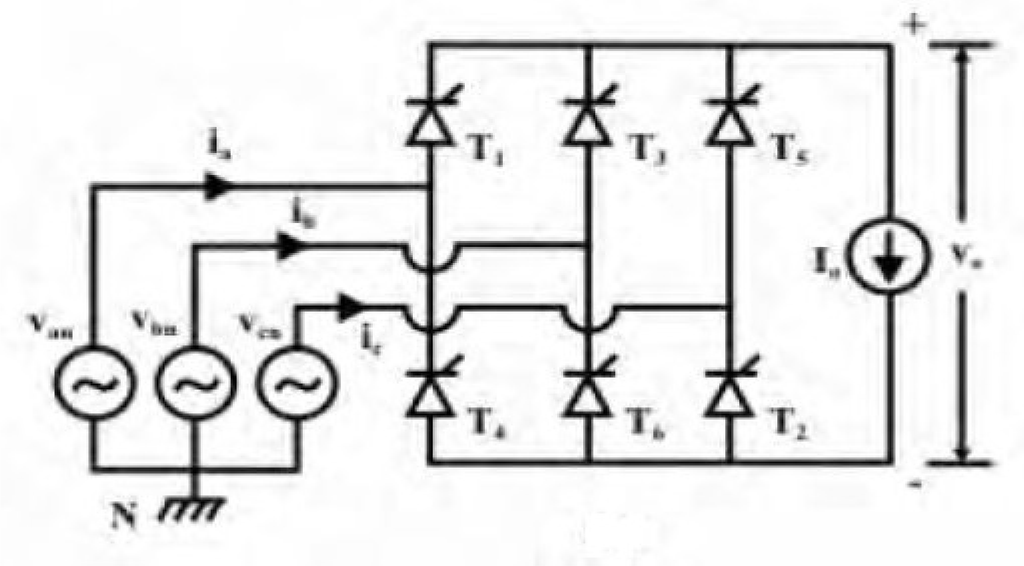


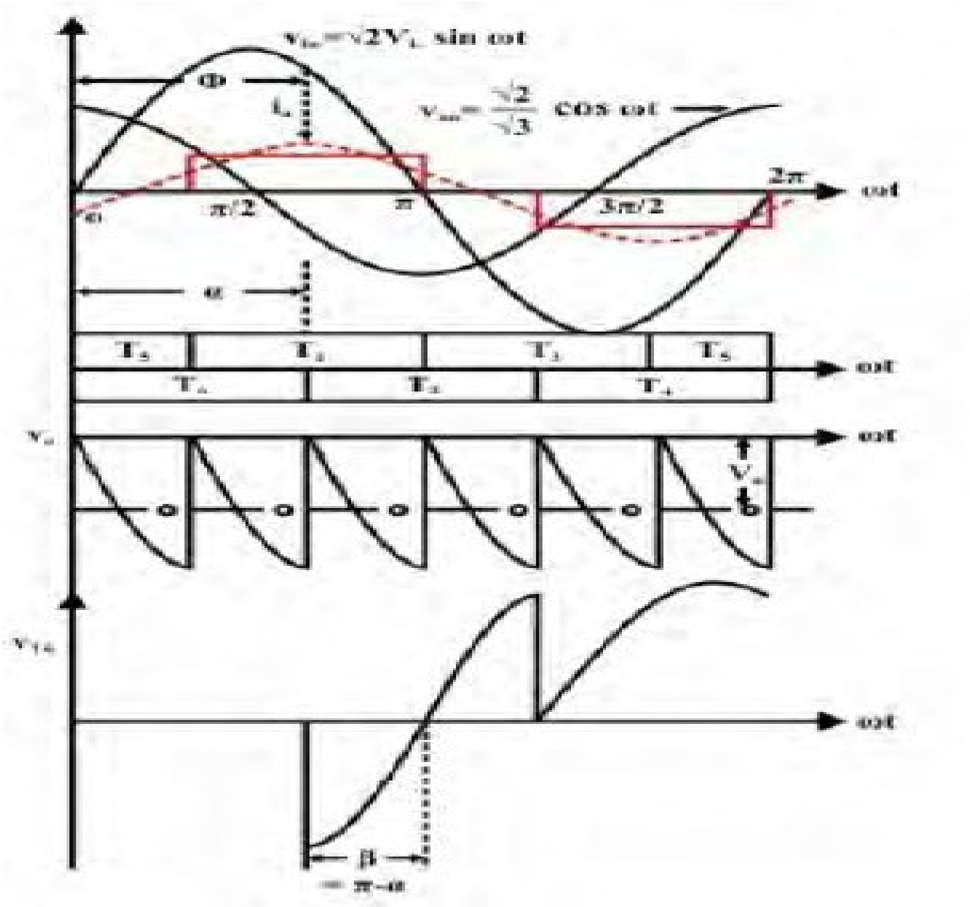
2. Explain the principle and operation of line commutated converters in inverse mode. (M.E-NOV/DEC2013) (M.E-APR/MAY2013)

Line Commutated Converters

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf for commutation and is referred to as the "Load commutated inverter".

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct. Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 –T2-T3-T4-T5-T6 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence cannot conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, and T5T6. If α is made larger than 90° the direction of power flow through the converter will reverse provided there exists a power source in the dc side of suitable polarity. The converter in that case is said to be operating in the inverter mode. It has been explained in connection with single phase converters that the polarity of EMF source on the dc side would have to be reversed for inverter mode of operator. Figure shows the circuit connection and wave forms in the inverting mode of operation where the load current has been assumed to be continuous and ripple free.





Analysis of the converter in the inverting mode is similar to its rectifier mode of operation. The same expressions hold for the dc and harmonic compounds in the output voltage and current. In particular

$$V_0 = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha$$

$$i_{a1} = \frac{2\sqrt{3}}{\pi} I_0 \cos(\omega t - \alpha)$$

For values of α in the range 90° < or < 180° it is observed from Figure above that the average dc voltage is negative and the displacement angle φ of the fundamental component of the input ac line current is equal to α > 90°. Therefore, power in the ac side flows from the converter to the source. It is observed form Figure above that an outgoing thyristor after commutation is impressed with a negative voltage of duration β=π-α. For successful commutation of the outgoing thyristor it is essential that this interval is larger than the turn off time of the thyristor i.e.,

β > ωtq, tq is the thyristor turn off time

Therefore π-α> ωtq.

This imposes an upper limit on the value of α. In practice this upper value of α is further reduced due to commutation overlap.

3. Draw the schematic of buck-boost converter and explain the operation in detail. (M.E-NOV/DEC2010)

BUCK BOOST CONVERTER

Introduction

The buck—boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output voltage is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (ifi for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

Principle of Operation

The basic principle of the buck—boost converter is fairly simple

- While in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- While in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

Compared to the buck and boost converters, the characteristics of the buck—boost converter are mainly:

- Polarity of the output voltage is opposite to that of the input;
- The output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter).
- The output voltage ranges for a buck and a boost converter are respectively 0 to V_i and V_i to ∞

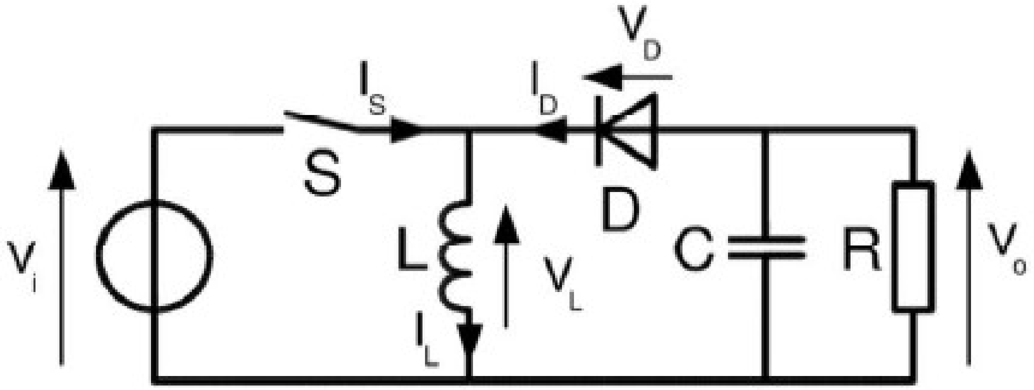
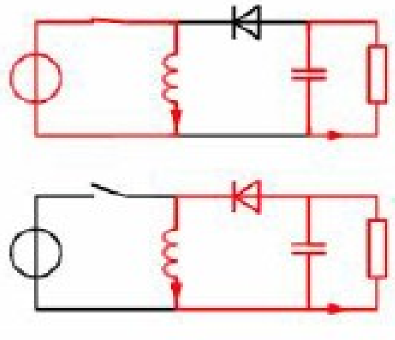


Fig 14 Buck Boost Converter



The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load). When the switch is opened, the inductor supplies current to the load via the diode D.

Continuous Conduction Mode

If the current through the inductor L never falls to Zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure below.

From t=0 to t=DT, the converter is in On-State, so the switch S is closed. The rate of change in the inductor current (I_L) is therefore given by

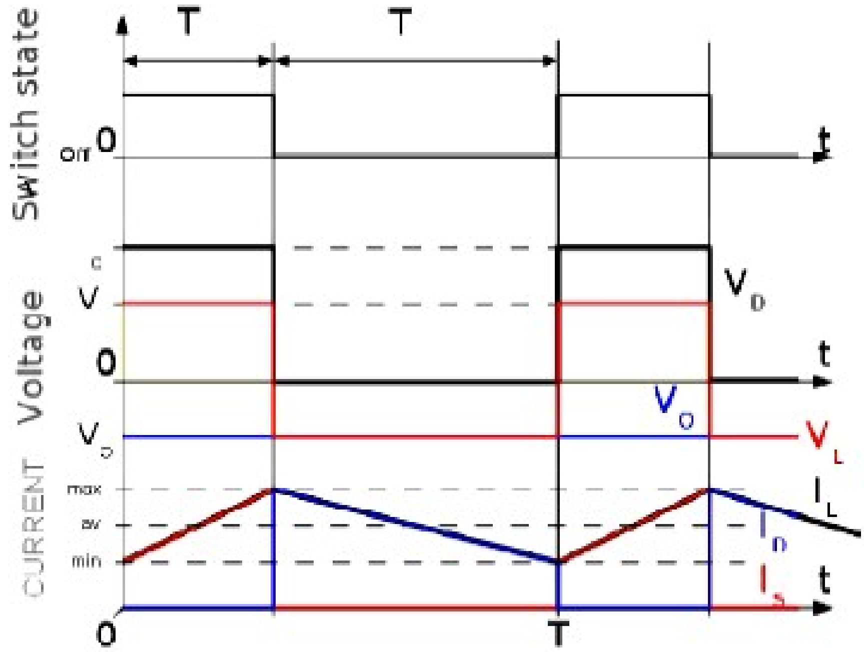
$$\frac{dI_L}{dt} = \frac{V_i}{L}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{On}} = \int_0^{DT} dI_L = \int_0^{DT} \frac{V_i}{L} dt = \frac{V_i DT}{L}$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is on. Therefore D ranges between 0 (S is never on) and 1 (S is always on). During the Off-state, the switch S is open, so the inductor current flows through the load. If We assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$\frac{dI_L}{dt} = \frac{V_o}{L}$$



Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{Off}} = \int_0^{(1-D)T} dI_L = \int_0^{(1-D)T} \frac{V_o \, dt}{L} = \frac{V_o \, (1-D)\, T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. As the energy in an inductor is given by:

$$E = \frac{1}{2} L \, I_L^2$$

It is obvious that the value of I_L at the end of the off state must be the same as the value off I_L at the beginning of the On-state, i.e. the sum of the variations of I_L during the on and the off states must be Zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting $\Delta I_{L_{On}}$ and $\Delta I_{L_{Off}}$ by their expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i D T}{L} + \frac{V_o (1-D) T}{L} = 0$$

This can be written as:

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

This in return yields that:

$$D = \frac{V_o}{V_o - V_i}$$

From the above expression it can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as D approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This is why it is referred to as a buck—boost converter.

Discontinuous Conduction Mode

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to Zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle. Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows: As the inductor current at the beginning of the cycle is zero, its maximum value I_{Lmax} (at t= D T) is

$$I_{L_{max}} = \frac{V_i D T}{L}$$

During the off-period, I_L falls to zero after δ.T:

$$I_{L_{max}} + \frac{V_o \delta T}{L} = 0$$

Using the two previous equations, δ is:

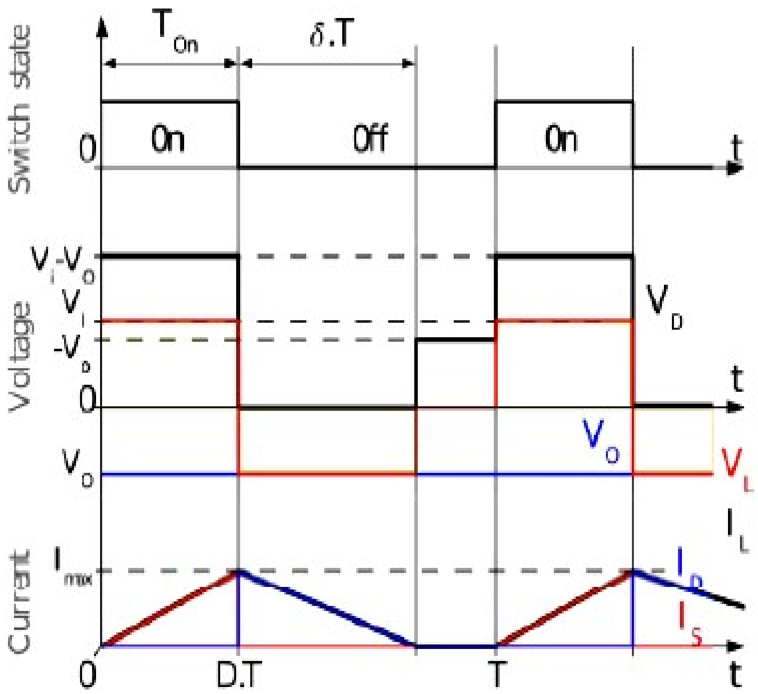
$$\delta = -\frac{V_i D}{V_o}$$

The load current I_O is equal to the average diode current (I_D). As can be seen on figure below, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta$$

Replacing $I_{L_{max}}$ and δ by their respective expressions yields:

$$I_o = -\frac{V_i D T}{2L}\frac{V_i D}{V_o} = -\frac{V_i^2 D^2 T}{2L V_o}$$



Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode

Therefore, the output voltage gain can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i D^2 T}{2L I_o}$$

Compared to the expression of the output voltage gain for the continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

4. Explain with neat diagram the philosophy of operation of a solar source fed boost converter. (M.E-APR/MAY2013)

Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

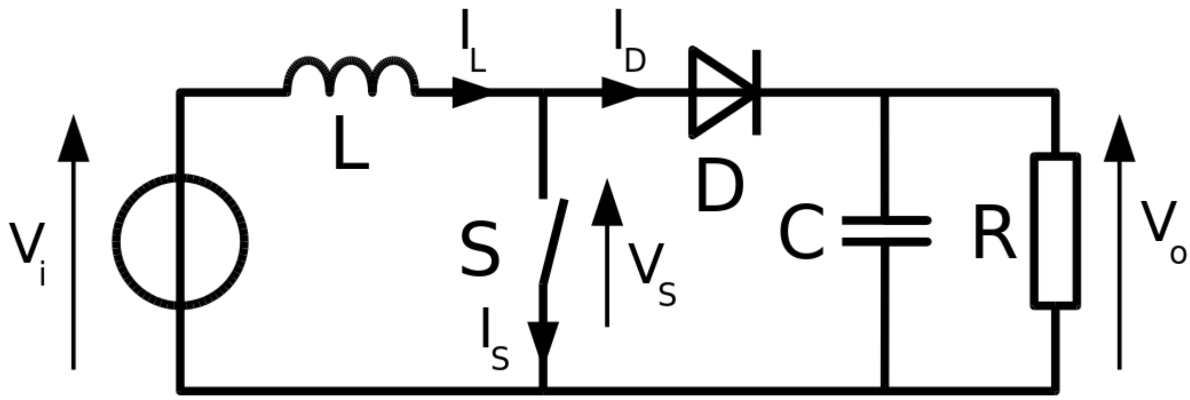
Operation

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Figure below.

(a) When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.

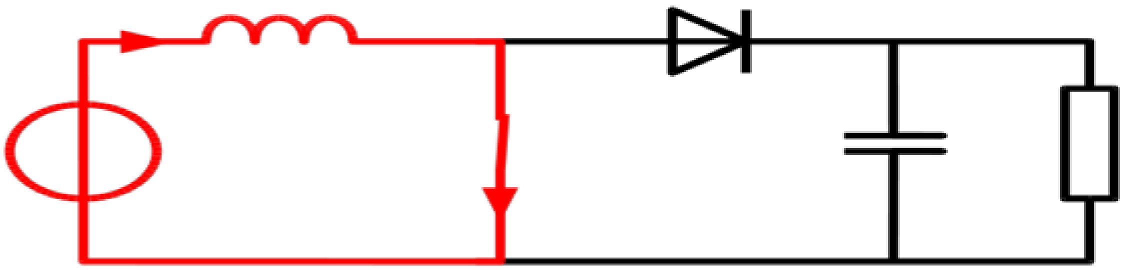
(b) When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

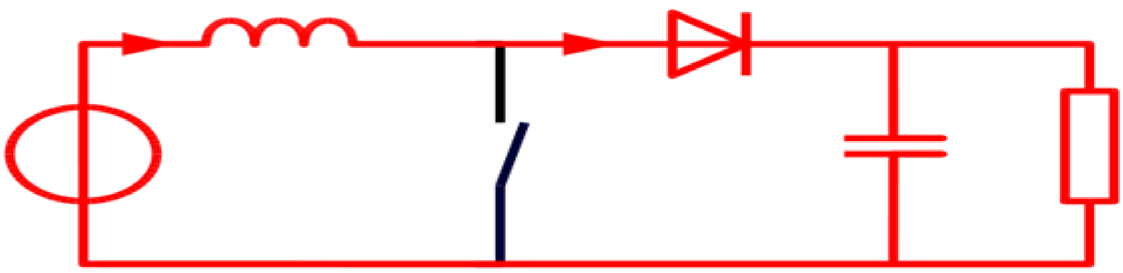
If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.



The basic principle of a Boost converter consists of 2 distinct states (see figure below):

- in the On-state, the switch S (see figure 1) is closed, resulting in an increase in the inductor current;
- In the Off-state, the switch is open and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. These results in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure below. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.





Continuous mode

When a boost converter operates in continuous mode, the current through the inductor (I_L) never falls to zero. Figure 3 shows the typical waveforms of currents and voltages in a converter operating in this mode. The output voltage can be calculated as follows, in the case of an ideal converter operating in steady conditions:
During the on state the switch S is closed, which makes the input voltage appear across the inductor, which causes a change in current flowing through the inductor during a time period by the formula

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L}$$

At the end of on state, the increase of I_L is therefore

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L}V_i$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is On. Therefore, D ranges between 0 (S is never on) and 1 (S is always on).

During the Off-state, the switch S is open, so the inductor current flows through the load. If we consider zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$V_i - V_o = L\frac{dI_L}{dt}$$

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{Off}} = \int_{DT}^{T} \frac{(V_i - V_o)\, dt}{L} = \frac{(V_i - V_o)(1-D)T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2}LI_L^2$$

So, the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting $\Delta I_{L_{On}}$ and $\Delta I_{L_{Off}}$ by their expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)(1-D)T}{L} = 0$$

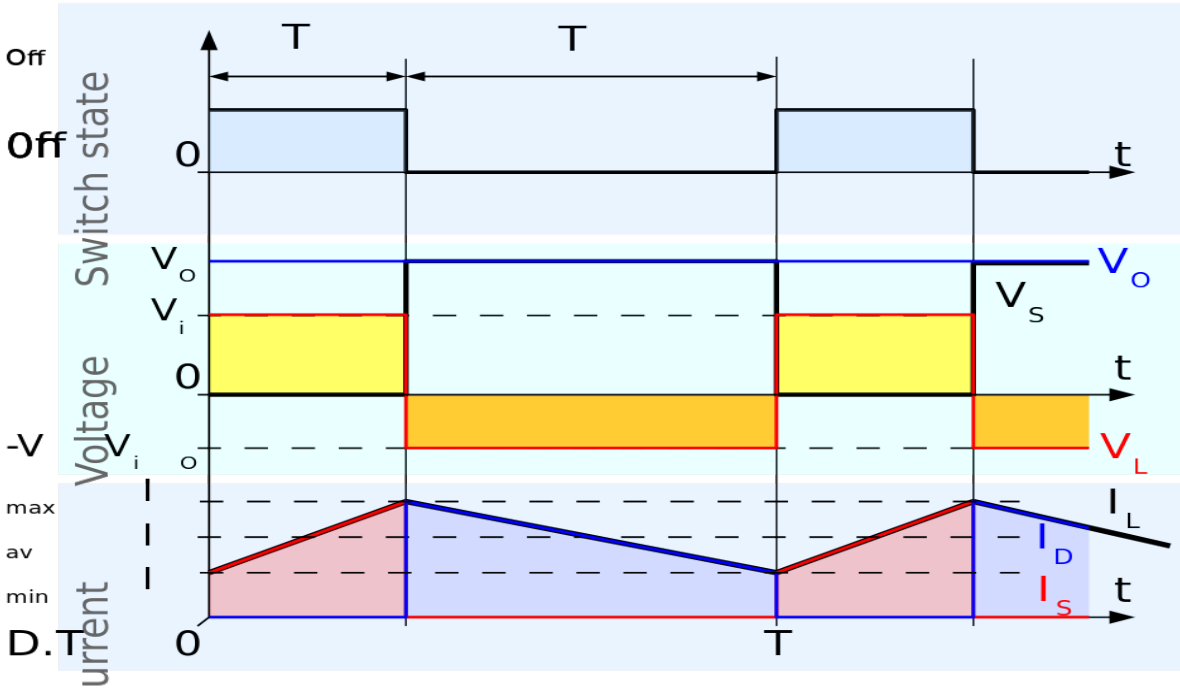
This can be written as:

$$\frac{V_o}{V_i} = \frac{1}{1-D}$$

The above equation shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a step-*up* converter.

Rearranging the equation reveals the duty cycle to be:

$$D = 1 - \frac{V_i}{V_o}$$



Waveforms of current and voltage in a boost converter operating in continuous mode.

