PSN COLLEGE OF ENGINEERING AND TECHNOLOGY

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UNIT-1 INTRODUCTION TO HYBRID ENERGY SYSTEMS
Part A

1. **What is meant by Hybrid energy system?**
Hybrid power systems are those that generate electricity from
two or more sources, usually renewable, sharing a single connection point.
2. **List some of the types of Hybrid energy system.**
• Hybrid wind-solar system
• Hybrid diesel-wind system
• Hybrid wind-hydropower system
• Hybrid fuel cell-solar system
• Hybrid solar-thermal system
3. **Predict the strengths in using a Hybrid energy system.**
   - Hybrid systems can reduce reliance on fossil fuels and increase the share of renewable energy resources, including intermittent ones, thus increasing the eco-efficiency of energy production and energy security.
   - Hybrid systems can reduce energy costs in the long run by offsetting fossil fuel use with renewable production.
4. **Interpret the challenges in using a Hybrid energy system.**
   - The multiple components required to form a hybrid system generally make them expensive to build.
   - These systems have limited scalability with the currently available technologies.
5. **Specify the need for Hybrid energy system?**
Hybrid energy system are preferred due to their high levels of efficiency, reliability and long term performance, these systems can also be used as an effective backup solution to the public grid in case of blackouts or weak grids, and for professional energy solutions, such as telecommunication stations or emergency rooms at hospitals.
6. **List the advantage and disadvantage of Tidal energy. Advantages:**
   - Reliable and predictable energy source ad available in abundance.
   - No liquid or solid pollution.

   Disadvantages:
   - Installation and maintenance are very costly.
   - They can also affect boat navigation.
   - Time lag 12 hours between high and low tides.
7. **Specify the function of Penstock in hydel power plant?**
The penstock is used to drain the water from the source to the hydro turbine in the powerhouse. This is the main part of the micro hydro as it converts the potential energy of the water
into kinetic energy.
8. **Mention the function of surge tank?**
The surge tank protects the penstock from bursting in case the turbine gates suddenly close due to electrical load being thrown off. When the turbine gates close, there is a sudden stopping of water at the lower end of the penstock which can burst the penstock. The surge tank absorbs these pressure swings (i.e. water surges) by increasing its water level.
9. **Articulate the purpose of impulse turbine? Give example.**
The force of the jet causes the turbine blades to rotate, transferring the energy to a shaft that drives the desired machinery. Impulse turbines are commonly used in hydropower plants and other applications where high-speed flows of water or steam are available, offering efficient and reliable power generation.
Example: .Pelton wheel, Turgo etc.
10. **Articulate the purpose of reaction turbine? Give example.**
If at the inlet of the turbine, the water possesses kinetic energy as well as pressure energy, the turbine is known as a reaction
turbine. Example: Francis and Kaplan turbine.
11. **What is biomass energy?**

Biomass can be defined as any organic material or waste that contains chemical building blocks like carbon, hydrogen, and other components that are vital to our modern energy and materials economy.

12. Recite the various process involved in the biomass energy conversion?

Biomass is converted to energy through various processes, including:

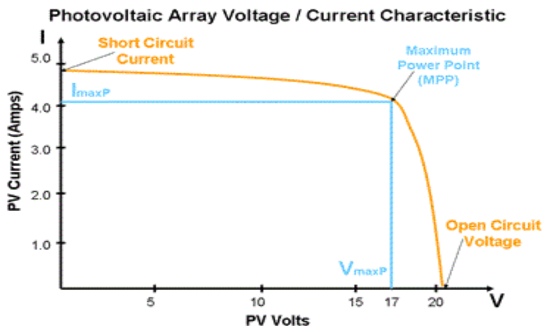
- Direct combustion (burning) to produce heat
- Thermochemical conversion to produce solid, gaseous, and liquid fuels
- Chemical conversion to produce liquid fuels
- Biological conversion to produce liquid and gaseous fuels

13. What is meant by biomass gasification?

The word gasification implies converting a solid or liquid into a gaseous fuel without leaving any solid carbonaceous residue.

14. Draw the VI characteristics of PV cell.

V-I Characteristics of a Photovoltaic Cell



15. Point out the materials used in solar cells.

Materials used in solar cells must possess a band gap close to
1.5 ev to optimize light absorption and electrical efficiency. Commonly used materials are-

1. Silicon.
2. GaAs.
3. CdTe.
4. $CuInSe_2$

Part B

1. Describe the importance of Hybrid energy system.

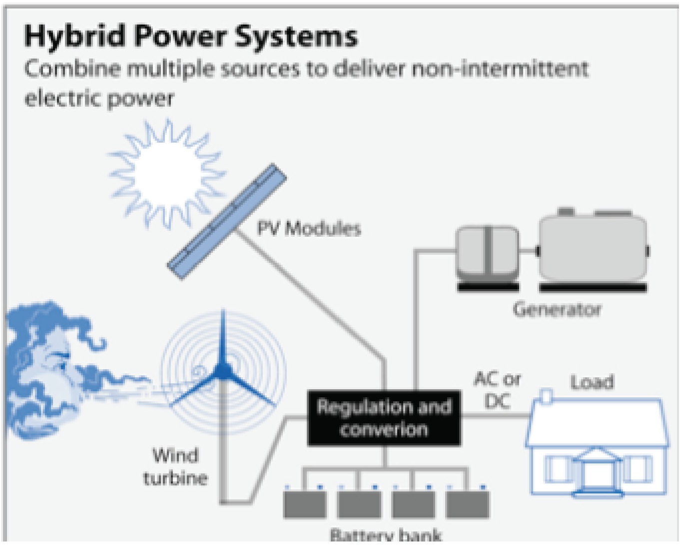
What is hybrid electrical power

Hybrid power systems are those that generate electricity from two or more sources, usually renewable, sharing a single connexion point. Although the addition of powers of hybrid generation modules are higher than evacuation capacity, inverted energy never can exceed this limit. In that way, a hybrid generation plant can, therefore, use, for example, photovoltaic energy when the sun shines and another source, such as wind, in cloudy weather, thus ensuring a more stable and efficient supply. Hybrid installation may or may not always include storage systems.

Types of hybrid electrical power

Leaving aside hybrid installations with diesel generators, the most common types of hybrid electrical power combinations are:

Photovoltaic + Wind.
Photovoltaic + Hydraulic.
Hydraulic + Wind.
Solar Thermal + Biomass.