Discontinuous mode

If the ripple amplitude of the current is too high, the inductor may be completely discharged before the end of a whole commutation cycle. This commonly occurs under light loads. In this case, the current through the inductor falls to zero during part of the period (see waveforms in figure). Although the difference is slight, it has a strong effect on the output voltage equation. The voltage gain can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{Max}}$ (at $t = DT$) is

$$I_{L_{Max}} = \frac{V_i DT}{L}$$

During the off-period, I_L falls to zero after δT:

$$I_{L_{Max}} + \frac{(V_i - V_o)\,\delta T}{L} = 0$$

Using the two previous equations, δ is:

$$\delta = \frac{V_i D}{V_o - V_i}$$

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta$$

Replacing I_{Lmax} and δ by their respective expressions yields:

$$I_o = \frac{V_i DT}{2L} \cdot \frac{V_i D}{V_o - V_i} = \frac{V_i^2 D^2 T}{2L\,(V_o - V_i)}$$

Therefore, the output voltage gain can be written as follows:

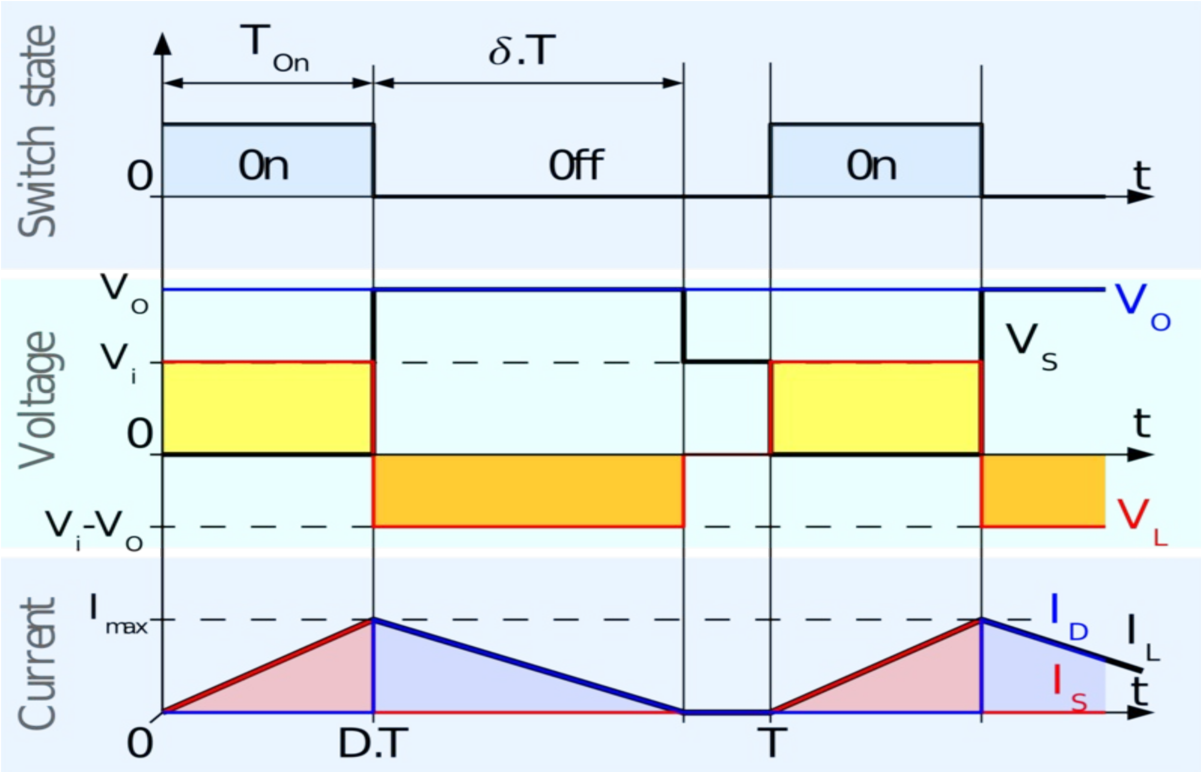
$$\frac{V_o}{V_i} = 1 + \frac{V_i D^2 T}{2LI_o}$$

Compared to the expression of the output voltage gain for continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage gain not only depends on the duty cycle (D), but also on the inductor value (L), the input voltage (V_i), the commutation period (T) and the output current (I_o).

Substituting $I_o = V_o/R$ into the equation (R is the load), the output voltage gain can be rewritten as:

$$\frac{V_o}{V_i} = \frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$$

where $K = \frac{2L}{RT}$



Waveforms of current and voltage in a boost converter operating in discontinuous mode

5. Explain the need of AC-DC-AC converters for wind energy conversion system. (APR/MAY2017)

AC-DC-AC converters

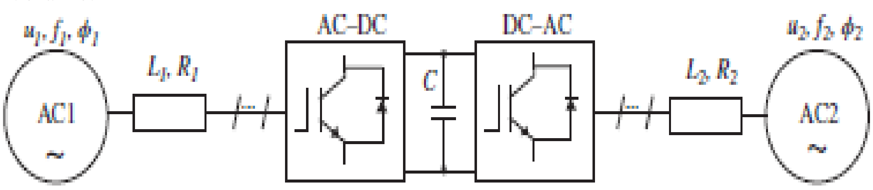
The AC–DC–AC is a connection through a DC-link of two single-phase, three-phase, or multiphase AC circuits with different voltage amplitude *u*, frequency *f*, or phase angle ϕ. The major application of AC–DC–AC converters is in adjustable speed drives. However, recently, these converters have begun to play an increasingly important role in *distributed power generation systems* (DPGSs) and *sustainable AC and DC grids*.

There are several possibilities for an AC–DC–AC converter configuration. Recently, bidirectional AC–DC–AC converters are available on the market for different voltage levels. Both parts of the converter (i.e., AC–DC and DC–AC) can be controlled independently. However, in some cases, there is a need for improving the control accuracy and dynamics. Therefore, it is useful to use an additional link between both control algorithms, which operates as an *active power feed forward* (APFF). The APFF gives information about the active power on one side of the AC–DC–AC converter to the other side directly, and consequently, the stability of the DC voltage is improved significantly.

Bidirectional AC–DC–AC Topologies

There are several configurations possible for three-phase to three-phase AC–DC–AC full-bridge converters, which can connect two AC systems. The most popular is a two-level converter, as shown in Figure below , which is used mostly in low voltage and low-power or medium-power applications, for example, adjustable speed drives. On the other hand, three-level *diode-clamped converters* (DCCs) and flying capacitor converters (FCCs) are becoming increasingly popular, but usually in the medium-voltage range for medium- and high-power applications, for example, marine propulsion, renewable energy conversion, rolling mills and railway traction. There are several advantages of multilevel converters, such as lower voltage stress of components, low current and voltage, total harmonic distortion factor and reduced volume of input passive filters. The main differences among the mentioned multilevel topologies are as follows:

- DCC is the most popular topology and needs fewer capacitors. However, for higher voltage levels, it requires serially connected clamping diodes, which increases the losses and switching losses. In addition, for higher voltage levels, the DC capacitor voltage balancing cannot be achieved with classical modulations.
- FCC is less popular because it needs initialization of the FC voltage, and higher switching frequency is required (greater than 1.2 kHz, whereas for high-power applications the switching frequency is usually between 500 and 800 Hz) in high-power applications because of the FC limits, that is, capacitance versus volume.



Another group of AC–DC–AC converters are simplified topologies obtained by reducing the number of power electronic switches. These attempts were based on the idea of replacing one of the semiconductor legs with a split capacitor bank and connecting a one-phase wire to its middle. In simplified topology, the lower number of switching devices, compared with that of a classical three-phase converter, corresponds to a reduced number of control channels and insulated-gate bipolar transistor (IGBT) driver circuits.

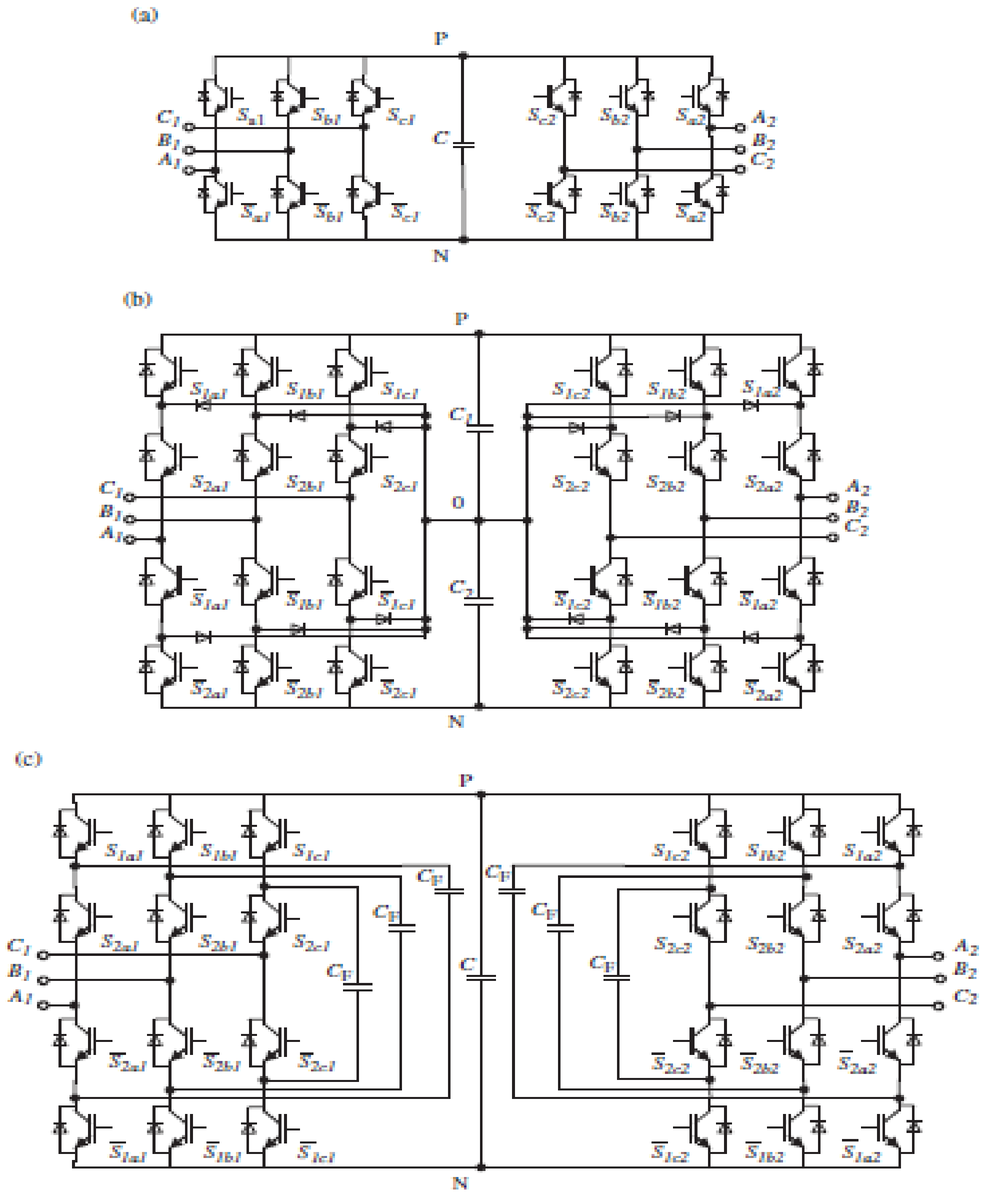


Figure Fully controlled three-phase/three-phase, transistor-based AC–DC–AC converter: (a) two-level (2L-3/3), (b) three-level DCC (3L-DCC-3/3) and (c) three-level FCC (3L-FCC-3/3)

Thus, connecting a three-phase AC system to a single-phase AC system is possible by using a single-standard three-leg integrated power module as the AC–DC–AC converter, as shown in Figure (a). The same concept can be used to simplify an AC–DC–AC converter by connecting one three-phase system to another using only one additional leg, as is shown in Figure (b). Despite the advantages of these solutions, there is a necessity to develop new modulation techniques and to keep the DC voltage significantly high in order to maintain all nominal phase-to-phase converter voltages, which places higher voltage stress on the converter semiconductor devices. This problem can be solved by application of a three-level DCC. When this technology was emerging in industry, not a single integrated power module product for three-level devices was available. Today, manufacturers are selling easy-to-use integrated half-bridge power modules with clamping diodes. New compact devices make it easier to improve the topology with a split capacitor in the DC-link. Thus, the improved topology of a simplified AC–DC–AC converter is shown in Figure below, for applications of three-phase to single-phase, as well as for three-phase to three-phase systems. The first topology is dedicated only to low-power applications, whereas the second is devoted to low- and medium-power applications.

The simplified three-level DCC has several advantages compared with that of a simplified two-level Topology: reduction of machine torque pulsations (mechanical stress in cases where generator/motor application is decreased), additional zero vectors, and reduction in size of passive filters on the AC side.

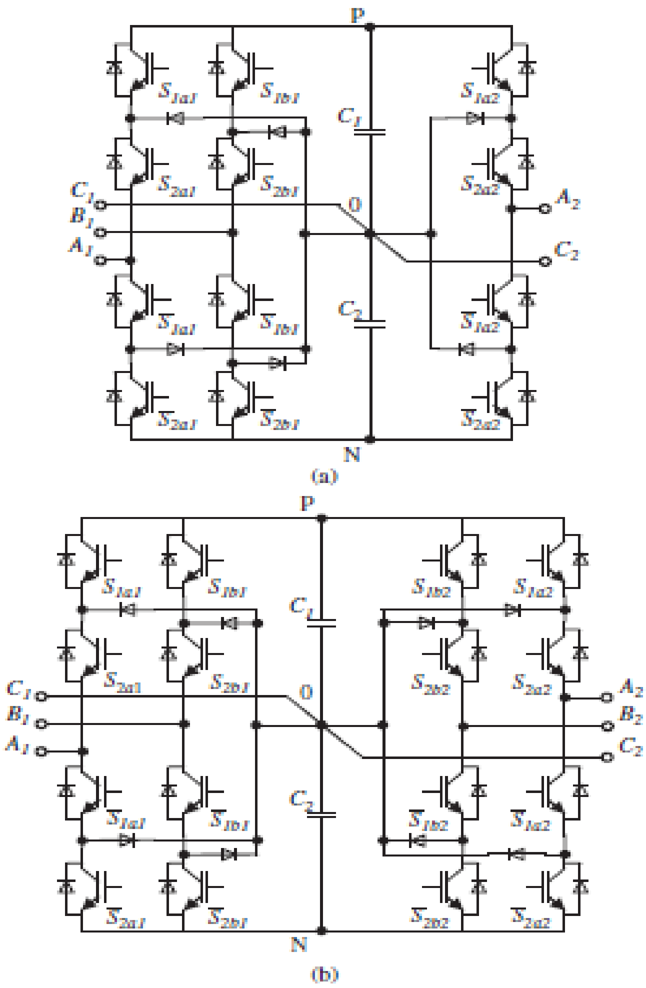


Figure Simplified DCC AC−DC−AC converters: (a) three-phase/one-phase (S3L-DCC 3/1) and (b) three-phase/three-phase (S3L-DCC 3/3)

6. Explain the space vector PWM technique to control 3-phase inverter with neat schematic diagrams. **(M.E-NOV/DEC2016)**

Space vector PWM

At present, the control strategies are implemented in digital systems, and therefore digital modulating techniques are also available. The SV-based modulating technique is a digital technique in which the objective is to generate PWM load line voltages that are on average equal to given load line voltages. This is done in each sampling period by properly selecting the switch states from the valid ones of the VSI (Table below) and by proper calculation of the period of times they are used. The selection and calculation times are based upon the space-vector transformation

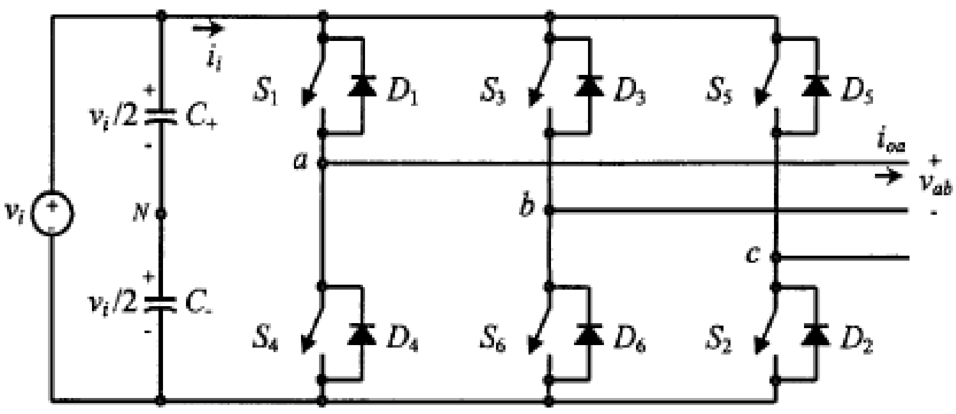


FIGURE Three-phase VSI topology.

TABLE Valild switch states for a three-phase VSI

State	State	v_{ab}	v_b	v_a	Space Vector
1, 2, and 6 are on and 4, 5, and 3 are off	1	v	0	$-v$	$V_1 = 1 + j0.5$
2, 3, and 1 are on and 5, 6, and 4 are off	2	0	v	$-v$	$V_2 = j1.155$
3, 4, and 2 are on and 6, 1, and 5 are off	3	$-v$	v	0	$V_3 = -1 + j0.5$
4, 5, and 3 are on and 1, 2, and 6 are off	4	$-v$	0	v	$V_4 = -1 - j0.5$
5, 6, and 4 are on and 2, 3, and 1 are off	5	0	$-v$	v	$V_5 = -j1.155$
6, 1, and 5 are on and 3, 4, and 2 are off	6	v	$-v$	0	$V_6 = 1 - j0.5$
1, 3, and 5 are on and 4, 6, and 2 are off	7	0	0	0	$V_7 = 0$
4, 6, and 2 are on and 1, 3, and 5 are off	8	0	0	0	$V_8 = 0$

Space-Vector Transformation

Any three-phase set of variables that add up to zero in the stationary abc frame can be represented in a complex plane by a complex vector that contains a real (α) and an imaginary (β) component. For instance, the vector of three-phase line modulating signals can be represented by the complex vector by means of the following transformation:

$$v_{c\alpha} = \frac{2}{3}[v_{ca} - 0.5(v_{cb} + v_{cc})]$$

$$v_{c\beta} = \frac{\sqrt{3}}{3}(v_{cb} - v_{cc})$$

If the line-modulating signals [vc] abc are three balanced sinusoidal waveforms that feature an amplitude vc and an angular frequency ω, the resulting modulating signals in the αβ stationary frame Vc =$[V_c]_{\alpha\beta}$ become a vector of fixed module vc , which rotates at frequency ω (Figure below). Similarly, the SV transformation is applied to the line voltages of the eight states of the VSI normalized with respect to vi (Table above), which generates the eight space vectors as in Figure below. As expected, V1 to V6 are Non null line voltage vectors and V7 and V8 are null line voltage vectors.

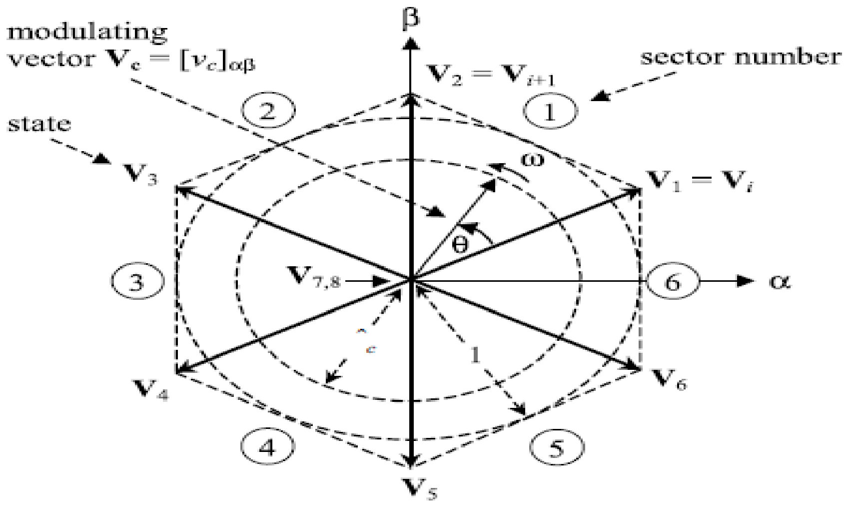


FIGURE The space-vector representation.

The objective of the SV technique is to approximate the line-modulating signal space Vc with the eight space vectors available in VSIs. However, if the modulating signal Vc is laying between the arbitrary vectors Vi and V_{i+1}, only the nearest two nonzero vectors (Vi and Vi+1) and one zero SV (Vz = V7 or V8) should be used. Thus, the maximum load line voltage is maximized and the switching frequency is minimized. To ensure that the generated voltage in one sampling period Ts (made up of the voltages provided by the vectors Vi , Vi+1, and Vz used during times Ti , Ti+1, and Tz) is on average equal to the vector Vc, the following expression should hold:

$$V_c \cdot T_s = V_i \cdot T_i + V_{i+1} \cdot T_{i+1} + V_z \cdot T_z$$

The solution of the real and imaginary parts of Equation above for a line-load voltage that features an amplitude restricted to 0≤Vc≤1 gives

$$T_i = T_s \cdot \hat{v}_c \cdot \sin(\pi/3 - \theta)$$
$$T_{i+1} = T_s \cdot \hat{v}_c \cdot \sin(\theta)$$
$$T_z = T_s - T_i - T_{i+1}$$

The preceding expressions indicate that the maximum fundamental line-voltage amplitude is unity as 0≤θ≤ π/3. This is an advantage over the SPWM technique which achieves√3/2 maximum fundamental line-voltage amplitude in the linear operating region. Although, the SVM technique selects the vectors to be used and their respective on-times, the sequence in which they are used, the selection of the zero space vectors, and the normalized sampled frequency remain undetermined. For instance, if the modulating line-voltage vector is in sector 1 (Figure above), the vectors V1, V2, and Vz should be used within a sampling period by intervals given by T1, T2, and Tz , respectively. The question that remains is whether the sequence (i) V1-V2 -Vz , (ii) Vz -V1 -V2 -Vz , (iii) Vz- V1- V2- V1- Vz , (iv) Vz - V1 - V2 –Vz-V2 - V1 -Vz , or any other sequence should actually be used. Finally, the technique does not indicate whether Vz should be V7, V8, or a combination of both.

Space-Vector Sequences and Zero Space-Vector Selection

The sequence to be used should ensure load line voltages that feature quarter-wave symmetry in order to reduce unwanted harmonics in their spectra (even harmonics). Additionally, the zero SV selection should be done in order to reduce the switching frequency. Although there is not a systematic approach to generate a SV sequence, a graphical representation shows that the sequence Vi , Vi+1, Vz (where Vz is alternately chosen among V7 and V8) provides high performance in terms of minimizing unwanted harmonics and reducing the switching frequency.

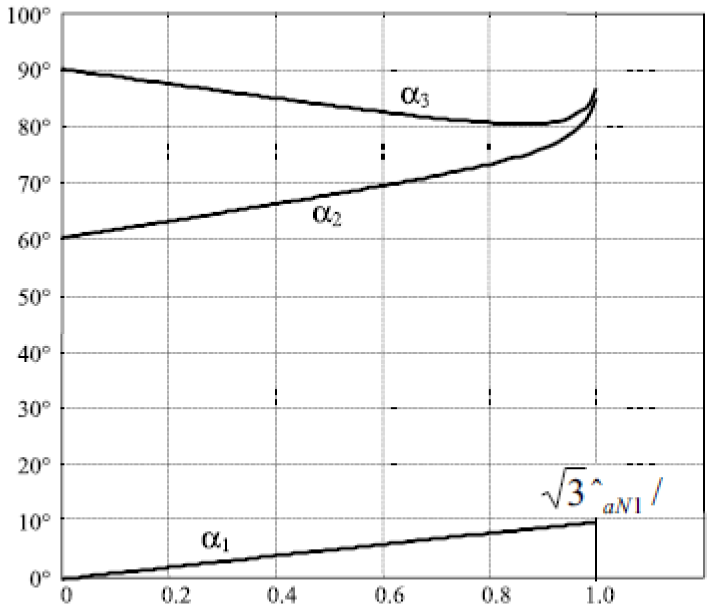


FIGURE Chopping angles for SHE and fundamental voltage control in three-phase VSIs: fifth and seventh harmonic elimination.