How it works

Hybrid energy systems can capitalize on existing energy infrastructure and add components to help reduce costs, environmental impacts and system disruptions. Planning a hybrid electricity system has a market focus rather than a technology focus: the priority is to choose a mix of energy technologies that is the most efficient and reliable way to meet users' needs. Generally, at least one source of the fuel used to power a generator is renewable. Such a system is designed to increase the reliability (and thus usability) of renewable energy sources by providing redundant energy production from conventional sources or, more efficiently, by providing storage for electricity produced by intermittent sources.1 Computer applications automatically increase or reduce conventional generation or battery usage as needed to respond to fluctuations in production from the renewable resources to maximize the amount of renewable energy in the system.2 An important issue in renewable energy development has been the inability to rely on intermittent renewable sources, such as wind and solar, for base load power. It is not economical to ramp up or reduce production at large conventional base load power plants; so even if wind or solar plants are producing enough electricity to supply both peaking and some base load demand, it does not generally offset fossil fuel-based or nuclear base load energy generation. Small, agile hybrid energy systems are one way to allow energy production from intermittent renewable sources into the grid more reliably. To respond accordingly to peaks and dips in renewable energy production, hybrid systems are best implemented on a small scale because small generators are more flexible. These agile systems can, when possible, be interconnected into the central grid system and function as small power plants.

Opportunities in Asia and the Pacific

• Hybrid energy systems are particularly well suited for use in remote locations. Hybrid systems can serve standalone mini-grids, thus avoiding costly transmission costs. The increased capability of integrating renewable energy production into the electricity mix reduces the costs of transporting fuel to remote areas.

• Applicable for combined heat and power and district heating: As technology systems that can be used for distributed generation, isolated grids or on-site application, hybrid energy systems are generally well suited for combined heat and power production or district heating.

Strengths in using a hybrid system

• Hybrid systems can reduce reliance on fossil fuels and increase the share of renewable energy resources, including intermittent ones, thus increasing the eco-efficiency of energy production and energy security.

• Hybrid systems can reduce energy costs in the long run by offsetting fossil fuel use with renewable production.

• Setting up isolated grids can help provide modern energy access to remote areas and avoid the cost of expensive transmission and distribution lines from the central grid. Particularly in poor areas using diesel gensets, for which fuel price fluctuations can mean no electricity for a period of time, hybrid systems can help provide more reliable modern energy access.

Challenges to using a hybrid energy system

Financial

• The multiple components required to form a hybrid system generally make them expensive to build.

Technical

• There is no single optimal hybrid energy system configuration. Rather, optimizing is based on the availability of renewable and non-renewable resources, on site-specific energy infrastructure, production costs and incentive policies. Planning a hybrid system thus necessitates an adequate study period for each proposed project site.Because many hybrid systems rely on the flexibility of small conventional power production facilities that can be dispatched as needed and/or on small storage devices to deal with intermittent renewable energy sources, these systems have limited scalability with the currently available technologies.

• Not all energy production and storage technologies that are potential hybrid system components are fully developed. It is risky to invest in long-term, expensive infrastructure that may improve significantly in the medium term.

• Implementing hybrid energy systems can create market opportunities for the deployment of energy technologies that are not yet mature.5 If a particular technology, such as a new type of fuel cell, is not yet efficient or reliable enough to produce electricity in a stand-alone system, it may fit well as an additional component to a hybrid system in which other components can cover possible bumps in the production process.

Institutional

• Transmission interests and large electric utility interests may rely on political clout or financial assets to try to limit the expansion of hybrid energy systems development because they encourage more decentralized energy production.

2. Compose the necessity of Hybrid energy system.

Need for Hybrid System

Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. A hybrid energy system, or hybrid power, usually consists of two or more renewable energy sources used together to provide increased system efficiency as well as greater balance in energy supply.

A combination of different but complementary energy generation systems based on renewable energies or mixed, is known as a hybrid power system. It describe any power system combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either.

Hybrid systems capture the best features of each energy resource and can provide “grid-quality” electricity, with a power range between 1 kilowatt (kW) to several hundred kilowatts. They can be developed as new integrated designs within small electricity distribution systems (mini-grids) and can also be retrofitted in diesel based power systems.

Hybrid systems can provide a steady community-level electricity service, such as village electrification, offering also the possibility to be upgraded through grid connection in the future. Furthermore, due to their high levels of efficiency, reliability and long term performance, these systems can also be used as an effective backup solution to the public grid in case of blackouts or weak grids, and for professional energy solutions, such as telecommunication stations or emergency rooms at hospitals.

Many hybrid systems are stand-alone systems, which operate “off-grid” — not connected to an electricity distribution system. For the times when neither the wind nor the solar system are producing, most hybrid systems provide power through batteries and/or an engine generator powered by conventional fuels, such as diesel. If the batteries run low, the engine generator can provide power and recharge the batteries.

Adding an engine generator makes the system more complex, but modern electronic controllers can operate these systems automatically. An engine generator can also reduce the size of the other components needed for the system. Keep in mind that the storage capacity must be large enough to supply electrical needs during non-charging periods. Battery banks are typically sized to supply the electric load for one to three days.

3. Examine the impacts of renewable energy generation on the environment.Environmental Impacts of Renewable Energy Technologies

All energy sources have some impact on our environment. Fossil fuels—coal, oil, and natural gas—do substantially more harm than renewable energy sources by most measures, including air and water pollution, damage to public health, wildlife and habitat loss, water use, land use, and global warming emissions.

However, renewable sources such as wind, solar, geothermal, biomass, and hydropower *also* have environmental impacts, some of which are significant.

The exact type and intensity of environmental impacts varies depending on the specific technology used, the geographic location, and a number of other factors. 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.

Environmental Impacts of Wind Power

Wind power generates electricity without toxic pollution or global warming emissions, but it does have some environmental impacts that should be recognized and mitigated.

Wind power

Harnessing power from the wind is one of the cleanest and most sustainable ways to generate electricity as it produces no toxic pollution or global warming emissions. Wind is also abundant, inexhaustible, and affordable, which makes it a viable and large-scale alternative to fossil fuels.

Despite its vast potential, there are a variety of environmental impacts associated with wind power generation that should be recognized and mitigated. They include land use issues and challenges to wildlife and habitat.

Environmental Impacts of Solar Power

The potential environmental impacts associated with solar power depend on the technology, which includes two broad categories: photovoltaic solar cells and concentrating solar thermal plants.

Like wind power, the sun provides a tremendous resource for generating clean and sustainable electricity.

The environmental impacts associated with solar power can include land use and habitat loss, water use, and the use of hazardous materials in manufacturing, though the types of impacts vary greatly depending on the scale of the system and the technology used—photovoltaic (PV) solar cells or concentrating solar thermal plants (CSP).

Environmental Impacts of Geothermal Energy

The environmental impacts of geothermal energy vary depending on the technology used to generate electricity and the type of cooling system utilized.

The most widely developed type of geothermal power plant (known as hydrothermal plants) are located near geologic “hot spots” where hot molten rock is close to the earth’s crust and produces hot water.

In other regions enhanced geothermal systems (or hot dry rock geothermal), which involve drilling into the earth’s surface to reach deeper geothermal resources, can allow broader access to geothermal energy.

Geothermal plants also differ in terms of the technology they use to convert the resource to electricity (direct steam, flash, or binary) and the type of cooling technology they use (water-cooled and air-cooled). Environmental impacts differ depending on the conversion and cooling technology used.

Biomass Resources in the United States

This analysis details the biomass resources that could be sustainably produced and utilized in the United States for energy and fuel, focusing on energy crops, agricultural residues, waste materials, and forest biomass.

Biomass for electricity

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. However, the feedstock of biomass plants can be sustainable produced, while fossil fuels are non-renewable.

Sources of biomass resources for producing electricity are diverse, ranging from energy crops (like switchgrass), to agricultural waste, manure, forest products and waste, and urban waste. Both the type of feedstock and the manner in which it is developed and harvested significantly affect land use and life-cycle global warming emissions impacts of producing power from biomass.

Environmental Impacts of Hydroelectric Power

Hydroelectric power includes both massive hydroelectric dams and small run-of-the-river plants, both of which have associated environmental impacts.

Hydroelectric power includes both massive hydroelectric dams and small run-of-the-river plants. Large-scale hydroelectric dams continue to be built in many parts of the world (including China and Brazil), but it is unlikely that new facilities will be added to the existing US fleet in the future.

Instead, the future of hydroelectric power in the United States will likely involve increased capacity at current dams and new run-of-the-river projects. There are environmental impacts at both types of plants.

Environmental Impacts of Hydrokinetic Energy

Hydrokinetic energy includes wave and tidal power and encompasses an array of energy technologies, many of which are still in the experimental stages or in the early stages of deployment.

Hydrokinetic energy, which includes wave and tidal power, encompasses an array of energy technologies, many of which still in the experimental stages or in the early stages of deployment. While actual impacts of large-scale operations have not been observed, a range of potential impacts can be projected.

Despite these environmental impacts, renewable energy technologies compare extremely favourably to fossil fuels, and remain a core part of the solution to climate change.

4. Summarize about the various environmental impacts of renewable energy sources.

Solar Energy

Positive Impacts:

- Scalability from small residential installations to large solar farms.
- Reduction in electricity bills and energy independence for users.

Negative Impacts:

- Use of hazardous materials like cadmium and lead in some types of solar panels.
- Large-scale solar farms can cause heat island effects in desert areas.
- Potential impacts on water resources in the manufacturing process.

Wind Energy

Positive Impacts:

- Can be placed offshore to minimize land use impacts.
- Wind farms can coexist with agricultural land.

Negative Impacts:

- Interference with radar and telecommunications.
- Visual impact on landscapes, which can affect tourism and property values.
- Potential for local climate effects, such as changes in temperature and humidity patterns around large wind farms.

Hydro Energy

Positive Impacts:

- Provides flood control and water supply benefits.
- Enables pumped-storage hydropower, which aids in energy storage and grid stability.

Negative Impacts:

- Displacement of local communities due to dam construction.
- Sediment trapping in reservoirs, affecting downstream ecosystems.
- Risk of dam failures, leading to catastrophic flooding.

Geothermal Energy

Positive Impacts:
- Provides a constant and reliable power source unaffected by weather conditions.
- Small land footprint for geothermal plants compared to other renewable sources.

Negative Impacts:
- Potential for induced seismicity (earthquakes) from geothermal drilling.
- Corrosion and scaling in geothermal power plants, leading to disposal challenges of mineral-laden brines.
- Limited to regions with suitable geothermal resources.

Biomass Energy

Positive Impacts:
- Utilizes a wide range of organic materials, including agricultural residues, wood waste, and dedicated energy crops.
- Can be used for producing biofuels, reducing dependence on fossil fuels in transportation.

Negative Impacts:
- High water consumption for growing biomass crops.
- Potential for soil erosion and nutrient depletion from intensive biomass harvesting.
- Monoculture plantations can reduce biodiversity and ecosystem resilience.

General Considerations

- **Energy Return on Energy Invested (EROEI):** The efficiency of energy production varies across renewable sources, with some requiring significant energy inputs for infrastructure.
- **Cumulative Impacts:** The combined effect of multiple renewable energy installations in an area can lead to greater environmental impacts, such as habitat fragmentation.
- **Decommissioning and Recycling:** Proper disposal and recycling of renewable energy infrastructure (e.g., wind turbine blades, solar panels) are essential to reduce long-term environmental impacts.
- **Integrated Planning:** Coordinated planning across energy, land use, and conservation sectors can mitigate the adverse effects and enhance the positive impacts of renewable energy deployment.

while renewable energy sources offer significant environmental benefits over fossil fuels, careful consideration and management of their potential negative impacts are crucial for ensuring a sustainable and environmentally friendly energy future.

5. Analyze with neat sketch about the Ocean Thermal Energy Conversion (OTEC).

Ocean energy:

Wave energy:

What is Wave Energy?

Wave energy is a form of renewable energy that can be harnessed from the motion of the waves. There are several methods of harnessing wave energy that involve placing electricity generators on the surface of the ocean.

How Does Wave Energy Work?

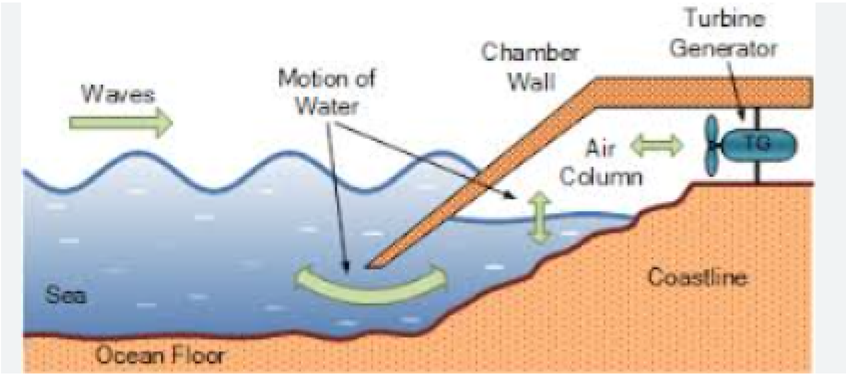
Did you know that waves are actually caused by tides, which vary depending on the lunar cycles? That's right – you can blame the moon for those days of rough surf on the beach.

Depending on the lunar cycles, tides, winds, and weather, waves can vary in size and strength. As waves roll through the ocean, they create kinetic energy, or movement. This movement can be used to power turbines, which, in turn, create energy that can be converted into electricity and power. There are also several ways of harnessing wave energy that utilize the up and down motion of the waves to power pistons/turn generators.

What Makes Wave Energy a Renewable Energy Source?