7. Explain the three phase uncontrolled rectifiers in detail. (M.E-NOV/DEC2013)

Three Phase Uncontrolled Rectifiers

Three-Phase Full-Wave Rectifier

The full-bridge rectifier is more common since it provides a high output voltage and less ripple. First let us consider the full-bridge circuit under a resistive load as shown in Figure below. Let us assume that v_a, v_b, and v_c are the three phase voltages. The easiest way to approach the full-bridge rectifier circuit is to consider it as a combination of a positive commutating diode groupD1, D2, and D3, and a negative commutating diode group D4, D5, and D6. Since no commutating inductance is included, at any given time only two diodes are conducting simultaneously—one from the positive group and the other from the negative group.

The output voltage V_0, is given by

$V_0=V_{01}-V_{02}$

where $V_{01}$and V_{02} are the output voltages of the positive and negative commuting diode groups to ground, respectively.

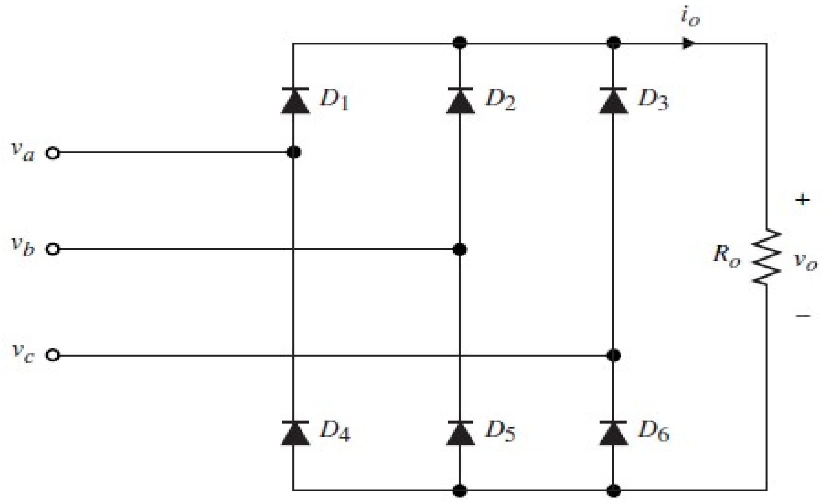


Figure Full-bridge rectifier circuit under resistive load.

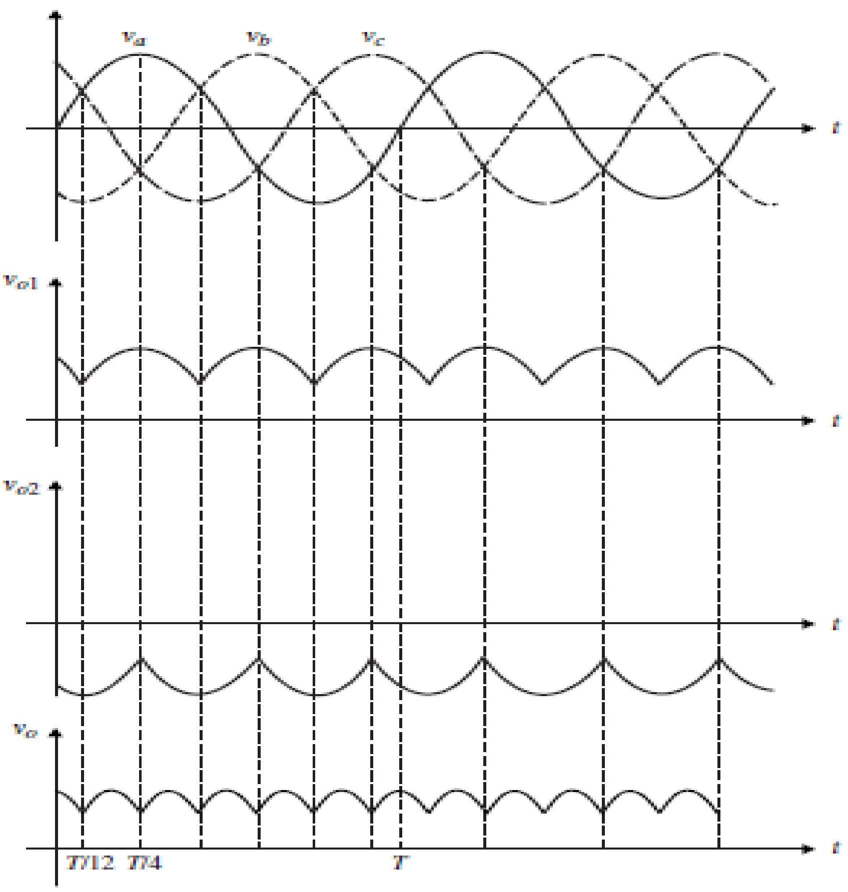


Figure Output voltage waveforms

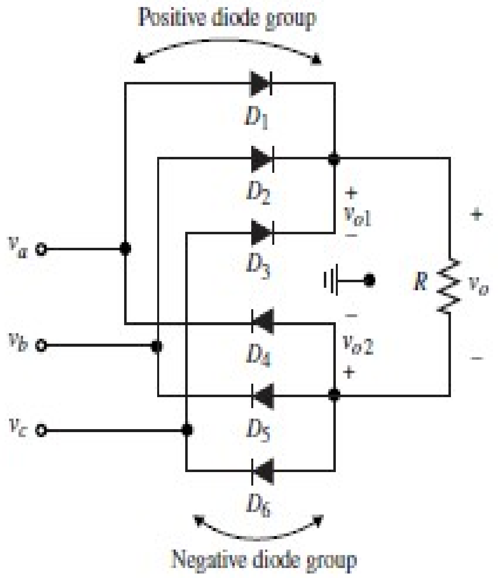


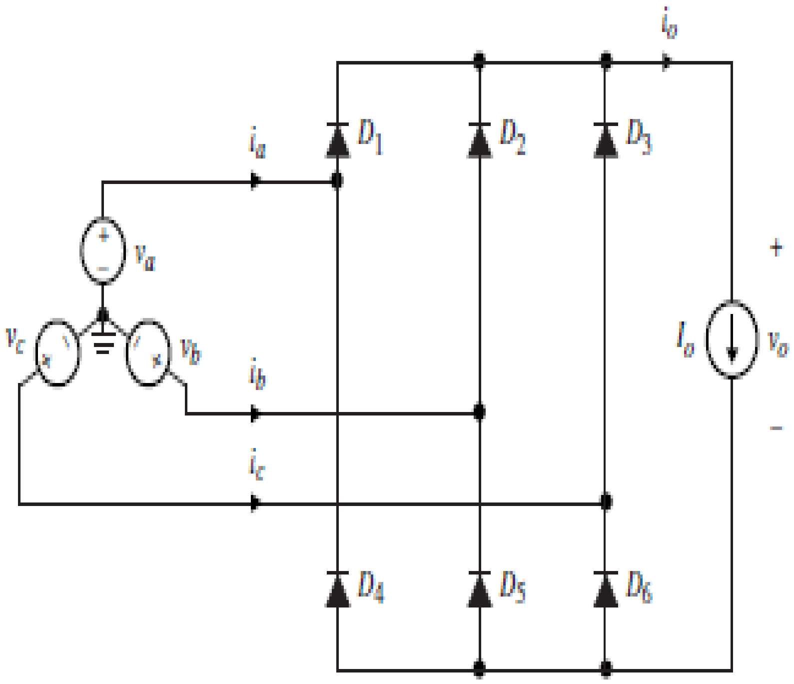
Figure Equivalent circuit

The average output voltage is given by

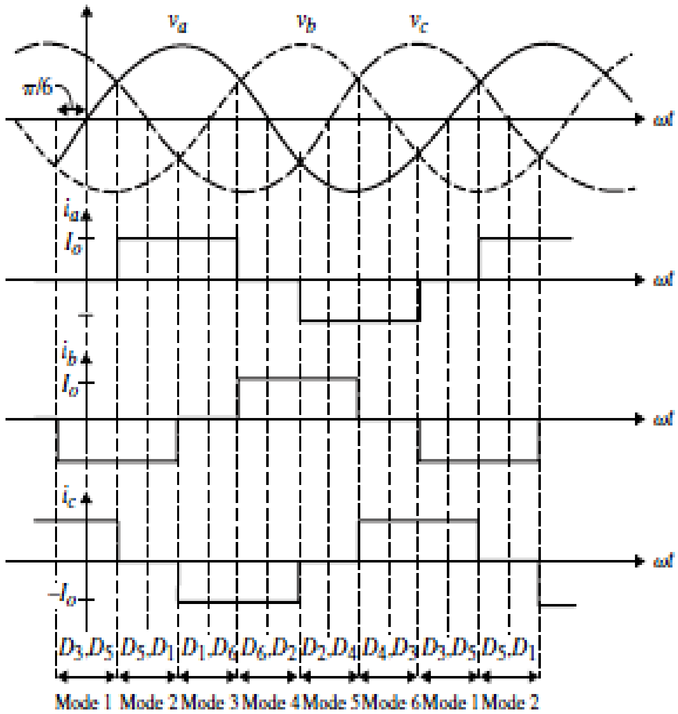
$$V_o = \frac{1}{T/6}\int_{T/12}^{T/4} V_a\, dt$$

$$= \frac{3\sqrt{3}}{\pi} V_s$$

Let us consider the full-bridge rectifier under 21 highly inductive load using a Y- connected voltage source with L/R >>T/6. Table below shows all six modes of operation with the corresponding diode conduction angles and currents, where θ=ωt.



(a)



(b)

Figure (a) Three-phase bridge rectifier with highly inductive load. (b) Phase current waveforms.

Table Conduction Modes

Mode	Conduction angle	Diodes conducting	i_a	i_b	i_c	Most positive absolute voltage
I	$-\pi/6 < \theta < \pi/6$	D_3, D_5	0	$-I_o$	I_o	$\lvert v_b \rvert$, v_c
II	$\pi/6 < \theta < \pi/2$	D_5, D_1	I_o	$-I_o$	0	v_a, $\lvert v_b \rvert$
III	$\pi/2 < \theta < 5\pi/6$	D_1, D_6	I_o	0	$-I_o$	v_a, $\lvert v_c \rvert$
IV	$5\pi/6 < \theta < 7\pi/6$	D_6, D_2	0	I_o	$-I_o$	v_b, $\lvert v_c \rvert$
V	$7\pi/6 < \theta < 9\pi/6$	D_2, D_4	$-I_o$	I_o	0	$\lvert v_a \rvert$, v_b
VI	$9\pi/6 < \theta < 11\pi/6$	D_4, D_3	$-I_o$	0	I_o	$\lvert v_a \rvert$, v_c

The waveforms for the output voltage and the diode and line currents are shown in Fig. (b). the output voltage is the same as that in the resistive case.

8. Draw and discuss the operation of a matrix converter. (M.E-NOV/DEC2013)

Matrix Converter

The matrix converter (MC) is a development of the force commutated cycloconverter (FCC) based on bidirectional fully controlled switches, incorporating PWM voltage control, as mentioned earlier. It provides a good alternative to the double-sided PWM voltage source rectifier-inverters having the advantages of being a single-stage converter with only nine switches for three phase to three-phase conversion and inherent bidirectional power flow, sinusoidal input/output waveforms with moderate switching frequency, the possibility of compact design due to the absence of dc link reactive components and controllable input power factor independent of the output load current. The main disadvantages of the matrix converters developed so far are the inherent restriction of the voltage transfer ratio (0.866), a more complex control and protection strategy, and above all the non availability of a fully controlled bidirectional high-frequency switch integrated in a silicon chip (Triac, though bilateral, cannot be fully controlled). The power circuit diagram of the most practical three-phase to three-phase matrix converter is shown in Figurea, which uses nine bidirectional switches so arranged that any of three input phases can be connected to any output phase as shown in the switching matrix symbol in Figure b.

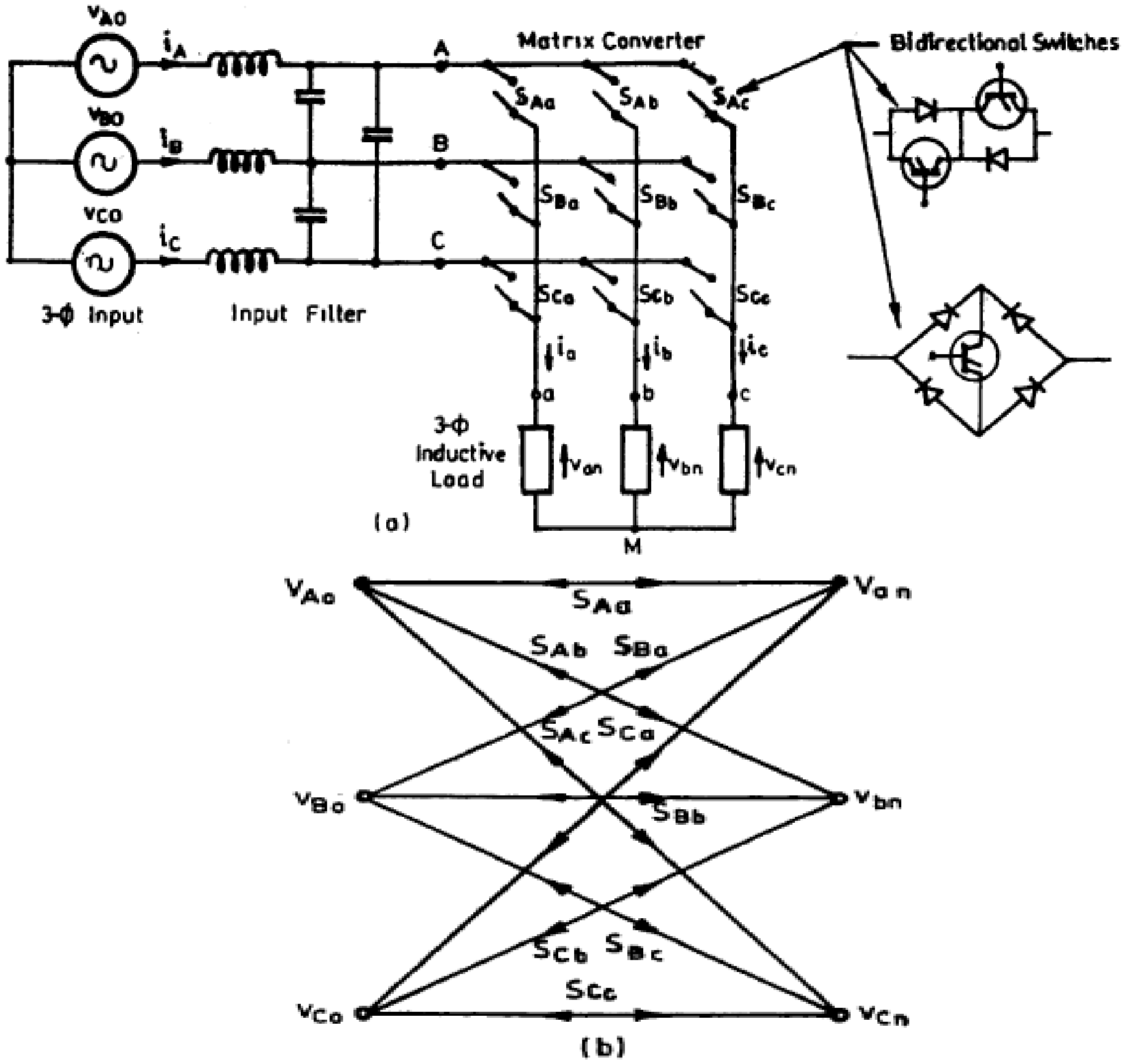


Figure (a) The 3φ-3φ Matrix converter (b) switching matrix symbol for converter

Thus, the voltage at any input terminal may be made to appear at any output terminal or terminals while the current in any phase of the load may be drawn from any phase or phases of the input supply. For the switches, the inverse-parallel combination of reverse-blocking self-controlled devices such as Power MOSFETs or IGBTs or transistor-embedded diode bridge as shown has been used so far. The circuit is called a matrix converter as it provides exactly one switch for each of the possible connections between the input and the output. The switches should be controlled in such a way that, at any time, one and only one of the three switches connected to an output phase must be closed to prevent ‘‘short-circuiting’’ of the supply lines or interrupting the load-current flow in an inductive load. With these constraints, it can be visualized that from the possible 512 states of the converter, only 27 switch combinations are allowed as given in Table below, which includes the resulting output line voltages and input phase currents. These combinations are divided into three groups. Group I consists of six combinations when each output phase is connected to a different input phase. In Group II, there are three subgroups, each having six combinations with two output phases short-circuited (connected to the same input phase). Group III includes three combinations with all output phases short-circuited. With a given set of input three-phase voltages, any desired set of three-phase output voltages can be synthesized by adopting a suitable switching strategy.

TABLE Three-phase/three-phase matrix converter switching combinati ons

Group	a	b	c	v_{ab}	v_{bc}	v_{ca}	i_A	i_B	i_C	S_{Aa}	S_{Ab}	S_{Ac}	S_{Ba}	S_{Bb}	S_{Bc}	S_{Ca}	S_{Cb}	S_{Cc}
	A	B	C	v_{AB}	v_{BC}	v_{CA}	i_a	i_b	i_c	1	0	0	0	1	0	0	0	1
	A	C	B	$-v_{CA}$	$-v_{BC}$	$-v_{AB}$	i_a	i_c	i_b	1	0	0	0	0	1	0	1	0
	B	A	C	$-v_{AB}$	$-v_{CA}$	$-v_{BC}$	i_b	i_a	i_c	0	1	0	1	0	0	0	0	1
I	B	C	A	v_{BC}	v_{CA}	v_{AB}	i_c	i_a	i_b	0	1	0	0	0	1	0	1	0
	C	A	B	v_{CA}	v_{AB}	v_{BC}	i_b	i_c	i_a	0	0	1	1	0	0	0	1	0
	C	B	A	$-v_{BC}$	$-v_{AB}$	$-v_{CA}$	i_c	i_b	i_a	0	0	1	0	1	0	1	0	0
	A	C	C	$-v_{CA}$	0	v_{CA}	i_a	0	$-i_a$	1	0	0	0	0	1	0	0	1
	B	C	C	v_{BC}	0	$-v_{BC}$	0	i_a	$-i_a$	0	1	0	0	0	1	0	0	1
	B	A	A	$-v_{AB}$	0	$-v_{AB}$	$-i_a$	i_a	0	0	1	0	1	0	0	1	0	0
II-A	C	A	A	v_{CA}	0	$-v_{CA}$	$-i_a$	0	i_a	0	0	1	1	0	0	1	0	0
	C	B	B	$-v_{BC}$	0	v_{BC}	0	$-i_a$	i_a	0	0	1	0	1	0	0	1	0
	A	B	B	v_{AB}	0	$-v_{AB}$	i_a	$-i_a$	0	1	0	0	0	1	0	0	1	0
	C	A	C	$-v_{CA}$	$-v_{CA}$	0	i_b	0	$-i_b$	0	0	1	1	0	0	0	0	1
	C	B	C	$-v_{BC}$	v_{BC}	0	0	i_b	$-i_b$	0	0	1	0	1	0	0	0	1
	A	B	A	v_{AB}	$-v_{AB}$	0	$-i_b$	i_b	0	1	0	0	0	1	0	1	0	0
II-B	A	C	A	$-v_{CA}$	v_{CA}	0	$-i_b$	0	i_b	1	0	0	0	0	1	1	0	0
	B	C	B	v_{BC}	$-_{BC}$	0	0	$-i_b$	i_b	0	1	0	0	0	1	0	1	0
	B	A	B	$-v_{AB}$	V_{AB}	0	i_b	$-i_b$	0	0	1	0	1	0	0	0	1	0
	C	C	A	0	v_{CA}	$-v_{CA}$	i_c	0	$-i_c$	0	0	1	0	0	1	1	0	0
	C	C	B	0	$-v_{BC}$	v_{BC}	0	i_c	$-i_c$	0	0	1	0	0	1	0	1	0
	A	A	B	0	v_{AB}	$-v_{AB}$	$-i_c$	i_c	0	1	0	0	1	0	0	0	1	0
II-C	A	A	C	0	$-v_{CA}$	v_{CA}	$-i_c$	0	i_c	1	0	0	1	0	0	0	0	1
	B	B	C	0	v_{BC}	$-v_{BC}$	0	$-i_c$	i_c	0	1	0	0	1	0	0	0	1
	B	B	A	0	$-v_{AB}$	v_{AB}	i_c	$-i_c$	0	0	1	0	0	1	0	1	0	0
	A	A	A	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
III	B	B	B	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
	C	C	C	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1

However, it has been shown that regardless of the switching strategy there are physical limits on the achievable output voltage with these converters as the maximum peak-to-peak output voltage cannot be greater than the minimum voltage difference between two phases of the input. The alternative is to use the space vector modulation (SVM) strategy as used in PWM inverters without adding third harmonic components but it also yields the maximum voltage transfer ratio as 0.866. The converter connects any input phase (A, B, and C) to any output phase (a, b, and c) at any instant. When connected, the voltages van, vbn, vcn at the output terminals are related to the input voltages VAo, VBo, VCo, as

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} v_{Ao} \\ v_{Bo} \\ v_{Co} \end{bmatrix}$$

where SAa through SCc are the switching variables of the corresponding switches shown . For a balanced linear star-connected load at the output terminals, the input phase currents are related to the output phase currents by

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The matrix converter should be controlled using a specific and appropriately timed sequence of the values of the switching variables, which will result in balanced output voltages having the desired frequency and amplitude, while the input currents are balanced and in phase (for unity IDF) or at an arbitrary angle (for controllable IDF) with respect to the input voltages. As the matrix converter, in theory, can operate at any frequency, at the output or input, including zero, it can be employed as a three-phase ac/dc converter, dc/three-phase ac converter, or even a buck/boost dc chopper and thus as a universal power converter.

9. Write short notes on PWM inverters. (M.E-NOV/DEC2013)

PWM inverters

The device that converts dc power into ac power at desired output voltage and frequency is called an inverter.

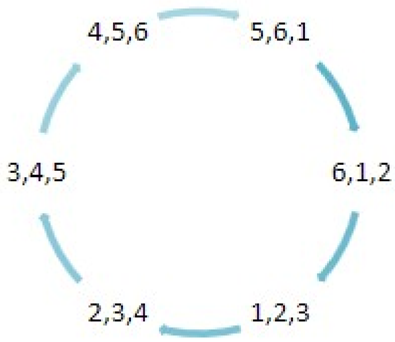
Three phase inverter

When three single phase inverters are connected in parallel a three phase inverter is formed. The gating signal has to be displaced by $120^0$with respect to each other so as achieve three phase balanced voltages. A 3 phase output can be achieved from a configuration of six transistors and six diodes. Two type of control signal can be applied to transistors, they are such as 180^0 or 120^0conduction.

180degree conduction

- WhenQ1 is switched on, terminal a is connected to the positive terminal of dc input voltage.
- When Q4 is switched on terminal a is brought to negative terminal of the dc source.
- There are 6 modes of operation is a cycle and the duration of each mode is 60^0.
- The conduction sequence of transistors is 123,234,345,456,561,612.
- The gating signals are shifted from each other by $60^0$to get 3φbalanced voltages.

Switching states:



V_{RN}	V_{YN}	V_{BN}	V_{RY}	V_{YB}	V_{BR}	V_1
$\frac{V}{3}$	$\frac{-2V}{3}$	$\frac{V}{3}$	V_{ac}	$-V_{dc}$	0	$\frac{2}{\sqrt{3}}(330^0)$
$\frac{2V}{3}$	$\frac{-V}{3}$	$\frac{-V}{3}$	V_{dc}	0	$-V_{dc}$	$\frac{2}{\sqrt{3}}(30^0)$
$\frac{V}{3}$	$\frac{V}{3}$	$\frac{-2V}{3}$	0	V	-V	$\frac{2}{\sqrt{3}}(90^0)$
$\frac{-V}{3}$	$\frac{2V}{3}$	$\frac{-V}{3}$	-V	V	0	$\frac{2}{\sqrt{3}}(150^0)$
$\frac{-2V}{3}$	$\frac{V}{3}$	$\frac{V}{3}$	-V	0	0	$\frac{2}{\sqrt{3}}(210^0)$
$\frac{-V}{3}$	$\frac{-V}{3}$	$\frac{2V}{3}$	0	-V	0	$\frac{2}{\sqrt{3}}(270^0)$

Modes of operation:

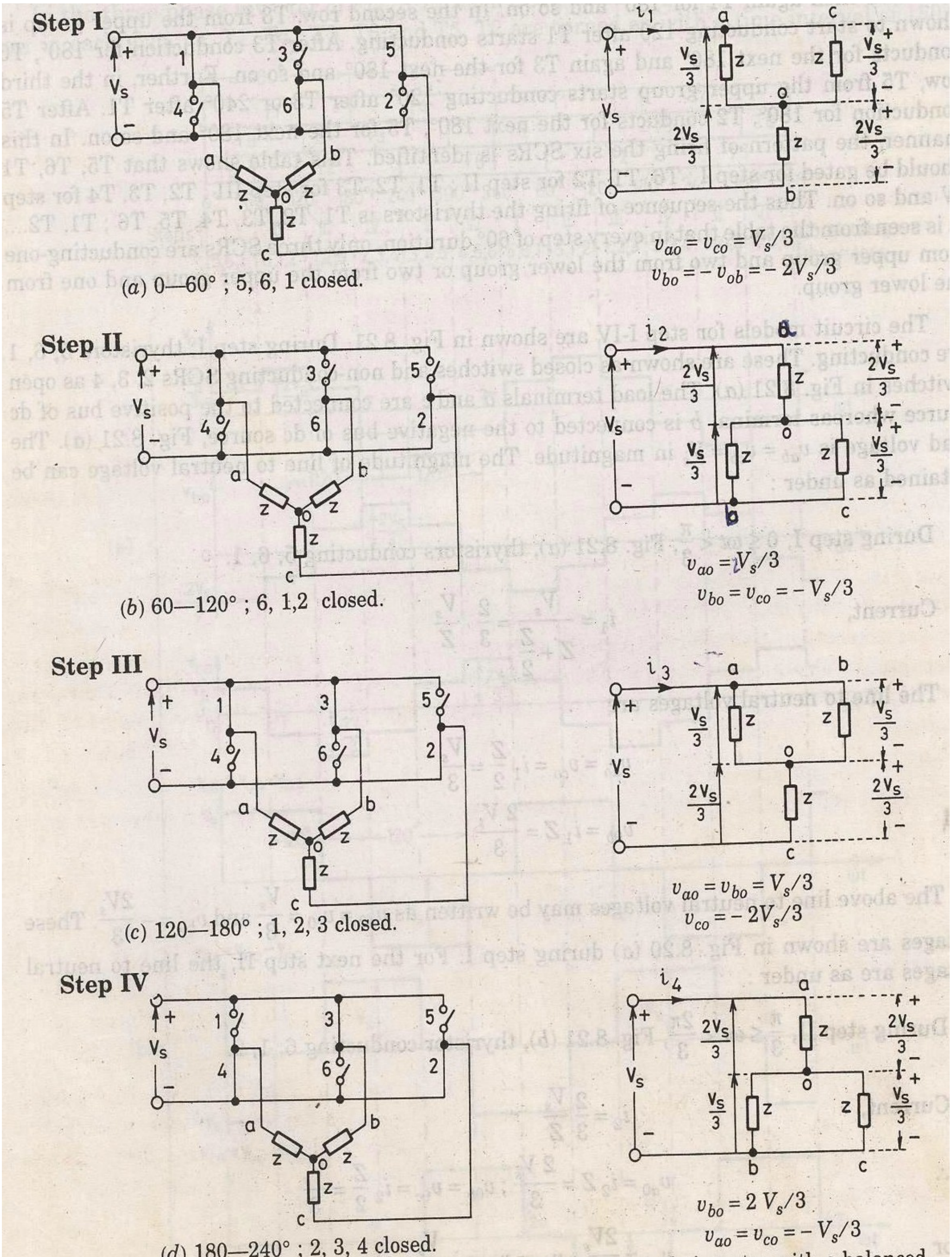


Fig. . Equivalent circuits for a 3-phase six-step 180° mode inverter with a balanced star-connected load.

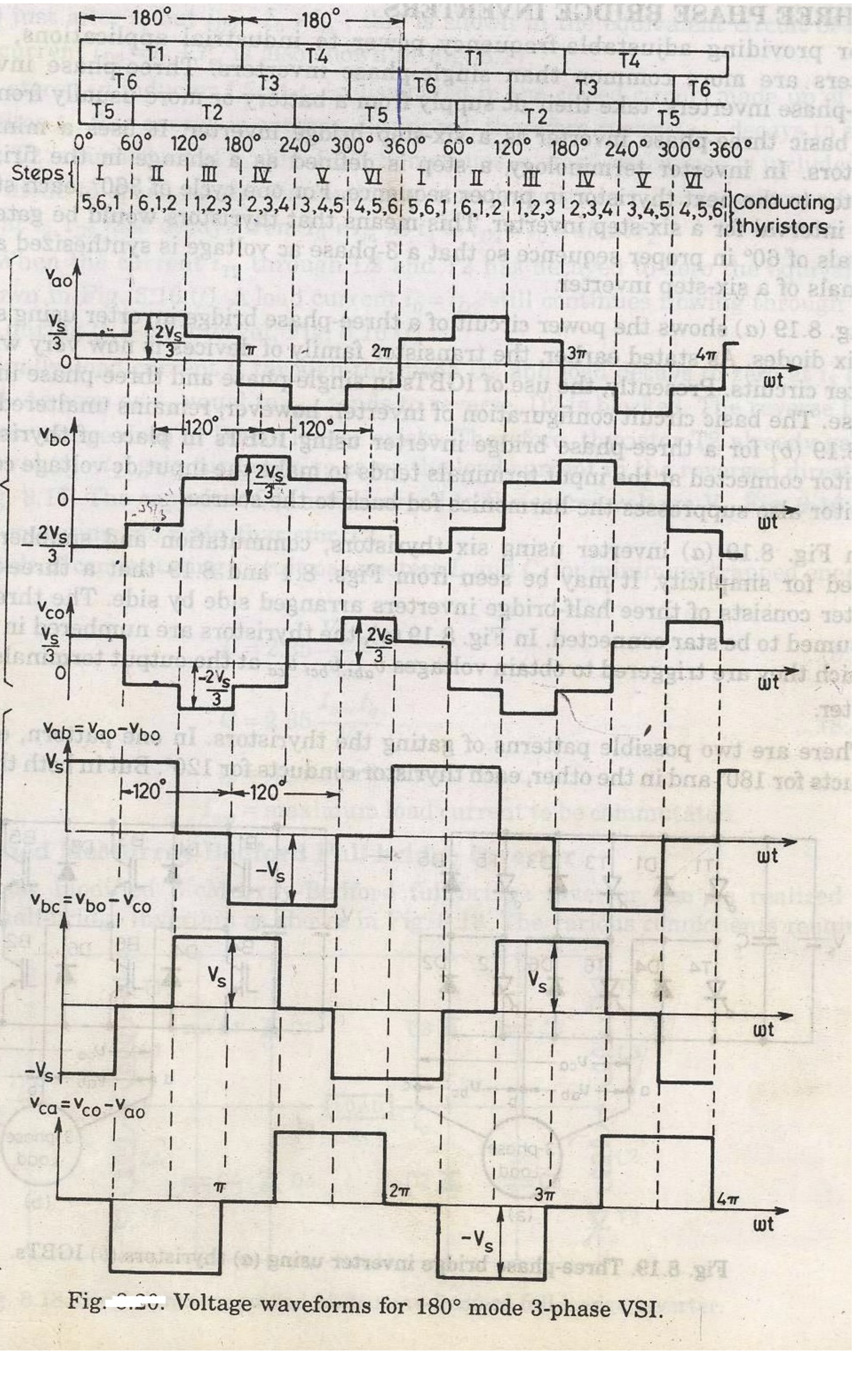
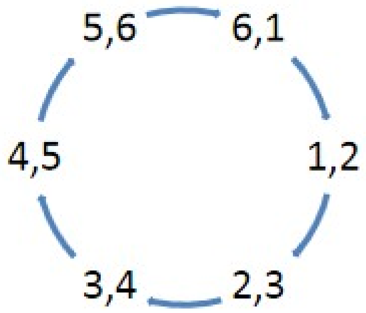


Fig. .20. Voltage waveforms for 180° mode 3-phase VSI.

120degree conduction

- The circuit diagram is same as that for 180^0 mode of conduction. Here each thyristor conducts for 120^0
- There are 6 steps each of 60^0duration, for completing one cycle of ac output voltage.



$\underline{120^0 \text{ conduction mode}}$

Step	Thyristor conducting	V_{Rn}	V_{Yn}	V_{Bn}
1	6,1	$V_s/_2$	$-V_s/_2$	0
2	1,2	$V_s/_2$	0	$-V_s/_2$
3	2,3	0	$V_s/_2$	$-V_s/_2$
4	3,4	$-V_s/_2$	$V_s/_2$	0
5	4,5	$-V_s/_2$	0	$V_s/_2$
6	5,6	0	$-V_s/_2$	$V_s/_2$

Modes of operation:

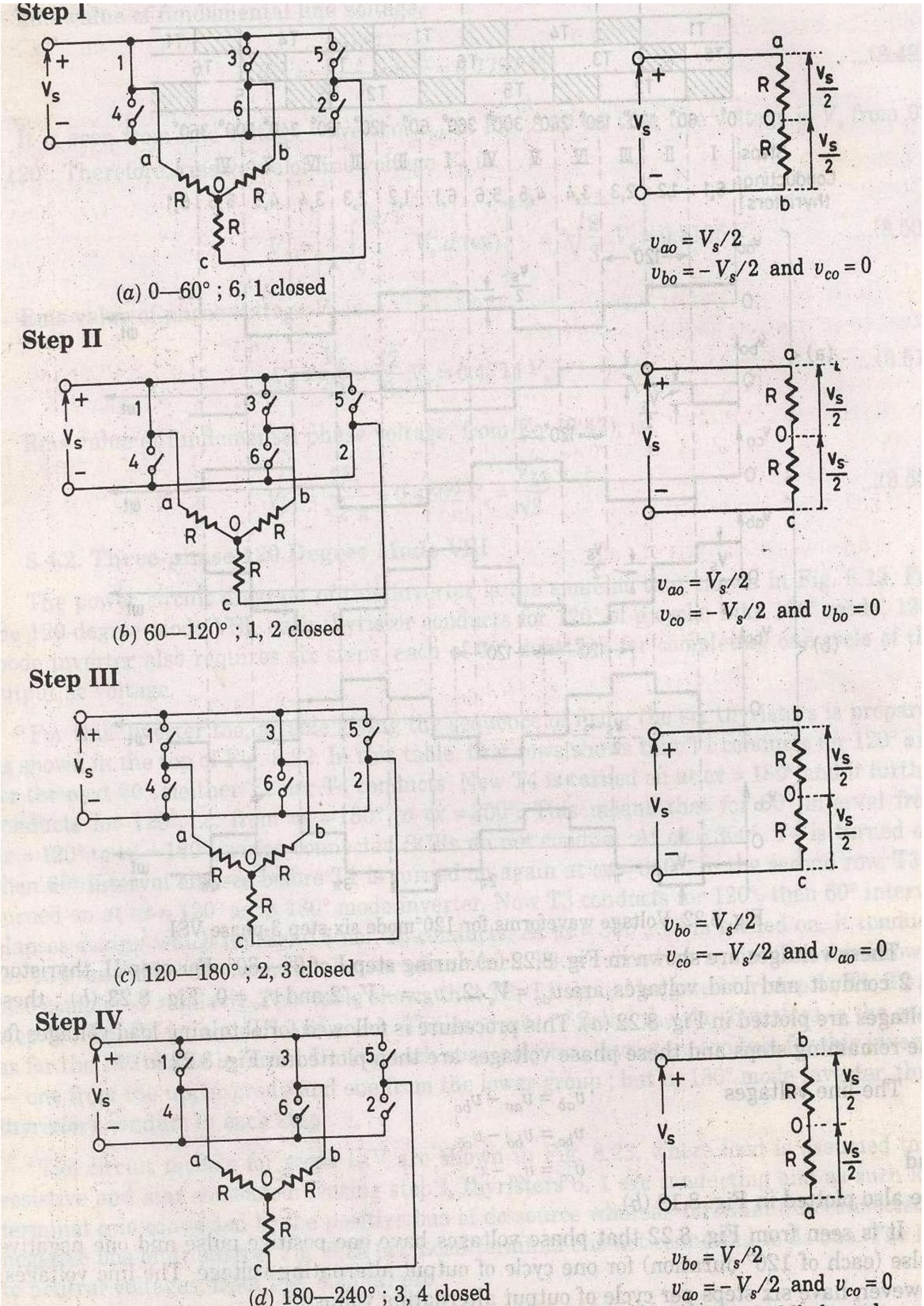


Fig. Equivalent circuits for a 3-phase six-step 120° mode inverter with balanced star-connected resistive load.

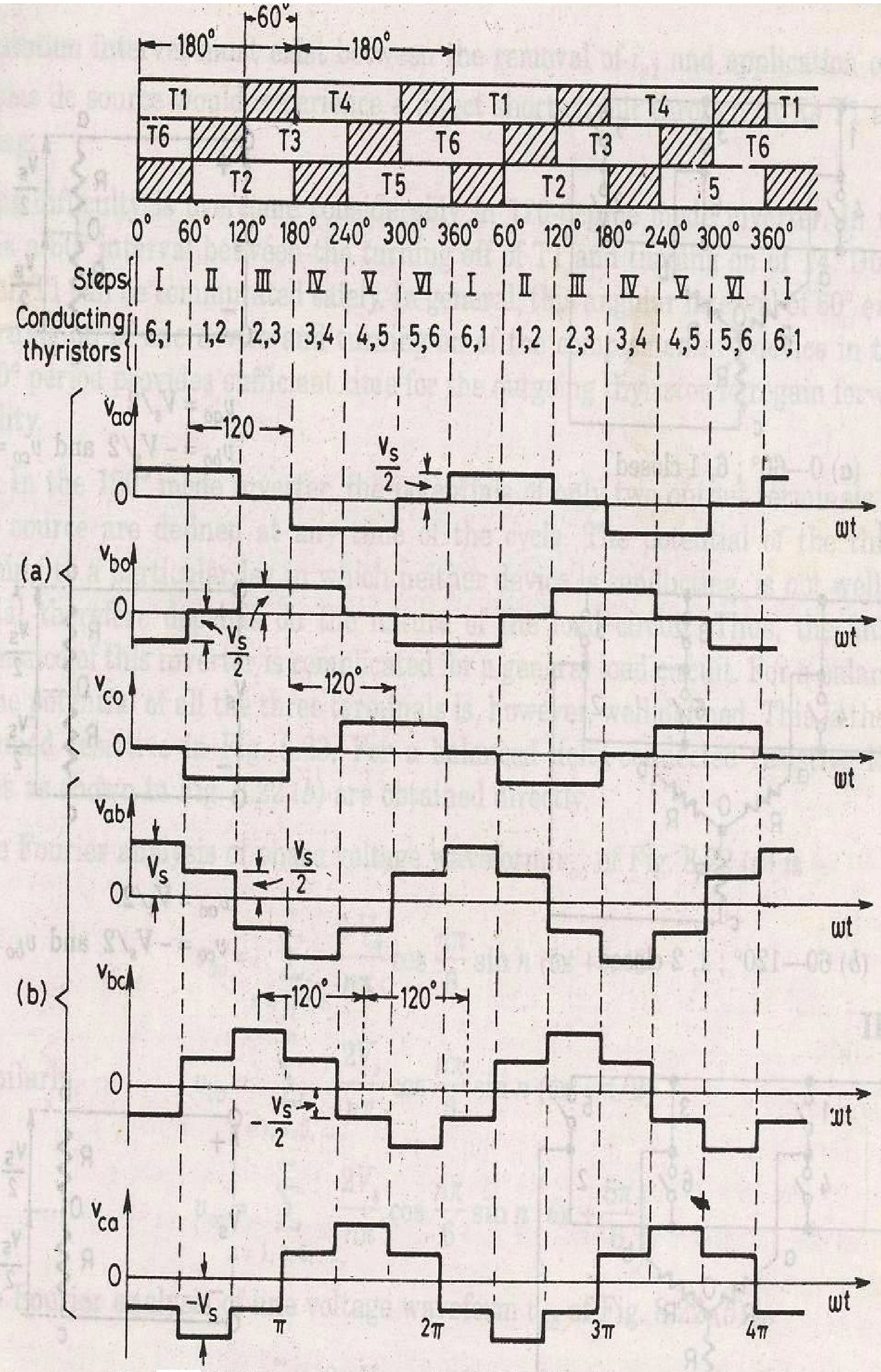


Fig. Voltage waveforms for 120°mode six-step 3-phase VSI.

10. Explain the three phase AC voltage controllers in detail. (M.E-NOV/DEC2010)

Three Phase Ac Voltage Controllers

The analysis of operation of the full-wave controller with isolated neutral as shown in Figure below is quite complicated in comparison to that of a single-phase controller, particularly for an RL or motor load. As a simple example, the operation of this controller is considered here with a simple star-connected R-load. The six SCRs are turned on in the sequence 1-2-3-4-5-6 at 60^0intervals and the gate signals are sustained throughout the possible conduction angle. The output phase voltage waveforms for α=30, 75, and120 degree for a balanced three-phase R-load are shown in Figure. At any interval, either three SCRs or two SCRs, or no SCRs may be on and the instantaneous output voltages to the load are either line-to-neutral voltages (three SCRs on), or one-half of the line-to-line voltage (two SCRs on) or zero (no SCR on). Depending on the firing angle a, there may be three operating modes.

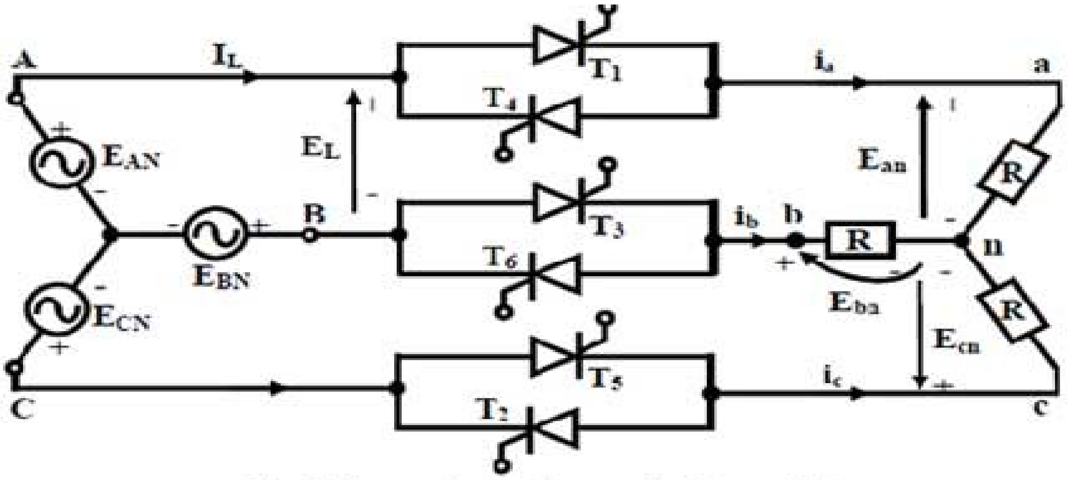


Fig: 1 Three-phase, three-wire Ac regulator

Mode I (also known as Mode 2=3): $0 \leq \alpha \leq 60^0$. There are periods when three SCRs are conducting, one in each phase for either direction or periods when just two SCRs conduct. For example, with $\alpha=30^0$, assume that at ωt=0, SCRs T5 and T6 are conducting, and the current through the R-load in a-phase is zero making van=0. At $\omega t = 30^0$, T1 receives a gate pulse and starts conducting; T5 and T6 remain on and van $=v_{AN}$. The current in T5 reaches zero at 60^0, turning T5 off. With T1 and T6 staying on, van =1/2vAB. At 90^0, T2 is turned on, the three SCRs T1, T2, and T6 are then conducting and van = v_{AN}. At 120^0, T6 turns off, leaving T1 and T2 on, so v_{AN} =1/2vAC. Thus with the progress of firing in sequence until $\alpha=60^0$, the number of SCRs conducting at particular instant alternates between two and three.

Mode II (also known as Mode 2/2): $60^0 \leq \alpha \leq 90^0$Two SCRs, one in each phase, always conduct. For $\alpha=75^0$ as shown in Fig. 16.12b, just prior to $\alpha=75^0$, SCRs T5 and T6 were conducting and van =0. At 75^0, T1 is turned on, T6 continues to conduct while T5 turns off as v_{CN} is negative; van =1/2vAB. When T2 is turned on at 135^0, T6 is turned off and van= 1/2vAC. The next SCR to turn on is T3, which turns off T1 and van . 0. One SCR is always turned off when another is turned on in this range of α and the output is either one-half line-to-line voltage or zero.