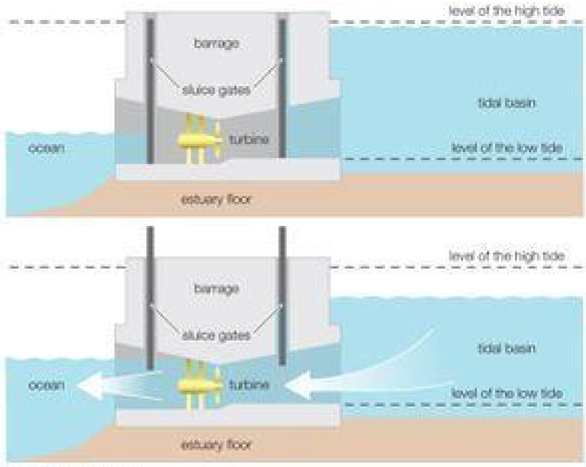
Similar to solar, wind, and geothermal energy, wave energy is a renewable source. As long as the Earth continues to track around the sun, and the moon around the Earth, waves will continue to be a viable source of kinetic energy. Wave energy also produces fewer carbon emissions than energy from traditional fossil fuels, such as coal or oil, making it a more **eco-friendly option.**

What's the Catch with Wave Energy?
One of the bigger roadblocks to wave energy is that most wave energy systems are fairly small, and aren't suitable for powering large buildings or structures.
Another problem with wave energy is that, similar to solar or wind power, the amount of energy that can be harnessed is contingent upon the size of the waves at any given time. Variable factors that go into wave energy include the wave height, wave speed, wavelength, and wave density – all of which can be unpredictable.
As technologies develop, scientists and experts are looking at ways to harness more power from waves and the ocean.



Tidal energy:

Tidal power, any form of renewable energy in which tidal action in the oceans is converted to electric power.



There are a number of ways in which tidal power can be harnessed. Tidal barrage power systems take advantage of differences between high tides and low tides by using a "barrage," or type of dam, to block receding water during ebb periods. At low tide, water behind the barrage is released, and the water passes through a turbine that generates electricity.
Tidal stream power systems take advantage of ocean currents to drive turbines, particularly in areas around islands or coasts where these currents are fast. They can be installed as tidal fences—where turbines are stretched across a channel—or as tidal turbines, which resemble underwater wind turbines (*see* wind power). (*See also* wave power.)

Electricity generation potential

Many tidal power technologies are not available at an industrial scale, and thus tidal energy contributes a negligible fraction of global energy today. There is, however, a large potential for its use, because much usable energy is contained in water currents. The total energy contained in tides worldwide is 3,000 gigawatts (GW; billion watts), though estimates of how much of that energy is available for power generation by tidal barrages are between 120 and 400 GW, depending on the location and the potential for conversion. By comparison, a typical new coal-based generating plant produces about 550 megawatts (MW; million watts). Although total global electricity consumption approached 21,000 terawatt-hours in 2016 (one terawatt [TW] = one trillion watts), energy experts speculate that fully built-out tidal power systems could supply much of this demand in the future. Estimates of tidal stream power—which uses ocean currents to drive underwater blades in a manner similar to wind power generation—in shallow water is capable of generating some 3,800 terawatt-hours per year.

Environmental concerns raised about tidal power stations are largely focused on the tidal barrage systems, which can disrupt estuarine ecosystems during their construction and operation. Tidal fences and turbines are expected to have minimal impact on ocean ecosystems. Tidal fences do have the potential to injure or kill migratory fish, however, but these structures can be designed to minimize such effects.

Ocean thermal energy conversion

OTEC is a way of getting useful energy from the world's oceans. The sun shines on the oceans of the world and in the hot parts near the water at the sea's surface can be quite warm, sometimes as high as 30°C.

Many oceans are very deep and the water at depths of 1,000 meters can be around 5 °C.

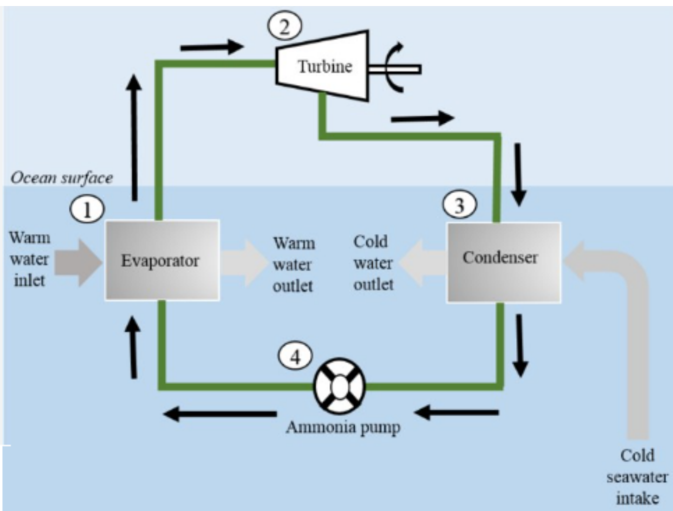
If a pipe is put down into the ocean we can bring the cold water to the surface where we also have warm water available.

The difference in temperature between the warm surface water and the cold deep water may only be around 15 °C. But we can build a machine called a heat engine, which can use this difference to generate power that can be used by people that live in that place. A machine which can do this is called an OTEC machine which stands for *ocean thermal energy conversion*.

Because the difference in temperature is small we will need to get large quantities of warm and cold water to go through the machine to get a useful amount of work, but large quantities are available in the ocean.

It has been estimated that OTEC could give amounts of energy that are 10 to 100 times greater than the other ocean energy source, wave power.

OTEC can also supply quantities of cold water as a by-product. This can be used for refrigeration and can help crops and fish grow. OTEC can also produce large amounts of salt-free water, which can be useful on mid-ocean islands as drinking water.



6. Discuss the various methods of production of hydrogen for use as an energy carrier. What are the various methods of hydrogen storage?

Hydrogen Energy:

Hydrogen is a clean fuel. It is an energy carrier that can be used for a broad range of applications. Also it could serve as a possible substitute to liquid and fossil fuels.Its physical properties could be stated as following. At standard temperature and pressure, hydrogen is a nontoxic, nonmetallic, odorless, tasteless, colorless, and highly combustible diatomic gas with the molecular formula H_2.

Occurrence and storage

Speaking of its natural occurrence, it is the most abundant element in the universe. The sun and other stars are composed largely of hydrogen. Astronomers estimate that 90% of the atoms in the universe are hydrogen atoms. Hydrogen is a component of more compounds than any other element. Water is the most abundant compound of hydrogen found on earth.

Molecular hydrogen is not available on Earth in convenient natural reservoirs. Most hydrogen on Earth is bonded to oxygen in water and to carbon in live or dead and/or fossilized biomass. It can be created by splitting water into hydrogen and oxygen. Water is again formed, when hydrogen is used.

On the other hand, its preparation could be done by breaking the chemical bonds from compounds. A few common methods include electrolysis, from steam and hydro carbon or carbon, reaction of metals with acids, ionic metal hydrides with water, etc. Currently, global hydrogen production is 48% from natural gas, 30% from oil, and 18% from coal; water electrolysis accounts for only 4%.

Its storage is important because it has wide range of applications. They range from stationary power, portable power to transportation, etc. Also it has the highest energy per mass of any fuel. However, its low ambient temperature density results in a low energy per unit volume, therefore requiring the development of advanced storage methods that have potential for higher energy density.