Mode III (also known as Mode 0/2): $90^0 \leq \alpha \leq 150^0$: When none or two SCRs conduct. For $\alpha=120^0$, earlier no SCRs were on and van =0. At $\alpha= 120^0$, SCR T1 is given a gate signal while T6, has a gate signal already applied. As v_{AB} is positive, T1 and T6 are forward-biased and they begin to conduct and van =1/2vAB. Both T1 and T6 turn off when v_{AB} becomes negative. When a gate signal is given to T2, it turns on and T1 turns on again. For $\alpha > 150^0$, there is no period when two SCRs are conducting and the output voltage is zero at $\alpha=150^0$. Thus, the range of the firing angle control is $0 \leq \alpha \leq 150^0$. For star-connected R-load, assuming the instantaneous phase voltages as

$$v_{AN} = \sqrt{2}V_s \sin \omega t$$
$$v_{BN} = \sqrt{2}V_s \sin(\omega t - 120°)$$
$$v_{CN} = \sqrt{2}V_s \sin(\omega t - 240°)$$

the expressions for the rms output phase voltage V_o can be derived for the three modes as

$$0 \le \alpha \le 60° \qquad V_o = V_s\left[1 - \frac{3\alpha}{2\pi} + \frac{3}{4\pi}\sin 2\alpha\right]^{1/2}$$

$$60° \le \alpha \le 90° \qquad V_o = V_s\left[\frac{1}{2} + \frac{3}{4\pi}\sin 2\alpha + \sin(2\alpha + 60°)\right]^{1/2}$$

$$90° \le \alpha \le 150° \qquad V_o = V_s\left[\frac{5}{4} - \frac{3\alpha}{2\pi} + \frac{3}{4\pi}\sin(2\alpha + 60°)\right]^{1/2}$$

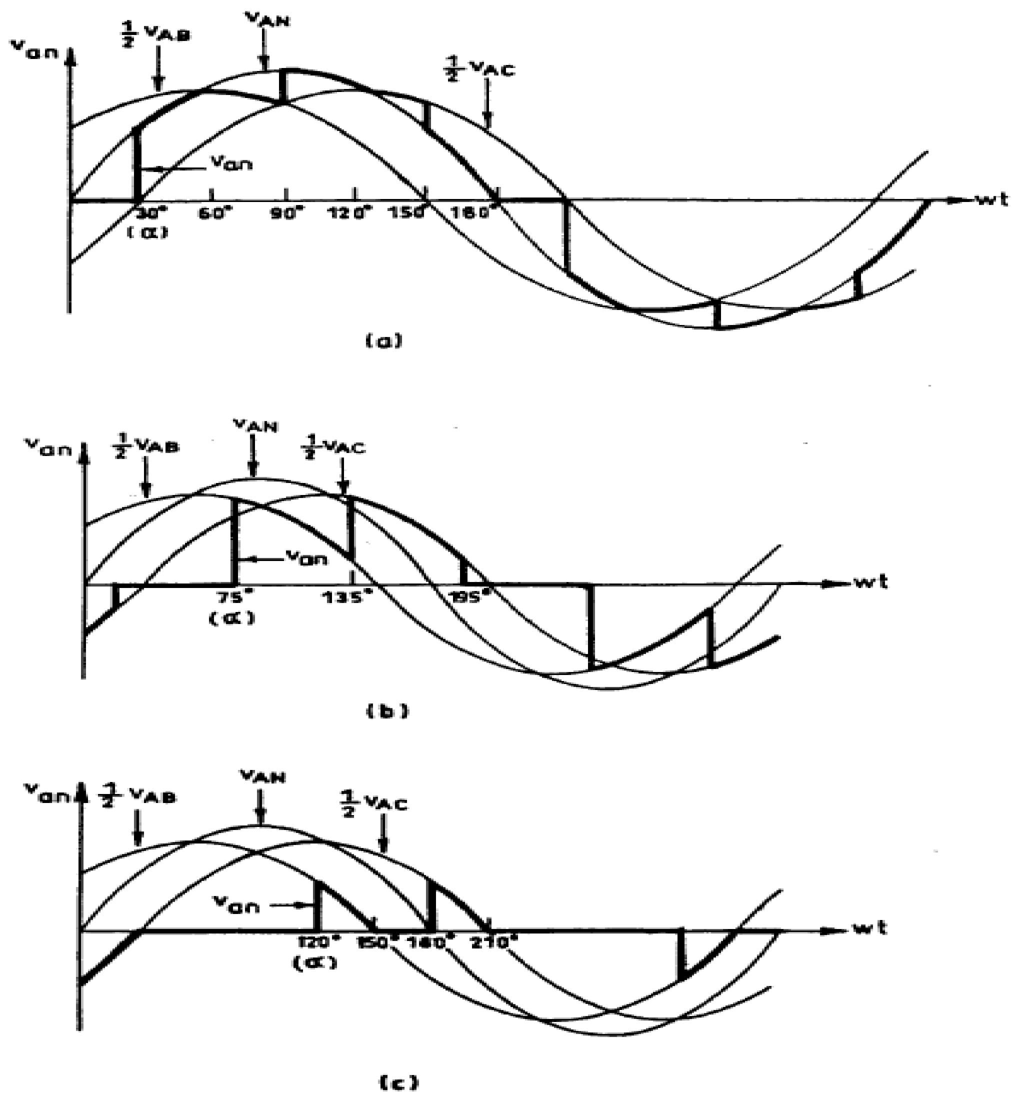


FIGURE Output voltage waveforms for a three-phase ac voltage controller with star-connected R-load: (a) v_{an} for $\alpha = 30°$; (b) v_{an} for $\alpha =$ 5°; and (c) $v_{an} = 120°$.

UNIT-4

PART-B

1. Explain the stand alone operation of variable speed wind energy conversion system. (APR/MAY2017) (M.E-NOV/DEC2010)

Variable speed wind energy conversion system

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. The doubly-fed-induction-generator (DFIG)-based WECS (below Figure), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry. The DFIG is a WRIG with the stator windings connected directly to the three phases, constant-frequency grid and the rotor windings connected to a back-to-back (AC—AC) voltage source converter. Thus, the term "doubly-fed" comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behavior being governed by the power electronics converter and its controllers. The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor. The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip. The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of 40% around the synchronous speed is used. DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

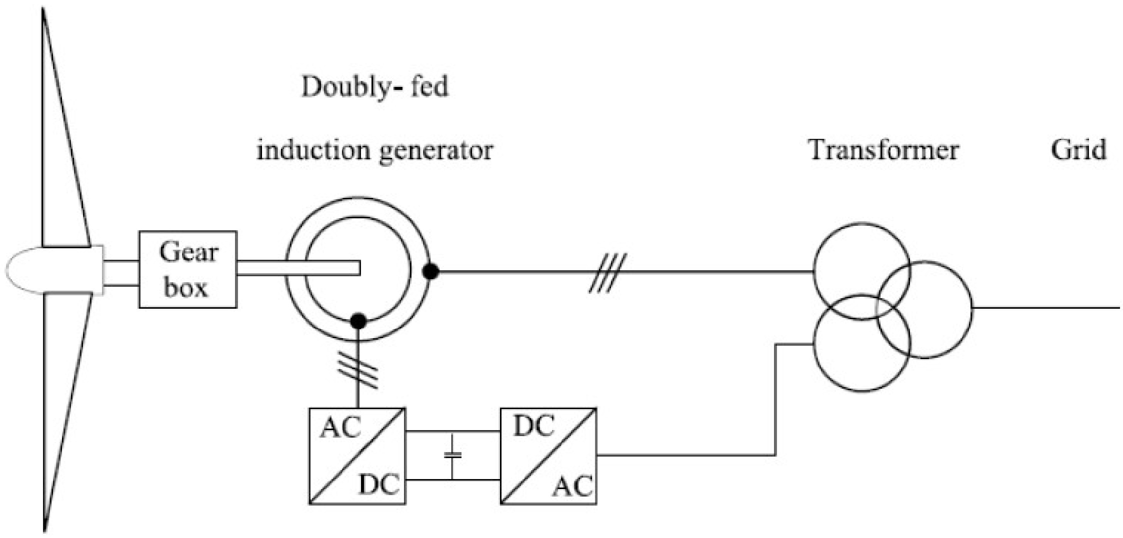


Fig General structure of an improved variable-speed WECS

Full variable-speed WECS are very flexible in terms of which type of generator is used. As presented in Figure below, it can be equipped with either an induction (SCIG) or a synchronous generator. The synchronous generator can be either a wound-rotor synchronous generator (WRSG) or a permanent-magnet synchronous generator (PMSG), the latter being the one mostly used by the wind turbine industry. The back-to-back power inverter is rated to the generator power and its operation is similar to that in DFIG-based WECS. Its rotor-side ensures the rotational speed being adjusted within a large range, whereas its grid-side transfers the active power to the grid and attempts to cancel the reactive power consumption. This latter feature is important especially in the case of SCIG-equipped WECS. The PMSG is considered, in many research articles, a good option to be used in WECS, due to its self—excitation property, which allows operation at high power factor and efficiency. PMSG does not require energy supply for excitation, as it is supplied by the permanent magnets. The stator of a PMSG is wound and the rotor has a permanent magnet pole system. The salient pole of PMSG operates at low speeds, and thus the gearbox can be removed. This is a big advantage of PMSG-based WECS as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multi pole PMSG with large diameter. The synchronous nature of PMSG may cause problems during start-up, synchronization and \voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature and they can loose their magnetic properties if exposed to high temperatures.

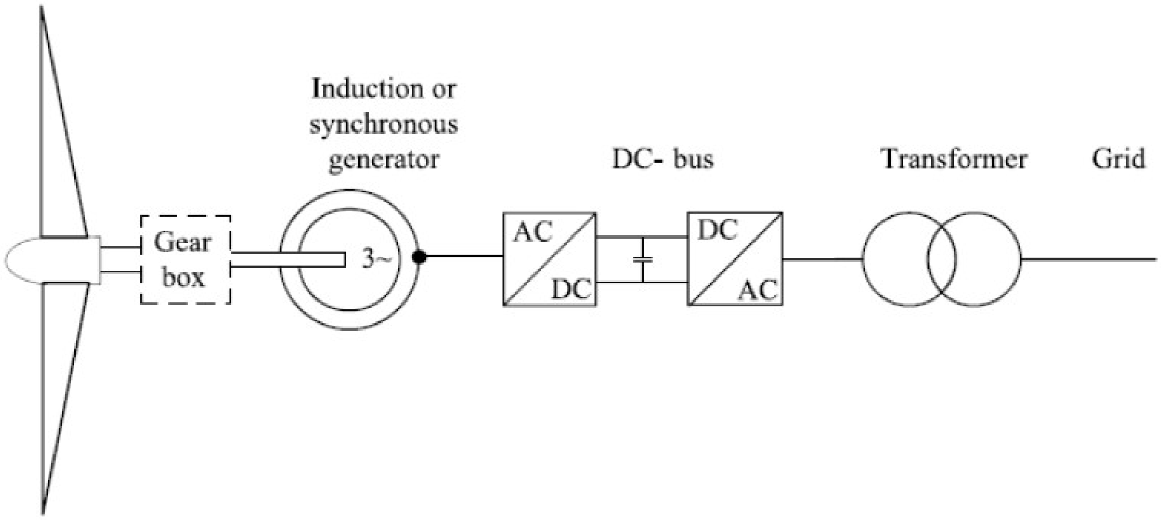


Fig General structure of a full variable-speed WECS

2. Explain the stand alone operation of fixed speed wind energy conversion system. (M.E-NOV/DEC20130

Fixed Speed Wind Energy Conversion System

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below. This WECS configuration is also known as the “Danish concept” because it was developed and widely used in Denmark. Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the Wind speed cubed, the associated electromagnetic variations are important.

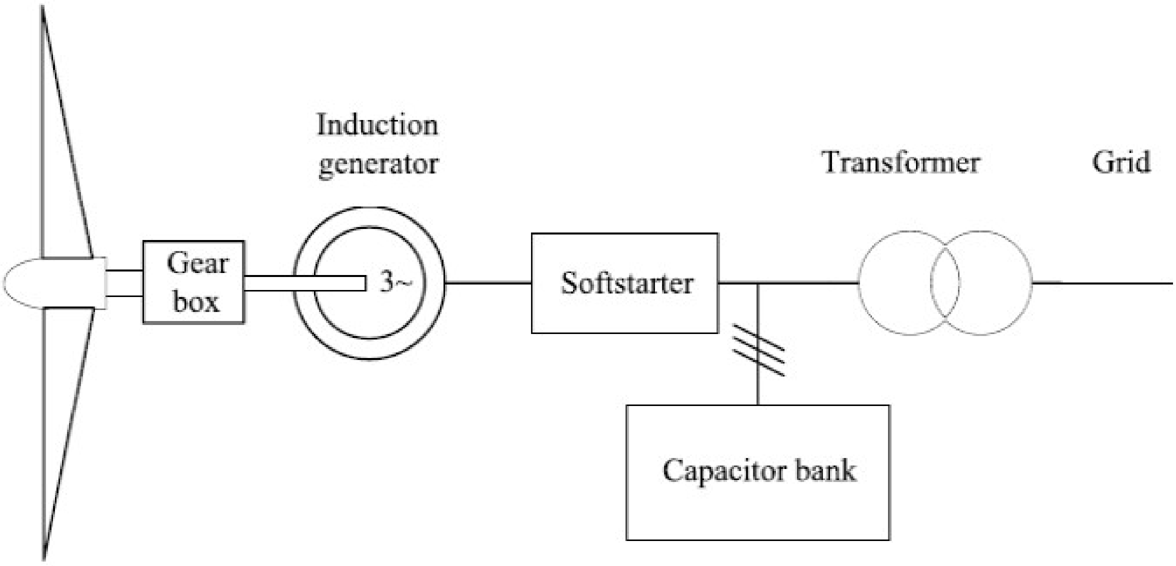


Fig General structure of a fixed-speed WECS

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection.

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).
Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed- speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.
An evolution of the fixed-speed SCIG-based WECS are the limited variable speed WECS. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance; see Figure below. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% over the synchronous speed.

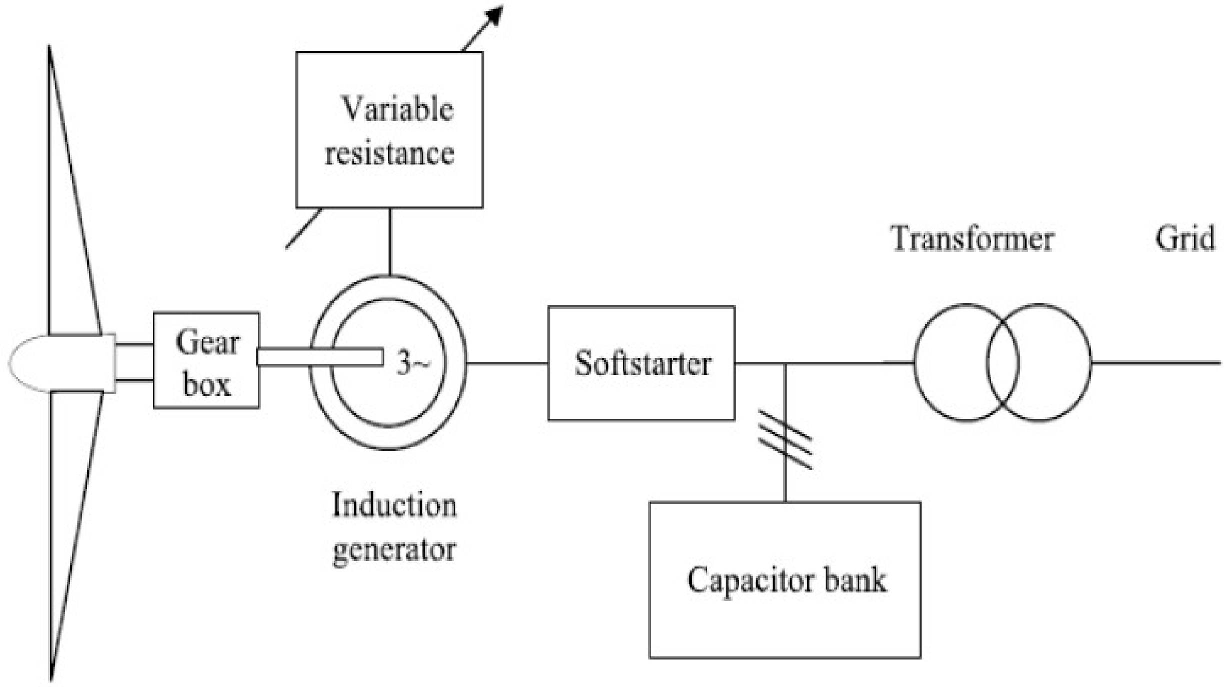


Fig. General structure of a limited variable-speed WECS.

3. Explain the operation of grid integrated PMSG system with a neat block diagram. (APR/MAY2017) (M.E-NOV/DEC2016)(M.E-NOV/DEC2013)(M.E-NOV/DEC2010)

GRID INTEGRATED PMSG SYSTEM

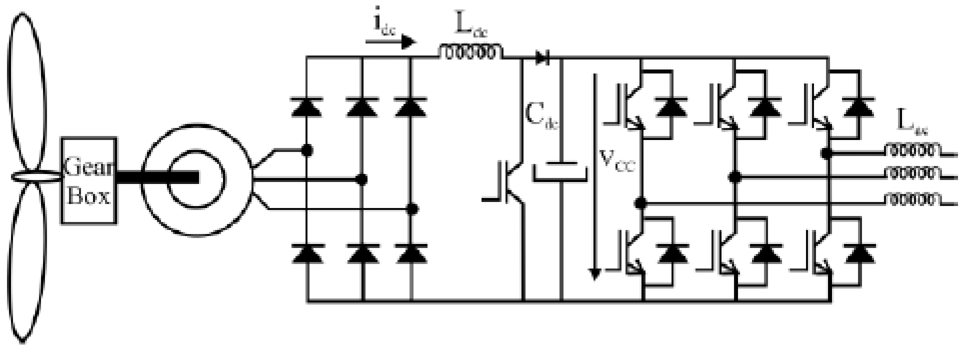


Figure a PMSG with the rectifier, boost chopper, and PWM line-side

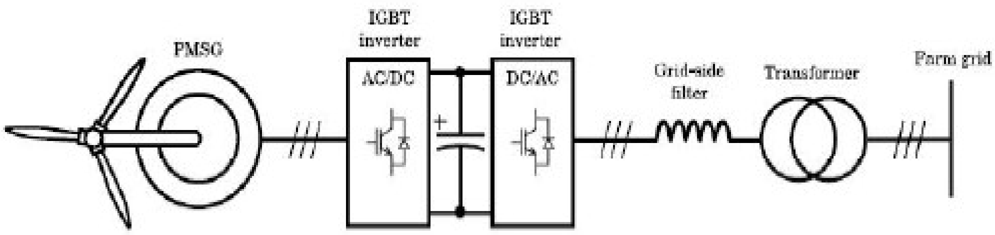


Figure b PMSG with back-to-back PWM converters

A typical power electronics topology that is used for a permanent magnet synchronous generator is shown in Figure a. The three-phase variable voltage, variable frequency output from the wind turbine is rectified using a diode bridge. With the change in the speed of the synchronous generator, the voltage on the DC side of the diode rectifier changes. To maintain a constant DC-link voltage of the inverter, a step-up chopper is used to adapt the rectifier voltage. As viewed from the DC inputs to the inverter, the generator/rectifier system is then modeled as an ideal current source. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor. The DC signal is then inverted through the use of semiconductor switches into a three-phase, 50 Hz waveform. This waveform can then be scaled using a transformer to voltage levels required by the utility's AC system. The generator is decoupled from the grid by a voltage-sourced DC-link; therefore, this PE interface provides excellent controllable characteristics for the wind energy system. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system where more sensitive power electronic parts are required. The diode rectifier is the most commonly used topology in power electronic applications. For a three-phase system it consists of six diodes. It is shown in Figure a. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It can be used in some applications such as pre-charging.

Figure b shows the scheme of a full power converter for a wind turbine. The machine- side three-phase converter works as a driver controlling the torque generator, using a vector control strategy. The grid-side three-phase converter permits wind energy transfer into the grid and enables to control the amount of the active and reactive powers delivered to the grid. It also keeps the total-harmonic-distortion (THD) coefficient as low as possible, improving the quality of the energy injected into the public grid. The objective of the dc link is to act as energy storage, so that the captured energy from the wind is stored as a charge in the capacitors and may be instantaneously injected into the grid. The control signal is set to maintain a constant reference to the voltage of the dc link Vdc. An alternative to the power-conditioning system of a wind turbine is to use a synchronous generator instead of an induction one and to replace a three-phase converter (connected to the generator) by a three phase diode rectifier and a chopper, as shown in Figure a. Such choice is based on the low cost as compared to an induction generator connected to a VSI used as a rectifier. When the speed of the synchronous generator alters, the voltage on the dc side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter. When the inverter system is analyzed, the generator/rectifier system can be modeled as an ideal current source. The step-up chopper used as a rectifier utilizes a high switching frequency, so the bandwidth of these components is much higher than the bandwidth of the generator. Controlling the inductance current in the step-up converter can control the machine torque and, therefore, its speed.

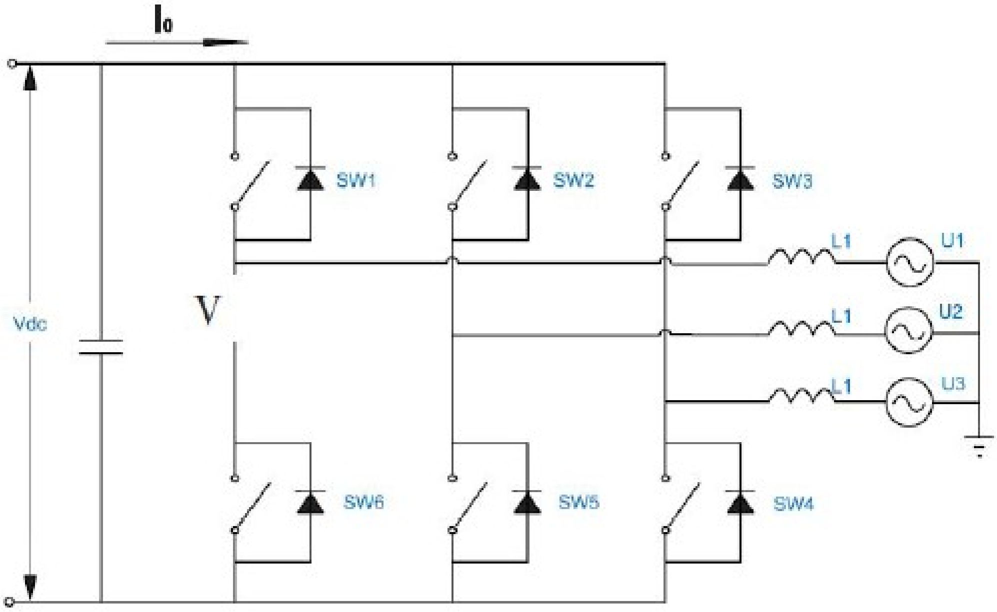
Based on the control design for the back-to-back PWM converter system, various advantages can be obtained such as:

- The line-side power factor is unity with no harmonic current injection (satisfies IEEE 519);
- Wind generator output current is sinusoidal;
- There are no harmonic copper losses;
- The rectifier can generate programmable excitation for the induction generator based system.
- Continuous power generation from zero to the highest turbine speed is possible.
- Power can flow in either direction, permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine; and
- Islanded operation of the system is possible with a start-up capacitor charging the battery.