Hydrogen can be stored physically as either a gas or a liquid. Storage of hydrogen as a gas typically requires high-pressure tanks (350–700 bar [5,000–10,000 psi] tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

Hydrogen as a fuel

Hydrogen is considered an alternative fuel. It is due to its ability to power fuel cells in zero-emission electric vehicles, its potential for domestic production, and the fuel cell's potential for high efficiency. In fact, a fuel cell coupled with an electric motor is two to three times more efficient than an internal combustion engine running on gasoline. Hydrogen can also serve as fuel for internal combustion engines. The energy in 2.2 pounds (1 kilogram) of hydrogen gas contains about the same as the energy in 1 gallon (6.2 pounds, 2.8 kilograms) of gasoline.

Hydrogen energy systems involve several key components and processes, including production, storage, transportation, and utilization. Here's an overview of each:

1. **Production**: Hydrogen can be produced through various methods:
    - **Electrolysis**: In this process, water (H2O) is split into hydrogen (H2) and oxygen (O2) using electricity. Renewable energy sources such as solar or wind power can be used to generate the electricity needed for electrolysis, making it a clean and sustainable method.
    - **Steam Methane Reforming (SMR)**: This is the most common method of industrial hydrogen production. It involves reacting methane (CH4), typically obtained from natural gas, with steam at high temperatures to produce hydrogen and carbon monoxide. The hydrogen is then separated and purified.
    - **Biomass Gasification**: Biomass, such as agricultural or forestry residues, can be converted into hydrogen-rich gas through a process called gasification. The gas can then be purified to extract hydrogen.
    - **Thermochemical Water Splitting**: High-temperature processes can be used to split water into hydrogen and oxygen without the need for electricity. These processes typically involve the use of heat from sources like concentrated solar energy or nuclear reactors.
2. **Storage**: Hydrogen is typically stored in one of three forms:
    - **Compressed Hydrogen**: Hydrogen gas is compressed and stored in high-pressure tanks.
    - **Liquid Hydrogen**: Hydrogen is cooled to very low temperatures (-253°C) to liquefy it, allowing for more compact storage.
    - **Hydrogen Chemical Storage**: Hydrogen can be chemically stored in materials such as metal hydrides or ammonia, which release hydrogen when needed.
3. **Transportation**: Once produced and stored, hydrogen needs to be transported to where it will be used. This can be done via pipelines, similar to natural gas transportation, or through trucks, ships, or railcars.

4. **Utilization**: Hydrogen can be used in various applications, including:
   - **Fuel Cells**: Hydrogen fuel cells combine hydrogen with oxygen from the air to produce electricity, heat, and water. Fuel cells are used to power vehicles, provide backup power for buildings, and even generate electricity for grid applications.
   - **Combustion**: Hydrogen can be burned in internal combustion engines or gas turbines to produce mechanical power or electricity. The only byproduct of hydrogen combustion is water vapor, making it a clean fuel option.
   - **Industrial Processes**: Hydrogen is used in industries such as refining, chemical production, and food processing as a feedstock or reducing agent.

Potential Applications

- Production of electricity, heat and water for various end uses
- Industrial applications
- Vehicular transportation
- Residential applications
- Commercial applications, including in telecom towers for providing back-up power

7. What is ocean energy? Explain in detail the various forms of ocean energy with a neat sketch.

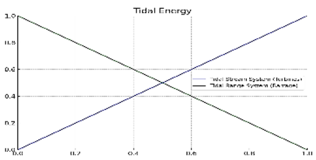
Ocean energy refers to the renewable energy harnessed from the ocean's various physical and chemical processes. This energy can be captured in several ways, utilizing the kinetic, thermal, and chemical properties of the ocean. Here are the main forms of ocean energy:

1. Tidal Energy

Tidal energy is generated by harnessing the energy from the rise and fall of sea levels caused by the gravitational forces of the moon and the sun.

Types of Tidal Energy:

- **Tidal Stream Systems:** Use underwater turbines placed in tidal streams or currents. These turbines capture the kinetic energy of moving water.
- **Tidal Range Systems:** Utilize the difference in height between high and low tides. Tidal barrages are built across estuaries or bays to capture the potential energy from the rising and falling water levels.



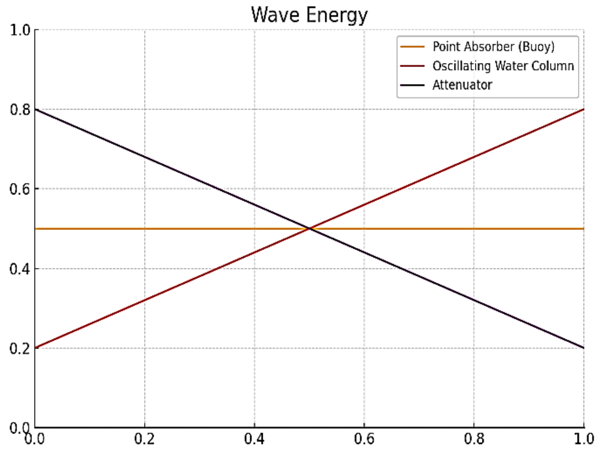
Tidal Energy

2. Wave Energy

Wave energy is captured from the surface motion of ocean waves, which are generated by wind passing over the surface of the sea.

Types of Wave Energy Converters:

- **Point Absorbers:** Float on the surface and move up and down with the waves, converting this motion into electricity.
- **Oscillating Water Columns:** Use the rise and fall of water within a column to drive air turbines.
- **Attenuators:** Long, multi-segment floating structures aligned perpendicular to the direction of the waves, flexing and converting wave energy into electricity.



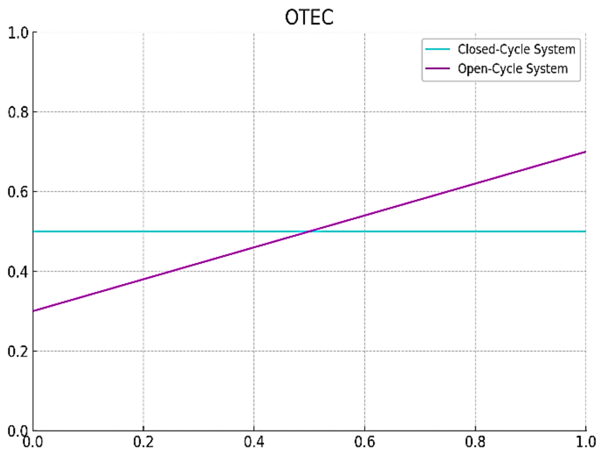
Wave Energy

3. Ocean Thermal Energy Conversion (OTEC)

OTEC exploits the temperature difference between the warm surface water and the colder deep water. This temperature gradient drives a heat engine to generate electricity.

Types of OTEC Systems:

- **Closed-Cycle Systems:** Use a working fluid with a low boiling point (e.g., ammonia) that vaporizes with warm surface water, drives a turbine, and is then condensed by cold deep water.
- **Open-Cycle Systems:** Use seawater directly. Warm surface water is evaporated in a low-pressure container, driving a turbine, and then condensed with cold deep water.



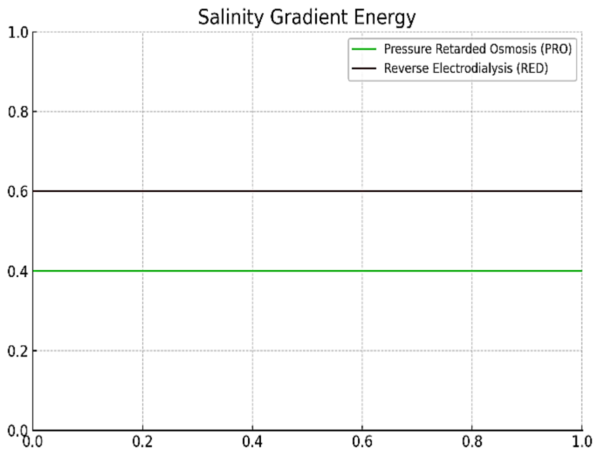
OTEC

4. Salinity Gradient Energy (Blue Energy)

Salinity gradient energy, also known as blue energy, harnesses the energy from the difference in salt concentration between seawater and freshwater, often at river mouths.

Types of Blue Energy Technologies:

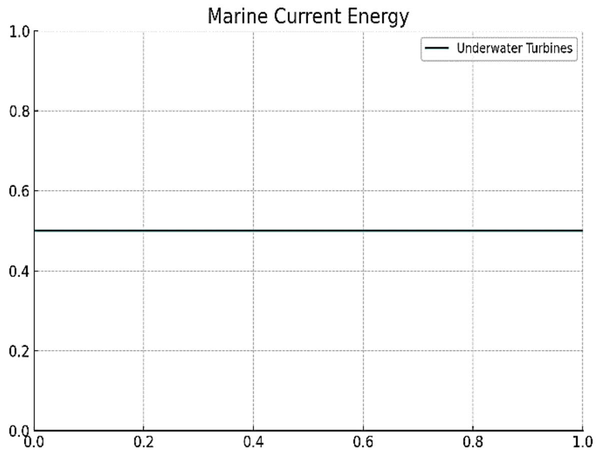
- **Pressure Retarded Osmosis (PRO):** Freshwater is drawn through a semi-permeable membrane into seawater, increasing pressure on the seawater side, which can then drive a turbine.
- **Reverse Electrodialysis (RED):** Uses selective ion exchange membranes to create a voltage from the movement of ions between freshwater and seawater.



Blue Energy:

5. Marine Current Energy

Marine current energy harnesses the kinetic energy of ocean currents, similar to tidal stream systems but from large-scale ocean currents like the Gulf Stream.



Marine Current Energy:

ocean energy encompasses a range of technologies that capture the power of the ocean's tides, waves, thermal gradients, salinity gradients, and currents. Each method offers unique advantages and challenges, contributing to the diversity of renewable energy solutions.

8. Summarize in detail about the Hydro electric energy system with a neat diagram.

Hydroelectric energy, or hydropower, is the process of generating electricity by harnessing the energy of flowing or falling water. This method is one of the oldest and most widely used forms of renewable energy.

Components of a Hydroelectric Energy System

1. **Dam:** A large structure built to block a river or stream, creating a reservoir or artificial lake. The dam increases the water level and controls the flow of water.
2. **Reservoir:** The stored water behind the dam. The potential energy of the stored water is converted to kinetic energy as it flows down.
3. **Penstock:** A large pipe or conduit that directs the water from the reservoir to the turbines. The penstock's steep angle allows water to flow with high pressure.
4. **Turbines:** The kinetic energy of flowing water spins the blades of the turbines. These turbines are connected to generators.
5. **Generator:** Converts the mechanical energy from the turbine into electrical energy using electromagnetic induction.
6. **Powerhouse:** The building that houses the turbines and generators.
7. **Outflow:** Water is released back into the river or stream after passing through the turbines, continuing the water cycle.

Working Principle

1. **Water Flow:** Water stored in the reservoir is released through the dam. The height difference between the reservoir and the turbines (head) determines the water pressure.
2. **Energy Conversion:** The high-pressure water flows through the penstock, driving the turbines. The turbines convert the water's kinetic energy into mechanical energy.
3. **Electricity Generation:** The turbines are connected to generators, which convert the mechanical energy into electrical energy.
4. **Transmission:** The generated electricity is transmitted via power lines to homes, businesses, and industries.

Types of Hydroelectric Power Plants

1. **Impoundment:** The most common type, using a dam to store water in a reservoir. Controlled water flow generates electricity.
2. **Diversion (Run-of-River):** Diverts a portion of the river's flow through a canal or penstock without a large reservoir, relying on the natural flow and elevation drop.
3. **Pumped Storage:** A type of hydroelectric power plant that stores energy by pumping water uphill to a reservoir during low demand periods and releasing it to generate electricity during high demand.

Advantages of Hydroelectric Energy

1. **Renewable:** Utilizes the natural water cycle and is constantly replenished.
2. **Clean:** No direct emissions of greenhouse gases or pollutants.
3. **Reliable:** Provides a consistent and stable power supply, especially suitable for base load electricity generation.
4. **Flexible:** Can quickly adjust to changes in electricity demand.

Disadvantages of Hydroelectric Energy

1. **Environmental Impact:** Dam construction can disrupt local ecosystems, fish migration, and sediment flow.
2. **High Initial Costs:** Building large dams and reservoirs require significant investment and long-term planning.
3. **Geographical Limitations:** Suitable sites for large-scale hydroelectric plants are limited to specific locations with sufficient water flow and elevation.
4. **Social Impact:** Can lead to displacement of local communities and changes in land use.

Diagram

Here's a neat diagram summarizing a hydroelectric energy system:

UNIT II: ELECTRICAL MACHINES FOR WIND ENERGY CONVERSION SYSTEMS (WECS)

Part A

1. **Define WECS.**

   A wind energy conversion system (WECS) is a complex system of interconnected components that operate together to convert the kinetic energy in the wind into mechanical energy and subsequently into electrical energy with the aid of generators.

2. **Classify the types of WECS.**
   - Rotational axis
   - Turbine
   - Power control
   - Rotational speed control

3. **State the principle of PMSG?**
   - A Permanent Magnet Synchronous Generator is a generator where the excitation field is provided by a permanent magnet instead of a coil.
   - The term synchronous refers to the fact that the rotor and magnetic field rotate with the same speed because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature synchronous generator.

4. **List out the advantages of PMSG.**

- ❖ Light weight and small size in construction.
- ❖ Low losses and high efficiency
- ❖ No need of external excitation current.
- ❖ No need of gearbox.

5. **List out the disadvantages of PMSG.**

- ❖ It is useful for small wind turbines, but for large wind turbines the size of the magnet has to be increased.
- ❖ Demagnetization of permanent magnet due to atmospheric conditions is a big problem.