Principle of Operation

Figure below shows the structure of the PWM line side converter. Power flow in the PWM Converter is controlled by adjusting the phase angle δ between the source voltage U1 and the respective converter reflected input voltage VS]. When U1 leads VS1 the real power flows from the ac source into the converter. Conversely, if U1 lags Vs1, power flows from the converter's dc side into the ac source. The real power transferred is given by the Equation below.

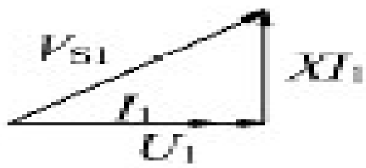
$$P = \frac{V_{S1} U_1}{X_1} \sin(\delta)$$



PWM converter.

The ac power factor is adjusted by controlling the amplitude of the converter synthesized voltage VS1. The per phase equivalent circuit and phase diagrams of the leading, lagging and unity power factor operation is shown in Figure below. The phasor diagram below shows that to achieve a unity power factor, VS1 has to be,

$$V_{S1} = \sqrt{U_1^2 + (X_1 I_1)^2}$$



4. Explain the block diagram of SCIG based wind energy conversion system. (M.E-NOV/DEC2013)(M.E-NOV/DEC2010)

SCIG based wind energy conversion system

Fixed speed system:

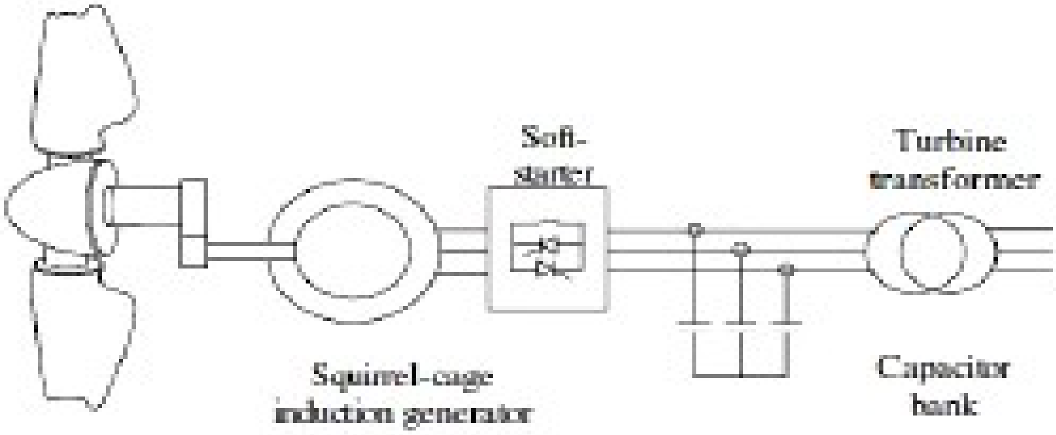


Fig SCIG Connected to Grid

Fixed—speed Wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator. From the electrical system viewpoint they are perhaps best considered as large fan drives with torque applied to the low-speed shaft from the wind flow.
It consists of a squirrel-cage induction generator coupled to the power system through a turbine transformer. The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, because the operating slip variation is generally less than 1%, this type of wind generation is normally referred to as fixed speed. Squirrel-cage induction machines consume reactive power and so it is conventional to provide power factor correction capacitors at each wind turbine.
The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator. Also, by applying the network voltage slowly to the generator, once energized, it brings the drive train slowly to its operating rotational speed.

Variable Speed System

The typical configuration of a Variable Speed Grid Connected SCIG based fully rated converter wind turbine is shown in Figure below. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine.

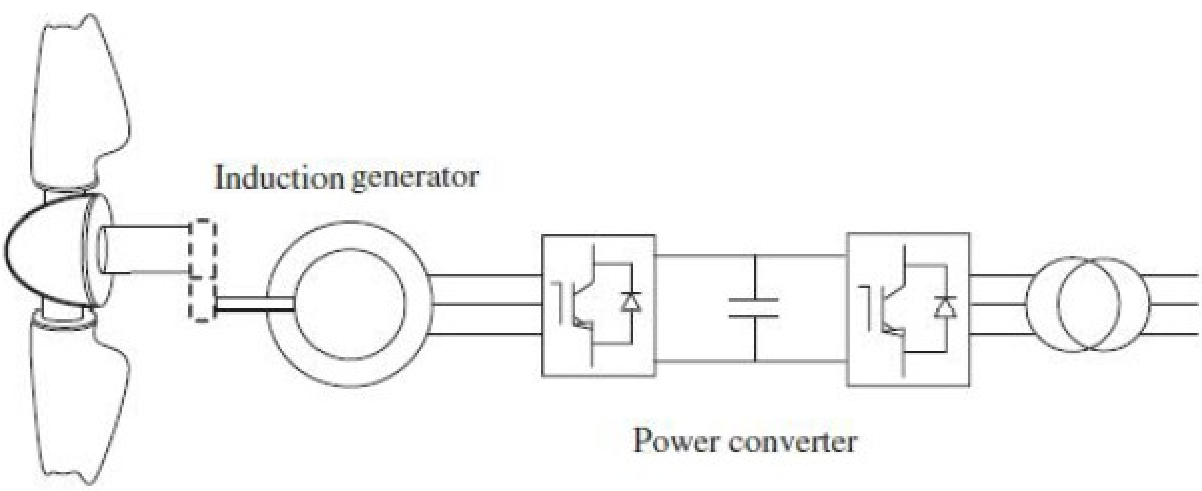


Figure Typical configuration of a fully rated converter-connected wind turbine

The power converters can be arranged in various ways. Whereas the generator-side converter (GSC) can be a diode rectifier or a PWM voltage source converter (VSC), the network- side converter (NSC) is typically a PWM VSC. The strategy to control the operation of the generator and the power flows to the network depends very much on the type of power converter arrangement employed. The network-side converter can be arranged to maintain the DC bus voltage constant with torque applied to the generator controlled from the generator-side converter. Alternatively, the control philosophy can be reversed. Active power is transmitted through the converters with very little energy stored in the DC link capacitor. Hence the torque applied to the generator can be controlled by the network-side converter. Each converter is able to generate or absorb reactive power independently.

5. Write short notes on grid integrated solar system. (M.E-NOV/DEC2010) (M.E-APR/MAY2013)

Photovoltaic (PV) Systems

Photovoltaic (PV) systems convert sunlight to electric current. You are already familiar with some simple PV applications in today's society, such as calculators and wrist watches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. Many road and traffic signs along highways are now powered by PV.

PV systems produce some electric current any time the sun is shining, but more power is produced when the sunlight is more intense and strikes the PV modules directly. While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun's heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules.

PV allows you to produce electricity—without noise or air pollution—from a clean, renewable resource. A PV system never runs out of fuel, and it won't increase oil imports.

Block Diagram of Solar Photovoltaic System

Generally there are two types of Solar Photovoltaic System they are

1. Autonomous Solar Photovoltaic system or Stand alone Solar Photovoltaic system.
2. Grid Connected PV system.

a) Without Battery.

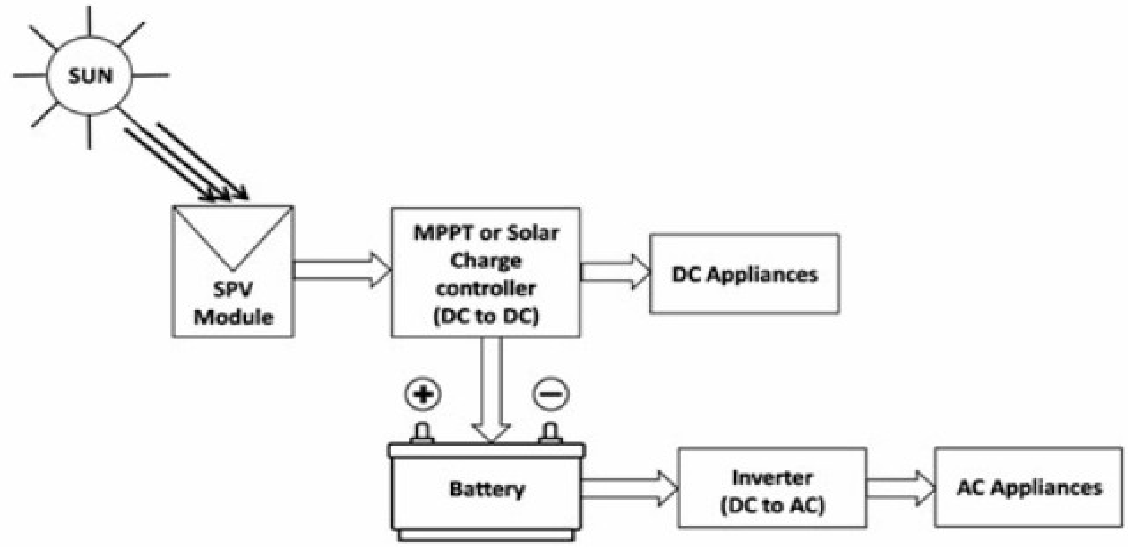
b) With Battery.

Autonomous PV system (or) Stand alone Solar Photovoltaic System (SPV)

A Standalone SPV system is the one which is not connected to the power grid. Standalone PV systems usually have a provision for energy storage. This system has battery support to supply the load requirements during the night hours or even when sunshine is not adequate (Cloudy conditions) during the day.

Block Diagram

Figure shows the block diagram of Standalone SPV system. Power is generated when sun light falls on the SPV module. This power is given to the MPPT or Charge controller block. The function of this block is to control the variation in the output of the SPV module and make it suitable for use at the output according to the supply required by a load. There are two types of the loads: AC and DC. DC components are directly connected to the MPPT or Charge controller block, where as the AC appliances are connected through the Battery and inverter.

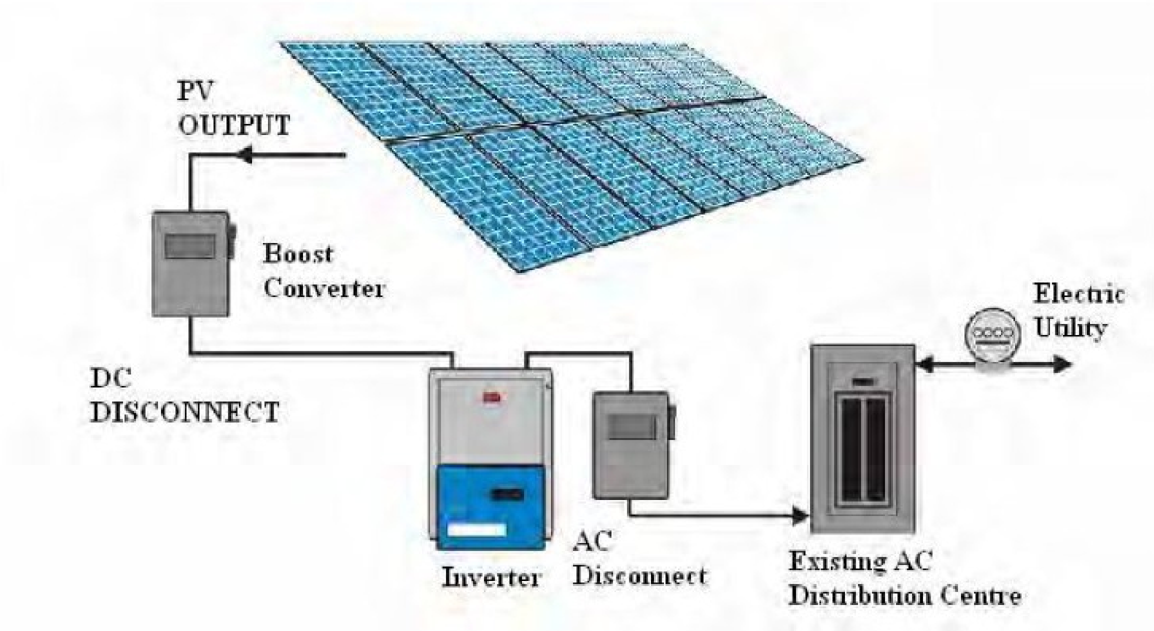


Simple Block Diagram of Standalone SPV system

In this way, a Standalone system is connected depending upon whether only AC load is present or both AC and DC load are present.

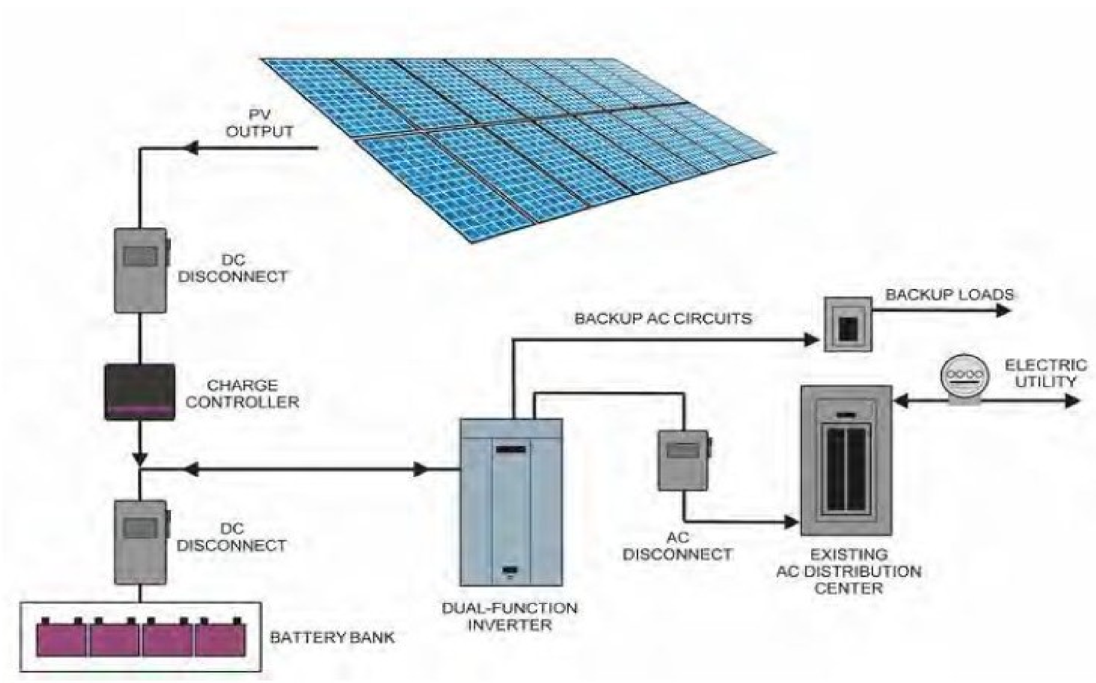
Typical Grid Tied System (Battery less)

There are no batteries to store excess power generated-the electric utility essentially stores it for you through a system called "net-metering." DC (direct current) generated by the PV panels is converted into AC (alternating current) power by the inverter (exactly the same high quality AC current delivered to your site by the utility-provided power grid). Output from the inverter is connected to your existing distribution panel (breaker panel) which feeds the rest of your site. While the system is generating electricity, power needs are provided by the PV system (up to its capacity), reducing or eliminating the power you would have drawn from the utility grid at that time. During periods when your grid-tie system is generating even more energy than your site requires, any excess is fed back into the grid for others to use and the electric utility company "buys" it from you at the retail rate. They provide credits to your account for all the power that is pushed back into the grid through the meter. And your meter will literally run backwards! When your site needs to draw more energy than it is producing (Say, during cloudy conditions or at night), electricity is provided by the power grid in the normal manner and is first paid for by your accumulated credits.



Typical Grid Tied System with Battery Backup

The "Grid-Tie With Battery Backup" PV system incorporates one or more special AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may power a refrigerator, selected lights, computers or servers... any devices the owner deems essential. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits when the grid is down. The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them.



6. Explain how the insolation and temperature affects the I-V characteristics of a solar cell. (M.E-APR/MAY2013)

Effect of Irradiance and Temperature

The term Irradiance is defined as the measure of power density of sunlight received at a location on the earth and is measured in watt per metre square. Whereas irradiation is the measure of energy density of sunlight .The term Irradiance and Irradiation are related to solar. Components. As the solar insolation keeps on changing throughout the day similarly I-V and P-V characteristics varies. With the increasing solar irradiance both the open circuit voltage and the short circuit current increases and hence the maximum power point varies. Temperature plays another major factor in determining the solar cell efficiency. As the temperature increases the rate of photon generation increases thus reverse saturation current increases rapidly and this reduces the band gap. Hence this leads to marginal changes in current but major changes in voltage. The cell voltage reduces by 2.2Mv per degree rise of temperature. Temperature acts like a negative factor affecting solar cell performance. Therefore solar cells give their full performance on cold and sunny days rather on hot and sunny weather. Nowadays Solar panels are made of non-silicon cells as they are temperature insensitive. Thus the temperature remains close to room temperature.

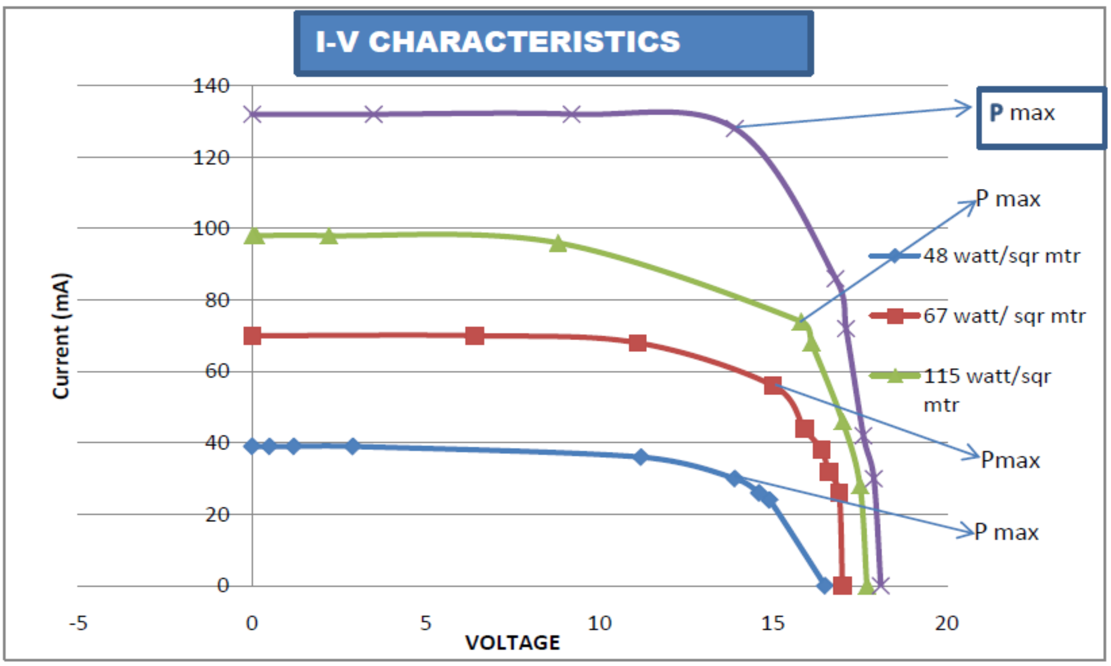


Fig Shows the current versus voltage curve at various irradiance level and the corresponding maximum power point.

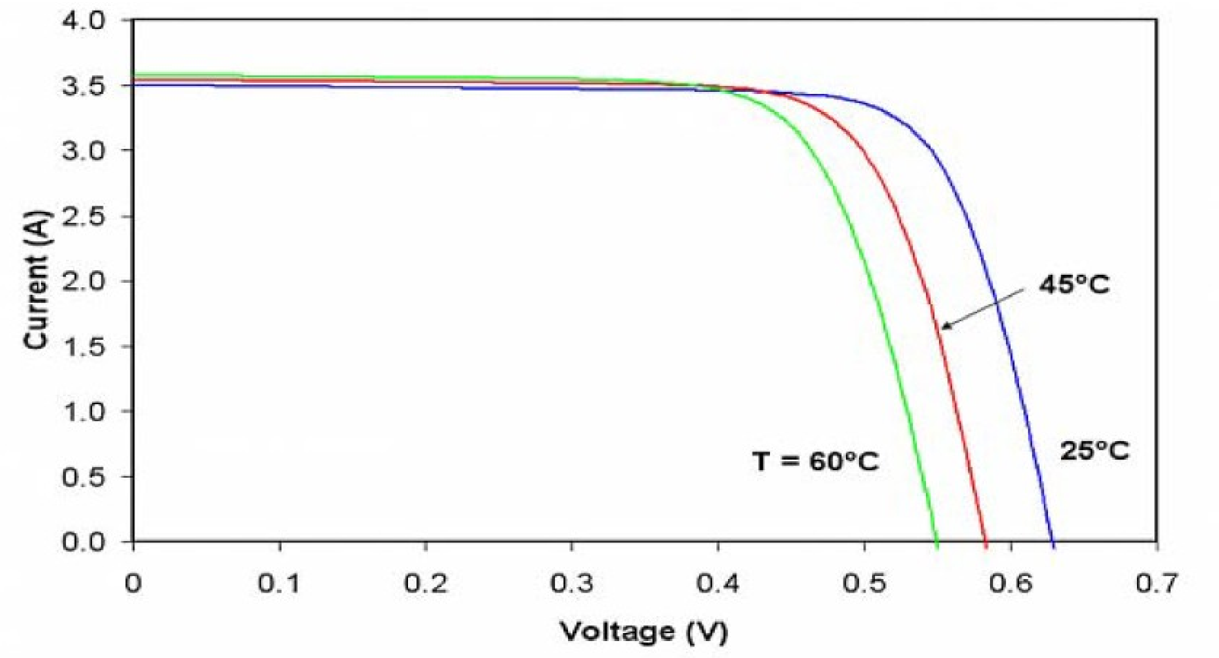


Fig Shows how the I-V curve varies with varying temperature.

7. A HAWT is installed at a location having free wind velocity of 15m/s. The 80m diameter rotor has three blades attached to the hub. Find the rotational speed of the turbine for optimal energy extraction. (M.E-APR/MAY2013)

Given:

Rotor diameter = 80m, r=40m, u_0=15m/s, n=3

Solution:

Tip speed ratio for optimum output, $\lambda_0 = 4\pi/n = 4.188$

Tip speed ratio $\lambda_0 = r\omega/u_0$

$4.188 = (40*\omega)/15$; $\omega = 1.57$; $\omega = 2\pi N/60$

N = 15 rpm.

Therefore, for optimum energy extraction rotor speed should be maintained at 15 rpm.

UNIT-5

PART-B

1. With a neat schematic explain the integration of wind energy system with solar thermal system. (M.E-NOV/DEC2010)

Wind – Photovoltaic systems:

In many regions of the world, wind generators and photovoltaic cells are combined to provide year-round renewable energy to non-grid connected households. This is possible since variations in wind and solar power resources are usually complementary. A wind generator is thus an excellent supplement to the PV system and vice versa. Moreover, interfacing of wind generators and PV cells minimizes battery capacity and extends the battery bank life compared to the storage requirement in solar or wind only systems. Figure below shows a typical wind/PV hybrid system configuration.