6. **State the principle of SCIG?**

The SCIG is a self-excited induction generator where a three-phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load. When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings. This EMF is applied to the capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine.

7. **List out the advantages of SCIG.**

- Robustness
- Mechanical simplicity
- Low price
- Improves Quality of life
- Provides flexibility

8. **List out the disadvantages of SCIG.**

- It is bulky in construction
- Low efficiency
- Low reliability
- Need of maintenance
- Results in electrical and mechanical loss.

9. **State the principle of DFIG?**

The principle of the Doubly-Fed Induction Generator (referred to as DFIG) is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converters that control both the rotor and the grid currents. 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.

10. **Specify the function of crowbar?**

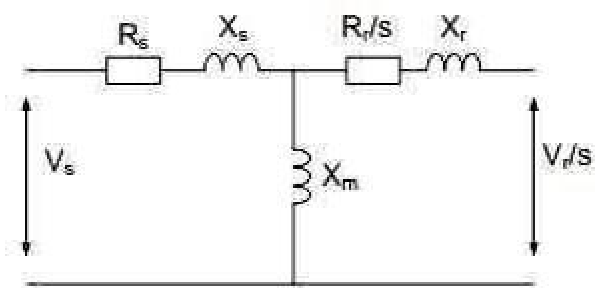
The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected.

11. **What are the control principle used in DFIG?**

The control principle used is either the

- Two-axis current vector control
- Direct torque control

12. **Draw the equivalent circuit of DFIG?**



The Equivalent Circuit of DFIG

13. **Write down the electromechanical torque (T_e) equation of**

DFIG?

$$T_e = \frac{3}{2}\frac{p}{2} Re\left(j\Psi_s I_s^*\right) = \frac{3}{2}\frac{p}{2} Re\left(j\Psi_r I_r^*\right) \qquad (3)$$

where

$$\Psi_s = \frac{X_s I_s + X_m I_r}{\omega_s};\ \Psi_r = \frac{X_r I_r + X_m I_s}{\omega_S}$$

Ψ_s and Ψ_r: the stator and the rotor flux, respectively.

p: the number of poles per phase.

I_s^*, I_r^*: the complex conjugates of the stator and the rotor current, respectively.

14. List out the advantages of DFIG.

- DFIG is a variable speed generator and therefore has the variable speed advantages compared to fixed speed generators.
- Only the rotor power needs to be converted.
- reduced losses and increased efficiency.

15. List out the disadvantages of DFIG.

- DFIG requires a speed increasing gearbox between the wind turbine and the generator whereas the PMSG can be constructed with a sufficient number of poles to allow direct drive.

Part B

2.1 INTRODUCTION TO ELECTRO-MECHANICAL ENERGY CONVERSION

Energy exists in many forms, and we use numerous devices on a daily basis that convert one form of energy into another. When we speak of electromechanical energy conversion, however, we mean either the conversion of electric energy into mechanical energy or vice versa. For example, an electric motor converts electric energy into mechanical energy. On the other hand, an electric generator transforms mechanical energy to electric energy. Electromechanical energy conversion is a reversible process except for the losses in the system. The term "reversible" implies that the energy can be transferred back and forth between the electrical and the mechanical systems. However, each time we go through an energy conversion process, some of the energy is converted into heat and is lost from the system forever.

When a current-carrying conductor is placed in a magnetic field, it experiences a force that tends to move it. If the conductor is free to move in the direction of the magnetic force, the magnetic field aids in the conversion of electric energy into mechanical energy. This is essentially the principle of operation of all electric motors. On the other hand, if an externally applied force makes the conductor move in a direction opposite to the magnetic force, the mechanical energy is converted into electric energy. Generator action is based upon this principle.

Introduction For energy conversion between electrical and mechanical forms, electromechanical devices are developed. In general, electromechanical energy conversion devices can be divided into three categories:

Transducers (for measurement and control): These devices transform the signals of different forms. Examples are microphones, pickups, and speakers.

Force producing devices (linear motion devices): These type of devices produce forces mostly for linear motion drives, such as relays, solenoids (linear actuators), and electromagnets.
Continuous energy conversion equipment: These devices operate in rotating mode. A device would be known as a generator if it converts mechanical energy into electrical energy, or as a motor if it does the other way around (from electrical to mechanical). Since the permeability of ferromagnetic materials is much larger than the permittivity of dielectric materials, it is more advantageous to use electromagnetic field as the medium for electromechanical energy conversion.

1. Propose the concept of Reference theory fundamentals in detail and describe the commonly used reference frames.

Transformation of three phase electrical quantities to two phase quantities is a usual practice to simplify analysis of three phase electrical circuits. Polyphase A.C machines can be represented by an equivalent two phase model provided the rotating polyphases winding in rotor and the stationary polyphase windings in stator can be expressed in a fictitious two axes coils. The process of replacing one set of variables to another related set of variable is called winding transformation or simply transformation or linear transformation. The term linear transformation means that the transformation from old to new set of variable and vice versa is governed by linear equations. The equations relating old variables and new variables are called transformation equation and the following general form:

[New Variable] = [Transformation matrix][Old variable]
[Old Variable] = [Transformation matrix][New variable]

Transformation matrix is a matrix containing the coefficients that relates new and old variables. Note that the second transformation matrix in the above-mentioned general form is inverse of first transformation matrix. The transformation matrix should account for power invariance in the two frames of reference. In case power invariance is not maintained, then torque calculation should be from original machine variables only.

INTRODUCTION TO REFERENCE FRAME THEORY

Overview

As the application of ac machines has continued to increase over this century, new techniques have been developed to aid in their analysis. Much of the analysis has been carried out for the treatment of the well-known induction machine. The significant breakthrough in the analysis of three-phase ac machines was the development of reference frame theory. Using these techniques, it is possible to transform the phase variable machine description to another reference frame. By judicious choice of the reference frame, it proves possible to simplify considerably the complexity of the mathematical machine model. While these techniques were initially developed for the analysis and simulation of ac machines, they are now invaluable tools in the digital control of such machines. As digital control techniques are extended to the control of the currents, torque and flux of such machines, the need for compact, accurate machine models is obvious.

Fortunately, the developed theory of reference frames is equally applicable to the synchronous machines, such as the Permanent Magnet Synchronous Machine (PMSM). This machine is sometimes known as the sinusoidal brushless machines or the brushless ac machine and is very popular as a high-performance servo drive due to its superior torque-to-weight ratio and its high dynamic capability. It is a three-phase synchronous ac machine with permanent-magnet rotor excitation and is designed to have a sinusoidal torque-position characteristic. The aim of this section is to introduce the essential concepts of reference frame theory and to introduce the space vector notation that is used to write compact mathematical descriptions of ac machines. Over the years, many different reference frames have been proposed for the analysis of ac machines. The most commonly used ones are the so-called stationary reference frame and the rotor reference frame.