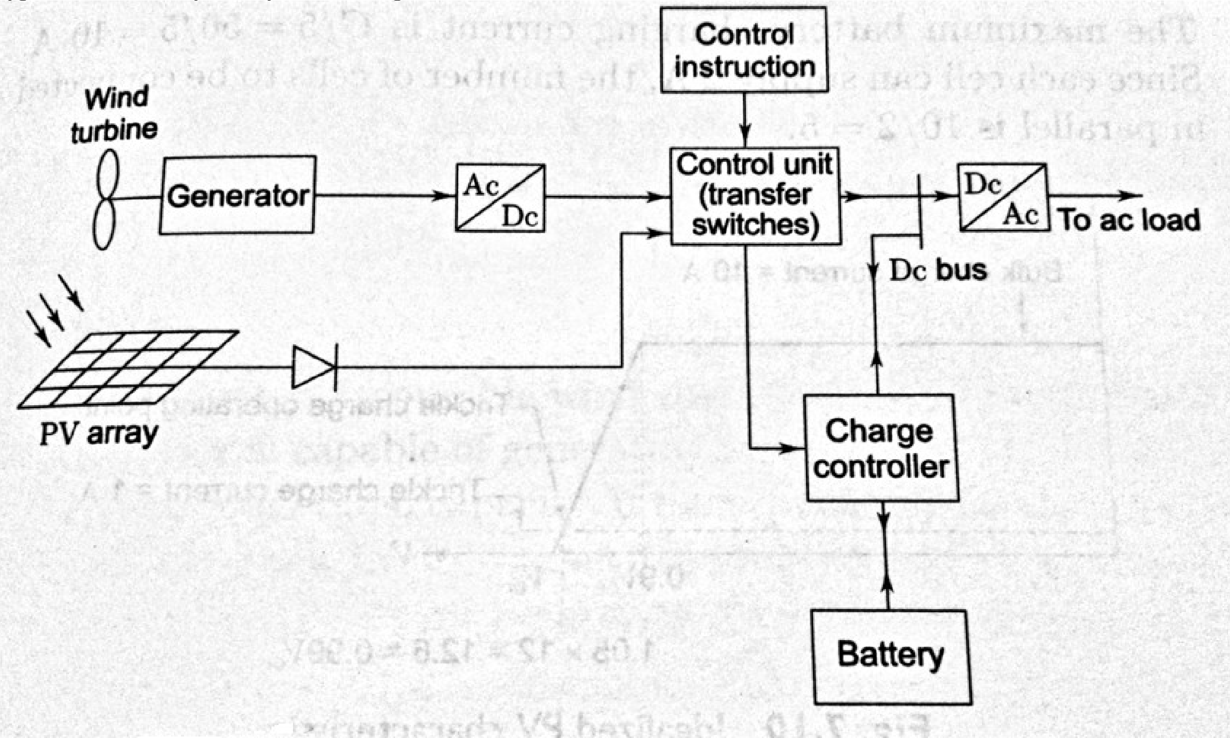


Fig. Configuration of a typical wind–PV system

The ac output of the wind generator feeds a rectifier which is connected in parallel to PV array through a controller to a dc bus. The dc bus also serves as a connection point for the battery through a charge controller. The blocking diode protects the PV array from voltage spikes and prevents the flow of current in the reverse direction at low irradiation. The controller decides the connection of the generating system/battery supply, or its charging, in specific situations and requirements.

2. Explain the incremental conductance based Maximum power point tracking algorithm with a suitable illustration.(M.E-NOV/DEC2016)

Incremental conductance based Maximum power point tracking algorithm:

The incremental conductance (IncCond) method is based on comparing the instantaneous panel conductance with the incremental panel conductance. The input impedance of the DC-DC converter is matched with optimum impedance of PV panel. As noted in literatures, this method has a good performance under rapidly changing conditions. The algorithm uses the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 0$$

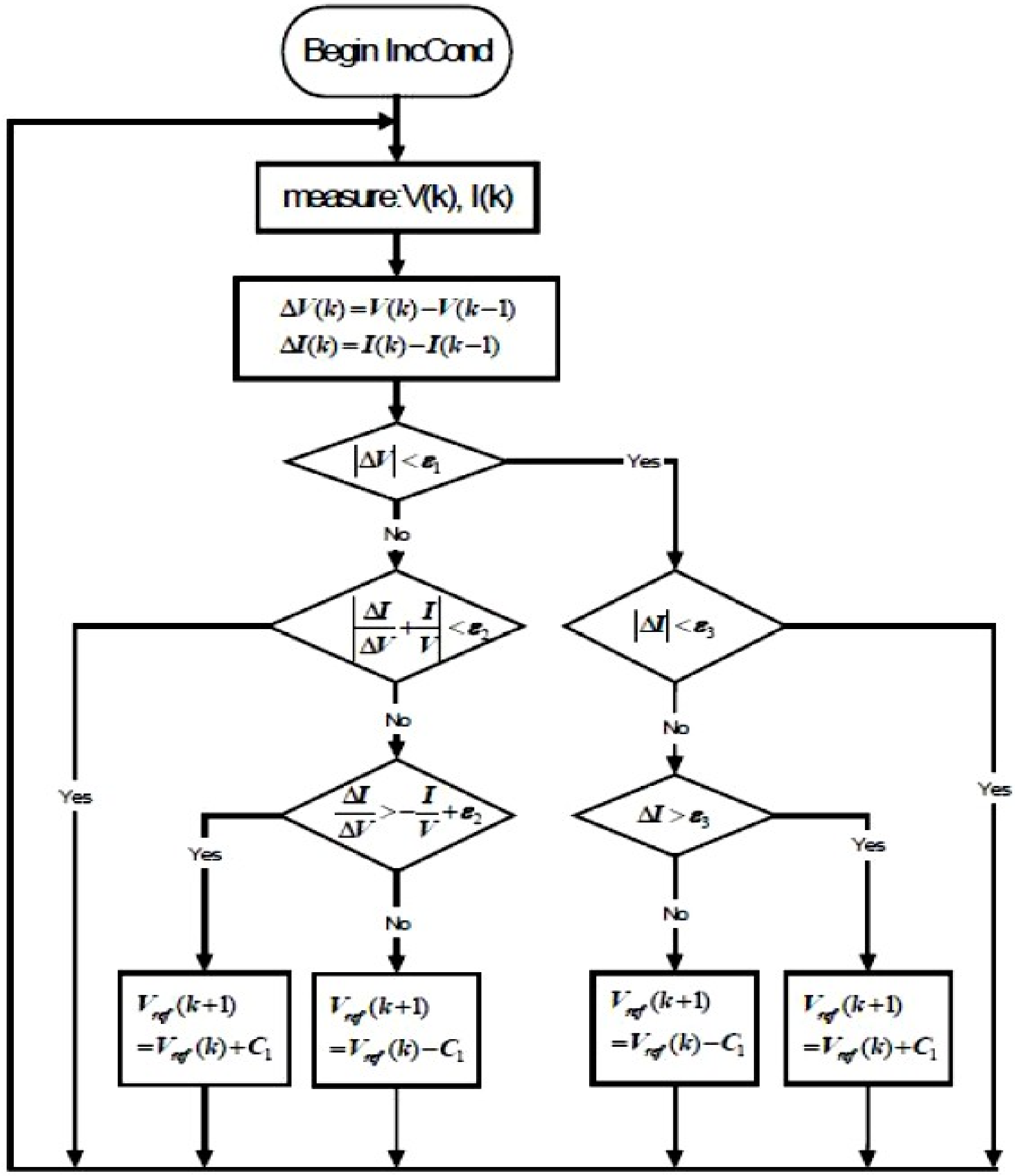


Figure: Incremental conductance algorithm flow chart

One of the advantages of the IncCond algorithm is that it does not oscillate around the MPP. The check of condition dl = O allows it to bypass the perturbation step and therefore maintain a constant operating voltage V once the MPP is found. Furthermore, condition dl > 0 make it possible to determine the relative location of the MPP. This leads to the advantage that an initial adjustment in the wrong direction, as with the “trial and error” P&O method, does not occur. A fast and correct system response to changing operating conditions should be the result yielding high system efficiency. A small marginal error could be added to the maximum power condition. The value of error was determined with consideration of the tradeoff between the problem of not operating exactly at the MPP and the possibility of oscillating around it. It will also depend on the chosen perturbation step size Cl.

3. Explain the various strategies used for the operation of an MPPT. (APR/MAY2017) (M.E-NOV/DEC2013) (M.E-NOV/DEC2013)

METHODS OF MPPT ALGORITHMS

1. Constant Voltage and Current.
2. Perturb-and-Observe.
3. Incremental Conductance.

Constant Voltage and Current Method

The constant voltage algorithm is based on the observation from I-V curves that the ratio of the array’s maximum power voltage, Vmp, to its open-circuit voltage, V_{oc}, is approximately constant:

$$Vmp / Voc = K < 1$$

The constant voltage algorithm can be implemented using the flow chart below. The solar array is temporarily isolated from the MPPT, and a Voc measurement is taken. Next, the MPPT calculates the correct operating point and the preset value of K, and adjusts the array's voltage until the calculated Vmp is reached. This operation is repeated periodically to track the position of the MPP. Although this method is extremely simple, it is difficult to choose the optimal value of the constant K. The literature reports success with K values ranging from 73 to 80%. Constant voltage control can be easily implemented with analog hardware. However, its MPPT tracking efficiency is low relative to those of other algorithms. Reasons for this include the aforementioned error in the value of K, and the fact that measuring the open-circuit voltage requires a momentary interruption of PV power.
It is also possible to use a constant current MPPT algorithm that approximates the MPP current as a constant percentage of the short-circuit current. To implement this algorithm, a switch is placed across the input terminals of the converter and switched on momentarily. The short-circuit current is measured and the MPP current is calculated, and the PV array output current is then adjusted by the MPPT until the calculated MPP current is reached. This operation is repeated periodically. However, constant voltage control is normally favored because of the relative ease of measuring voltages, and because open-circuiting the array is simple to accomplish, but it is not practically possible to short-circuit the array (i.e., to establish zero resistance across the array terminals) and still make a current measurement.

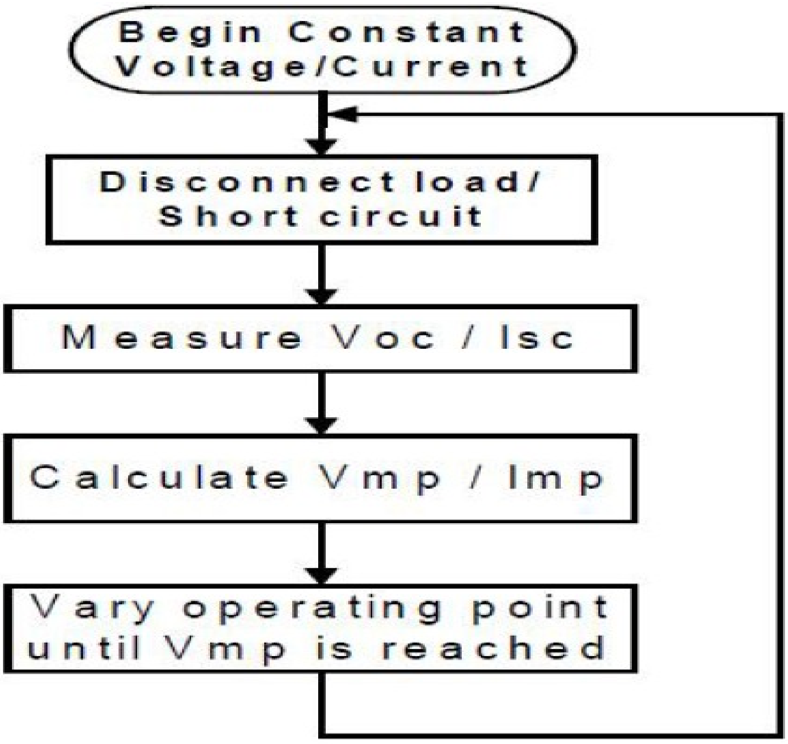
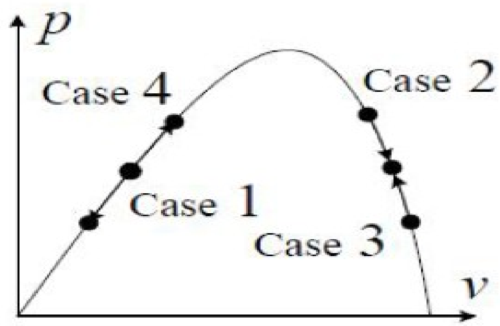


Figure Constant voltage/current algorithm flowchart

Perturb-and-Observe

As the name of the perturb-and-observe (P&O) states, this process works by perturbing the system by increasing or decreasing the array operating voltage and observing its impact on the array output power. The operating voltage is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage Vmp. Figure below summarized the control action of the P&O method. The value of the reference voltage, Vref, will be changed according to the current operating point. For example, for when the controller senses that the power from solar array increases (dP > 0) and voltage decreases (dV < 0), it will decrease (-) Vfef by a step size Cl, so V,-Bf is closer to the MPP. The MPP represents the point where Vref and scaled down Vsa become equal.
The oscillation around a maximum power point causes a power loss that depends on the step width of a single perturbation. The value for the ideal step width is system dependent and needs to be determined experimentally to pursue the tradeoff of increased losses under stable or slowly changing conditions. In fact, since the AC component of the output power signal is much smaller than the DC component and will contain a high noise level due to the switching DC-DC converter, an increase in the amplitude of the modulating signal had to be implemented to improve the signal to noise ratio (SNR), however, this will lead to higher oscillations at the MPP and therefore increase power losses even under stable environmental conditions.



Case	dP	dV	Action
1	< 0	< 0	+
2	< 0	> 0	-
3	> 0	< 0	-
4	> 0	> 0	+

Figure Perturb & Observe (P&O) control action

Several improvements of the P&O algorithm have been proposed. One of the simplest entails the addition of a ‘waiting’ function that causes a momentary cessation of perturbations if the algebraic sign of the perturbation is reversed several times in a row, indicating that the MPP has been reached. This reduces the oscillation about the MPP in the steady state and improves the algorithm’s efficiency under constant irradiance conditions. However, it also makes the MPPT slower to respond to changing atmospheric conditions, worsening the erratic behavior on partly cloudy days. Another modification involves measuring the array’s power Pl at array voltage Vl, perturbing the voltage and again measuring the array’s power, P2, at the new array voltage V2, and then changing the voltage back to its previous value and re measuring the array’s power, Pl, at V1. From the two measurements at Vl, the algorithm can determine whether the irradiance is changing. Again, as with the previous modifications, increasing the number of samples of the array’s power slows the algorithm down. Also, it is possible to use the two measurements at Vl to make an estimate of how much the irradiance has changed between sampling periods, and to use this estimate in deciding how to perturb the operating point. This, however, increases the complexity of the algorithm, and also slows the operation of the MPPT. The flow chart for P&O algorithm is shown below

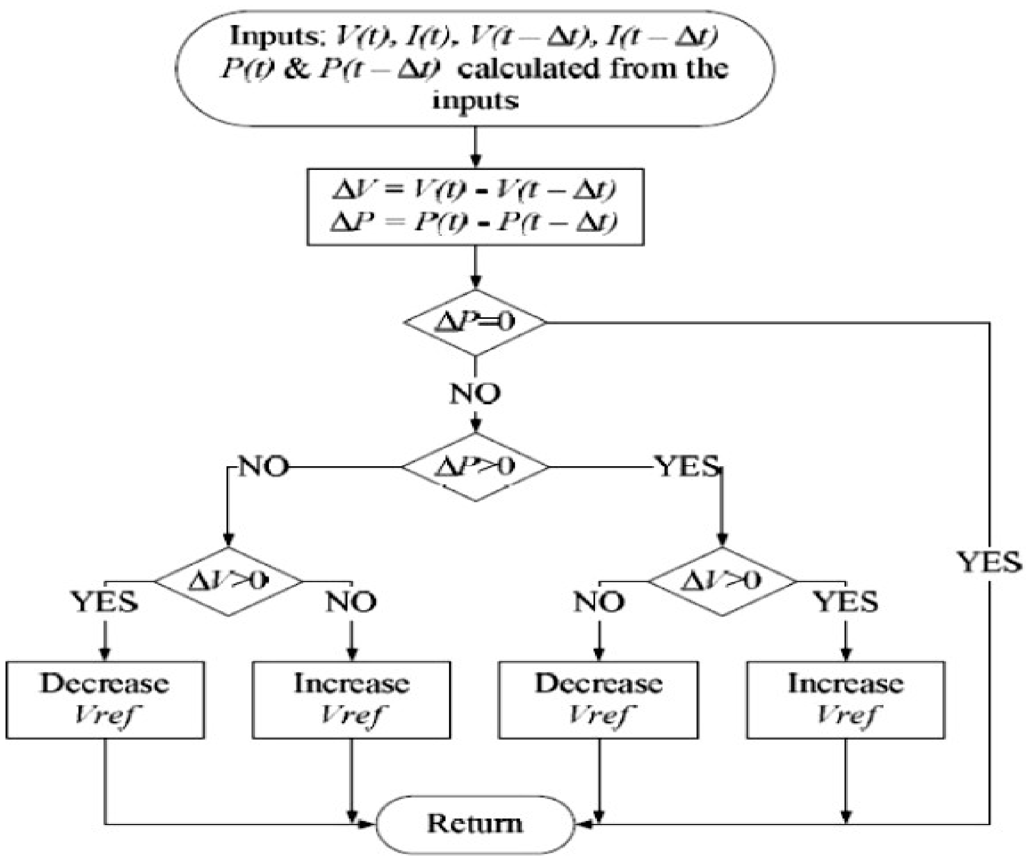


Figure - The flowchart of the P&O Algorithm.

Incremental conductance based Maximum power point tracking algorithm:

The incremental conductance (IncCond) method is based on comparing the instantaneous panel conductance with the incremental panel conductance. The input impedance of the DC-DC converter is matched with optimum impedance of PV panel. As noted in literatures, this method has a good performance under rapidly changing conditions. The algorithm uses the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 0$$

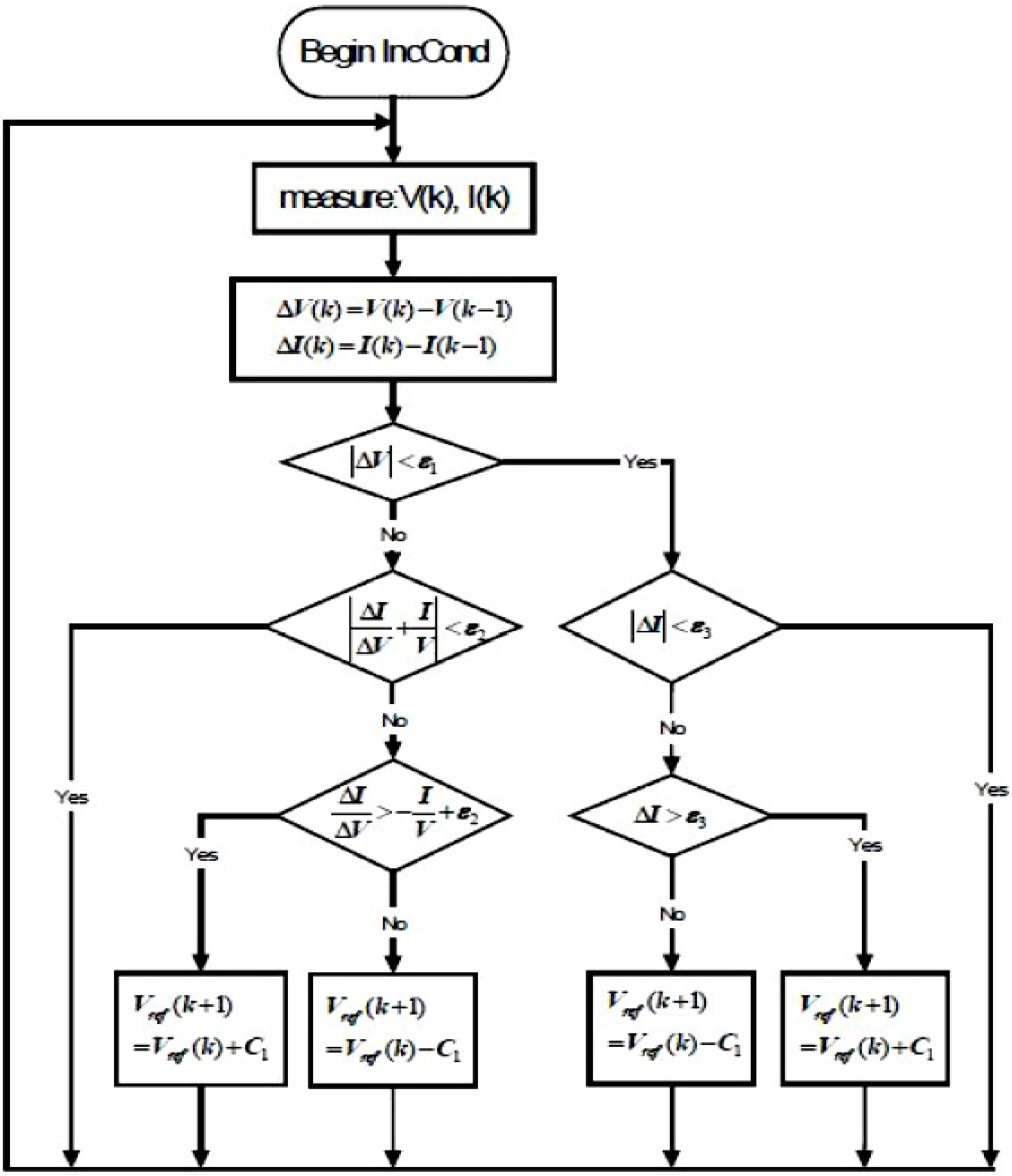


Figure: Incremental conductance algorithm flow chart

One of the advantages of the IncCond algorithm is that it does not oscillate around the MPP. The check of condition dl = O allows it to bypass the perturbation step and therefore maintain a constant operating voltage V once the MPP is found. Furthermore, condition dl > 0 make it possible to determine the relative location of the MPP. This leads to the advantage that an initial adjustment in the wrong direction, as with the “trial and error”

P&O method, does not occur. A fast and correct system response to changing operating conditions should be the result yielding high system efficiency. A small marginal error could be added to the maximum power condition. The value of error was determined with consideration of the tradeoff between the problem of not operating exactly at the MPP and the possibility of oscillating around it. It will also depend on the chosen perturbation step size Cl.

4. Enumerate the importance of MPPT in the operation of a photovoltaic system. (M.E-APR/MAY2013)

Need of Maximum Power Point Tracking for PV systems

The environmental condition under which a solar power system operates can be wide, as shown in I-V curves in Figure l. The current-voltage relation of a solar array is variable throughout the day, as it varies with environmental conditions such as irradiance and temperature. In terrestrial applications, Low Irradiance, Low Temperature (LILT) condition reflects morning condition where the sun just rises. A High Irradiance, High Temperature (HIHT) condition might represent a condition near high noon in a humid area. High Irradiance, Low Temperature (HILT) condition can represent a condition with healthy sunlight in the winter. Finally, condition near sunset can be described by Low Irradiance, High Temperature (LIHT) condition. For space application, LILT characterizes a deep space mission or aphelion period, While HIHT condition is when satellite orbits near the sun (perihelion).

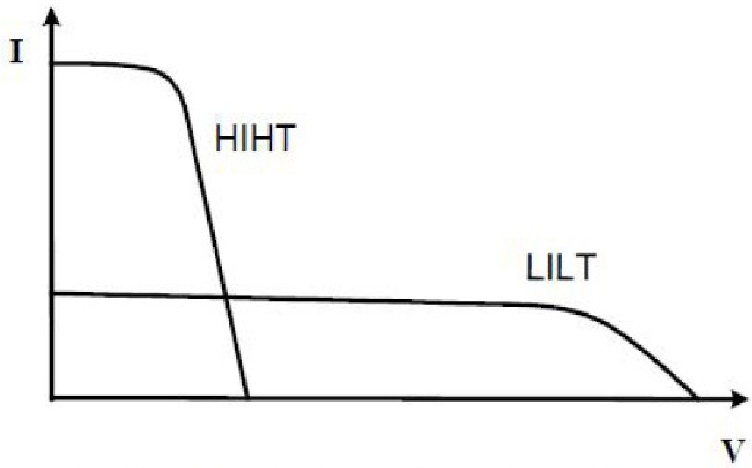


Figure 1: I-V characteristics under wide operating conditions

For a uniformly illuminated array, there is only one single point of operation that will extract maximum power from the array. In a battery charging system where the load seen by the solar modules is a battery connected directly across the solar array terminals, the operating point is determined by the battery's potential. This operating point is typically not the ideal operating voltage at which the modules are able to produce their maximum available power. In the direct coupled method, in which the solar array output power is delivered directly to the loads, as shown in Figure 2. To match the MPPs of the solar array as closely as possible, it is important to choose the solar array I-V characteristic according to the I-V characteristics of the load. A general approach for the power feedback control is to measure and maximize the power at the load terminal, and it assumes that the solar array maximum power is equal to the maximum load power. However, this maximizes the power to the load not the power from the solar array. The direct-coupled method cannot automatically track the MPPs of the solar array when the insolation or temperature changes. The load parameters or solar array parameters must be carefully selected for the direct coupled method.

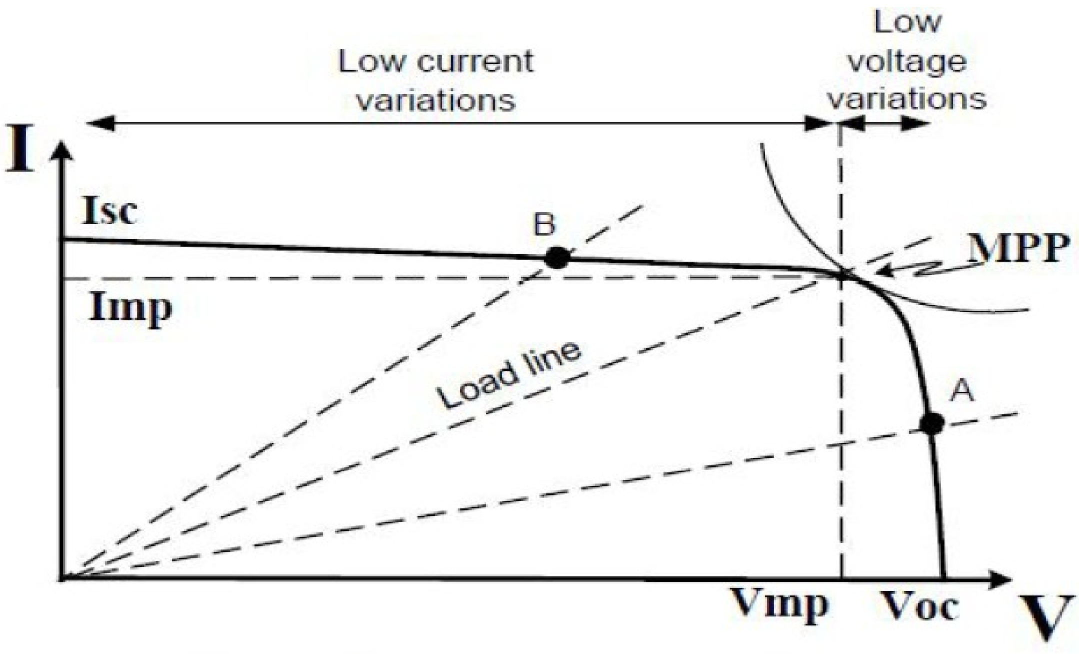


Figure 2: Direct coupled method

To be able to extract the maximum power from the solar array and to track the changes due to environment, therefore, a maximum power point tracking should be implemented. Devices that perform the desired function are known as Maximum Power Point Trackers, also called MPPTs or trackers.

5. Explain the need of hybrid systems for the renewable energy power generation. (M.E-NOV/DEC2010)

- Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand.
- Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply.
- The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people.
- Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance.
- Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area.
- Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.

6. Enumerate the importance of MPPT in the operation of a wind energy conversion system.

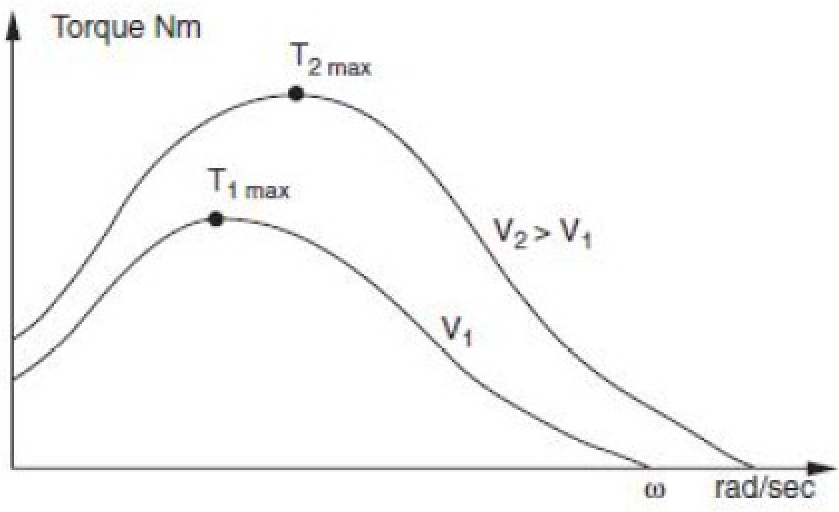
Need of MPPT for Wind Energy Conversion Systems:

The typical turbine torque vs. rotor speed is plotted in Figure below. It shows a small torque at Zero speed, rising to a maximum value before falling to nearly Zero when the rotor just floats with the wind. Two such curves are plotted for different wind speeds V1 and V2, with V; being higher than V1. The corresponding power vs. rotor speed at the two wind speeds are plotted in Figure. As the mechanical power convened into the electric power is given by the product of the torque T and the angular speed, the power is zero at zero speed and again at high speed with zero torque. The maximum power is generated at a rotor speed somewhere in between, as marked by P1max and P2max for speeds V1 and V2, respectively. The speed at the maximum power is not the same speed at which the torque is maximum. The operating strategy of a well-designed wind power system is to match the rotor speed to generate power continuously close to the Pmax points. Because the Pm“ point changes

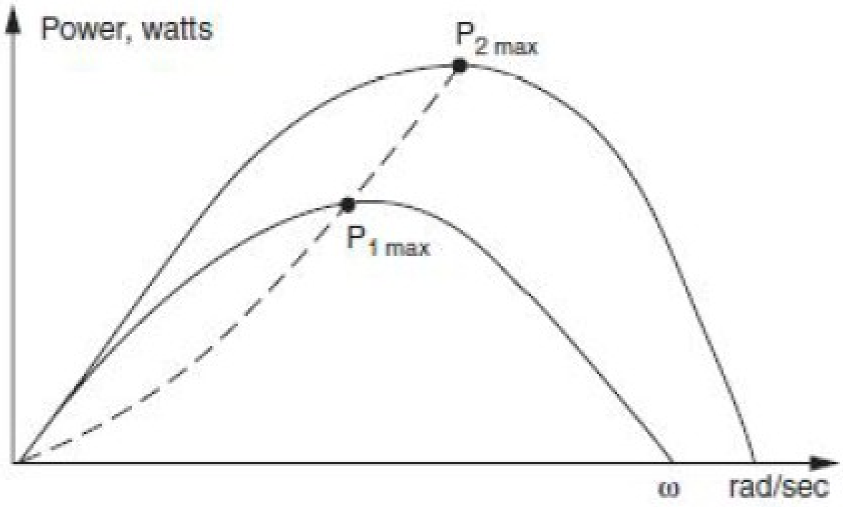
with the wind speed, the rotor speed must, therefore, be adjusted in accordance with the wind speed to force the rotor to work continuously at Pm". This can be done with a variable-speed system design and operation.
At a given site, the wind speed varies over a wide range from zero to high gust. We define tip speed ratio (TSR) as follows:

$$TSR = \frac{\text{Linear speed of the blade's outermost tip}}{\text{Free upstream wind velocity}} = \frac{\omega R}{V}$$

For a given wind speed, the rotor efficiency Cp varies with TSR. The maximum value of Cp occurs approximately at the same wind speed that gives peak power in the power distribution curve. To capture high power at high wind, the rotor must also turn at high speed, keeping TSR constant at the optimum level.



Wind turbine torque vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

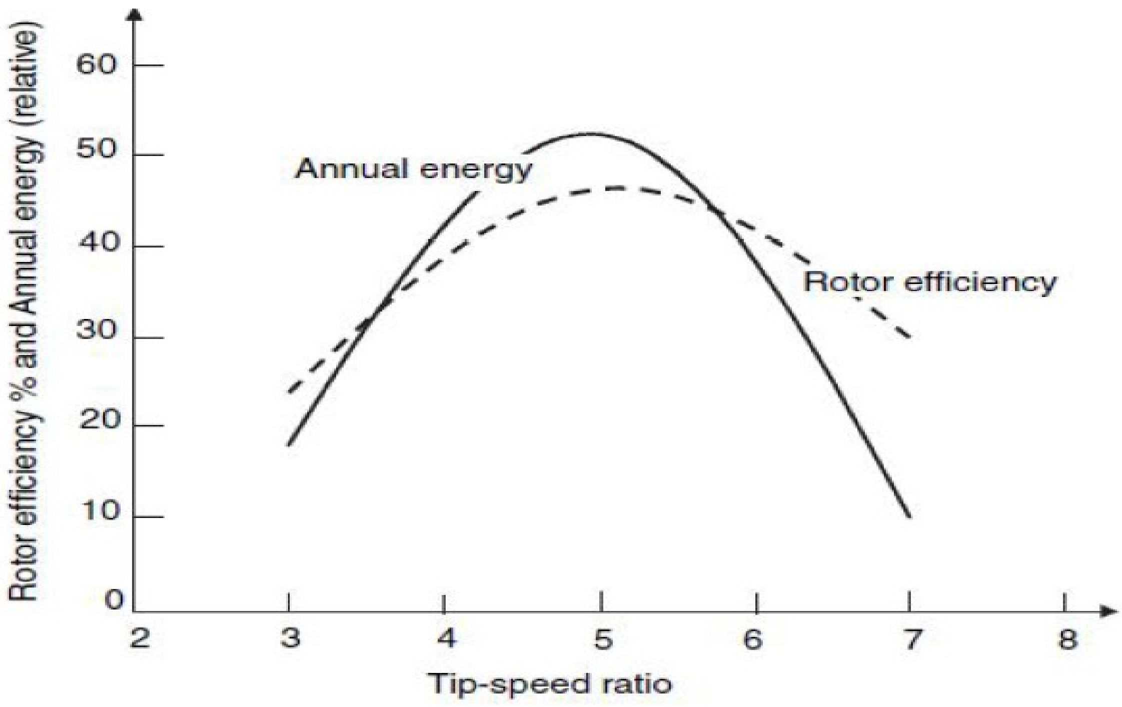


Wind turbine power vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

However, the following three system performance attributes are related to TSR:

1. The maximum rotor efficiency Cp is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine.
2. The centrifugal mechanical stress in the blade material is proportional to the TSR. The machine working at a higher TSR is necessarily stressed more. Therefore, if designed for the same power in the same wind speed, the machine operating at a higher TSR would have slimmer rotor blades.
3. The ability of a wind turbine to start under load is inversely proportional to the design TSR. As this ratio increases, the starting torque produced by the blade decreases.

A variable-speed control is needed to maintain a constant TSR to keep the rotor efficiency at its maximum. At the optimum TSR, the blades are oriented to maximize the lift and minimize the drag on the rotor. The turbine selected for a constant TSR operation allows the rotational speed of both the rotor and generator to vary up to 60% by varying the pitch of the blades



Rotor efficiency and annual energy production vs. rotor TSR.

7. Draw the basic structure of MPPT and explain the components in it.

To be able to extract the maximum power from the solar array and to track the changes due to environment, therefore, a maximum power point tracking should be implemented. Devices that perform the desired function are known as Maximum Power Point Trackers, also called MPPTs or trackers. A tracker consists of two basic components, as shown in Figure : a switch-mode converter and a control with tracking capability. The switch-mode converter is the core of the entire supply. The converter allows energy at one potential to be drawn, stores as magnetic energy in an inductor, and then releases at a different potential. By setting up the switch-mode section in various topologies, either high-to-low (buck converter) or low-to-high (boost) voltage converters can be constructed. The goal of a switch-mode power supply is to provide a constant output voltage or current. In power trackers, the goal is to provide a fixed input voltage and/or current, such that the array is held at the maximum power point, while allowing the output to match the load voltage.

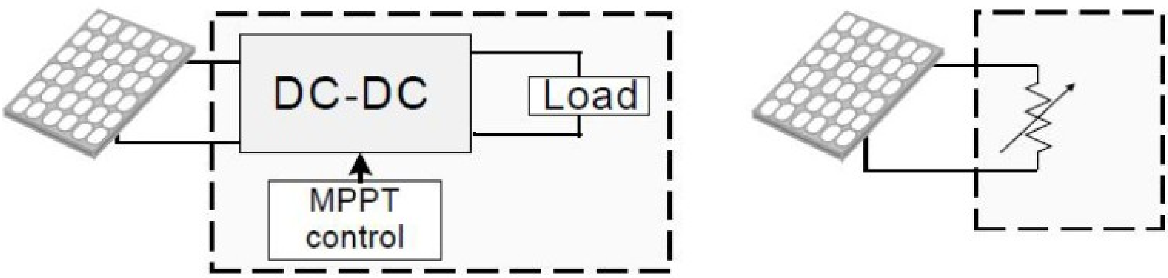


Figure . Basic components of a maximum power pointer tracker

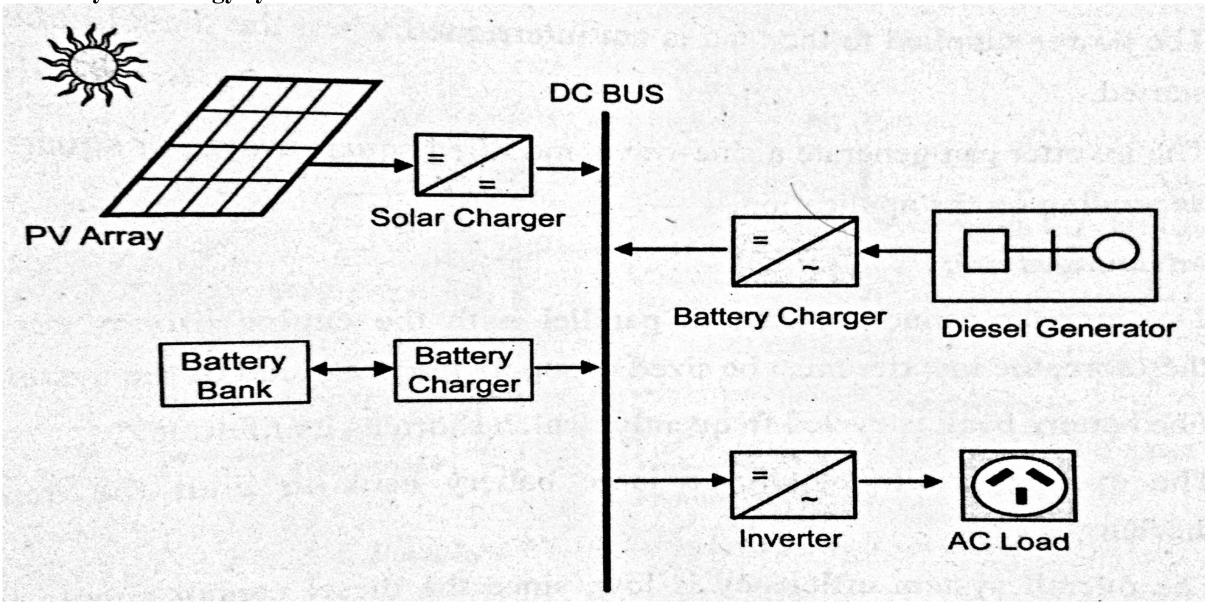
When properly applied, a maximum power point tracking control can prevent the collapse of the array voltage under excessive load demand, particularly when supplying a constant-power type of load. One of the proper approaches is to operate the system in a solar array voltage regulation mode where the array voltage is clamped to a commanding set point, Vmp, which is dynamically updated by the MPPT control circuit. The control processes feedback signals, such as the array current and voltage, to determine a proper direction to move the operating point. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. By adjusting the operating point of the array to the point Vmp, power output of the array is maximized, and the most efficient use of the solar array may be realized.

8. Explain in detail about the types of PV-Diesel Hybrid System.

TYPES OF PV-DIESEL HYBRID SYSTEMS

Series hybrid energy systems
Switched hybrid energy systems
Parallel hybrid energy systems

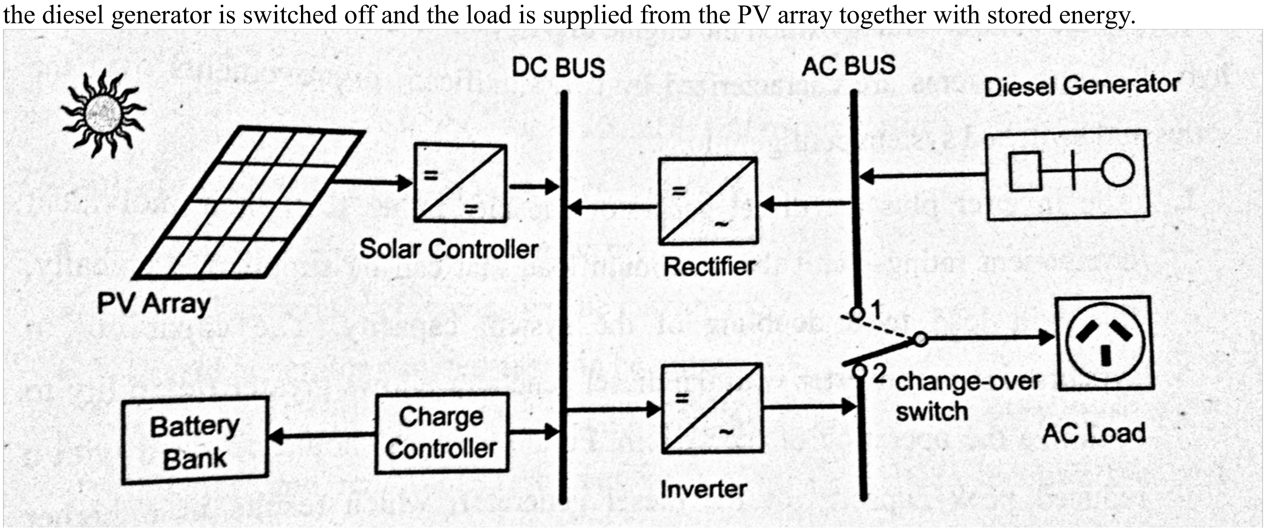
Series hybrid energy systems



The above figure shows a series PV-diesel hybrid system. to ensure reliable operation of series hybrid energy systems, both the diesel generator and inverter have to be sized to meet peak loads. AC power delivered to the load is converted from dc to regulated ac by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to ac before being supplied to the load, which leads to significant conversion losses. The solar controller prevents overcharging of the battery bank from PV generator when PV power exceeds the load demand and batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of engine-driven generator.

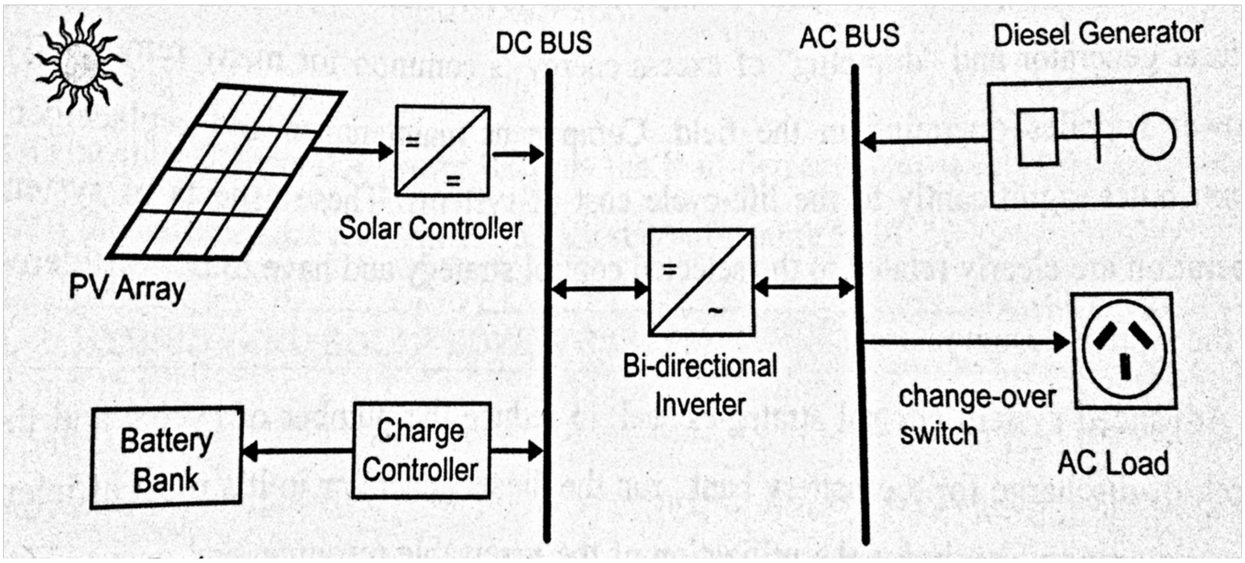
Switched hybrid energy systems

It allows operation with either engine driven generator or the inverter as the ac source, yet no parallel operation of the main generation sources is possible. The diesel generator and renewable energy source can charge the battery bank. The main advantage is that the load can be supplied directly by the engine driven generator, which results in a high overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy.



Parallel hybrid energy systems

The another configuration called parallel one allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronizing the inverter with alternator output waveform. Such a configuration is represented in the below figure. The bidirectional inverter can charge the battery bank when excess energy is available from engine driven generator, as well as a DC-AC converter. The bidirectional inverter may provide peak saving as part of control strategy when engine driven generator is overloaded.



DC BUS
AC BUS
Diesel Generator
Solar Controller
PV Array
Bi-directional
Inverter
change-over
switch
AC Load
Battery
Bank
Charge
Controller