2. Compute the Clark's transformation and Park's transformation.

Clarke's Transformation

The transformation of stationary circuits to a stationary reference frame was developed by E. Clarke. The stationary two-phase variables of Clarke's transformation are denoted as α and β. As shown in Figure 2.1, α-axis and β-axis are orthogonal.

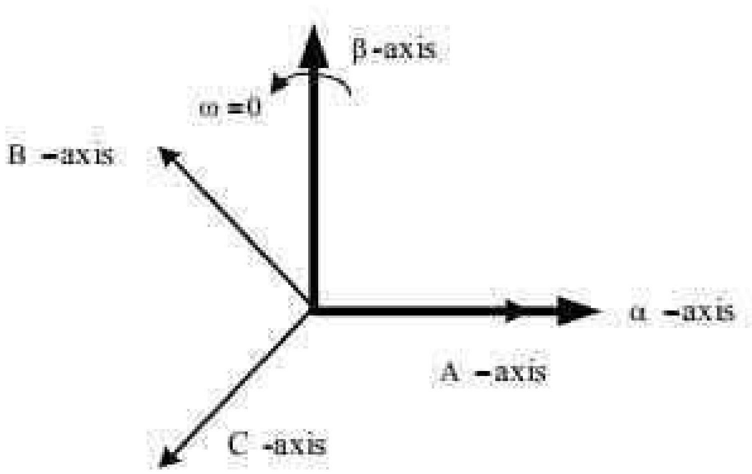


Figure 2.1: Clarke's transformation

In order for the transformation to be invertible, a third variable, known as the zero-sequence component, is added. The resulting transformation is

$$[f_{\propto\beta 0}] = T_{\propto\beta 0}[f_{abc}] \tag{1}$$

where

$$[f_{\propto\beta 0}] = [f_{\propto} \quad f_{\beta} \quad f_0]^T$$

and

$$[f_{abc}] = [f_a \quad f_b \quad f_c]^T$$

Where f represents voltage, current, flux linkages, or electric charge and the transformation matrix, $T_{\propto\beta 0}$ is given by

$$T_{\propto\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2}$$

The inverse transformation is given by

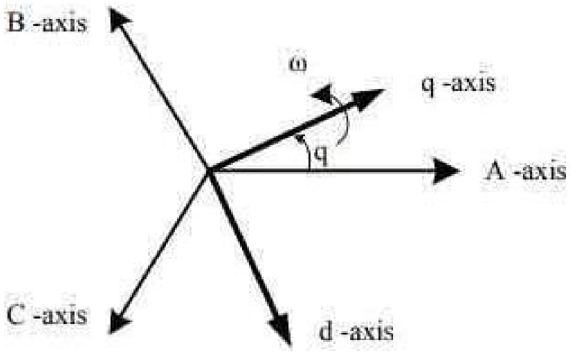
$$[f_{abc}] = T_{\propto\beta 0}{}^{-1}[f_{\propto\beta 0}] \tag{3}$$

where the inverse transformation matrix is presented by

$$T_{\propto\beta 0}{}^{-1} = \frac{2}{3}\begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \tag{4}$$

Park's Transformation

Park‘s transformation, a revolution in machine analysis, has the unique property of eliminating all time varying inductances from the voltage equations of three-phase ac machines due to the rotor spinning. Although changes of variables are used in the analysis of ac machines to eliminate time-varying inductances, changes of variables are also employed in the analysis of various static and constant parameters in power system components. Fortunately, all known real transformations for these components are also contained in the transformation to the arbitrary reference frame. The same general transformation used for the stator variables of ac machines serves the rotor variables of induction machines. Park‘s transformation is a well-known three-phase to two-phase transformation in synchronous machine analysis.



Park's transformation

The transformation equation is of the form

$$[f_{dq0s}] = T_{dq0}(\theta)[f_{abcs}] \qquad (1)$$

where

$$[f_{dq0s}] = [f_{qs} \quad f_{ds} \quad f_{0s}]^T$$

and

$$[f_{abcs}] = [f_{as} \quad f_{bs} \quad f_{cs}]^T$$

and the dq0 transformation matrix is defined as

$$T_{dq0}(\theta) = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (2)$$

θ is the angular displacement of Park's reference frame and can be calculated by

$$\theta = \int_0^t \omega(\zeta)\, d\zeta + \theta(0) \qquad (3)$$

where ζ is the dummy variable of integration. It can be shown that for the inverse transformation we can write

$$[f_{abcs}] = T_{dq0}(\theta)^{-1}.[f_{dq0s}] \qquad (4)$$

where the inverse of Park's transformation matrix is given by

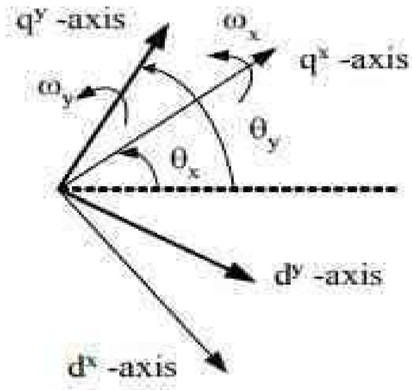
$$T_{dq0}(\theta)^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \qquad (5)$$

In the previous equations, the angular displacement θ must be continuous, but the angular velocity associated with the change of variables is unspecified. The frame of reference may rotate at any constant, varying angular velocity, or it may remain stationary. The angular velocity of the transformation can be chosen arbitrarily to best fit the system equation solution or to satisfy the system constraints. The change of variables may be applied to variables of any waveform and time sequence; however, we will find that the transformation given above is particularly appropriate for an a-b-c sequence.

3. Analyze the transformation between reference frames and deduce the transformation of variables from one reference frame to another.

Transformations between Reference Frames

In order to reduce the complexity of some derivations, it is necessary to transform the variables from one reference frame to another one. To establish this transformation between any two reference frames, we can denote y as the new reference frame and x as the old reference frame. Both new and old reference frames are shown in Figure.



Transformation between two reference frames

It is assumed that the reference frame x is rotating with angular velocity ωx and the reference frame y is spinning with the angular velocity ωy. θx and θy are angular displacements of reference frames x and y, respectively. In this regard, we can rewrite the transformation equation as

$$[f_{dq0s}^{y}] = T_{dq0s}^{x\rightarrow y}.[f_{dq0s}] \qquad (1)$$

But we have

$$[f_{dq0s}^{x}] = T_{dq0s}^{x}.[f_{abcs}] \qquad (2)$$

If we substitute (2) in (1) we get

$$[f_{dq0s}^{y}] = T_{dq0s}^{x\rightarrow y}.T_{dq0s}^{x}.[f_{abcs}] \qquad (3)$$

In another way, we can find out that

$$[f_{dq0s}^{y}] = T_{dq0s}^{y}.[f_{abcs}] \quad (4)$$

From (3) we obtain

$$T_{dq0s}^{x\to y} = T_{dq0s}^{y}.{T_{dq0s}^{x}}^{-1} \quad (5)$$

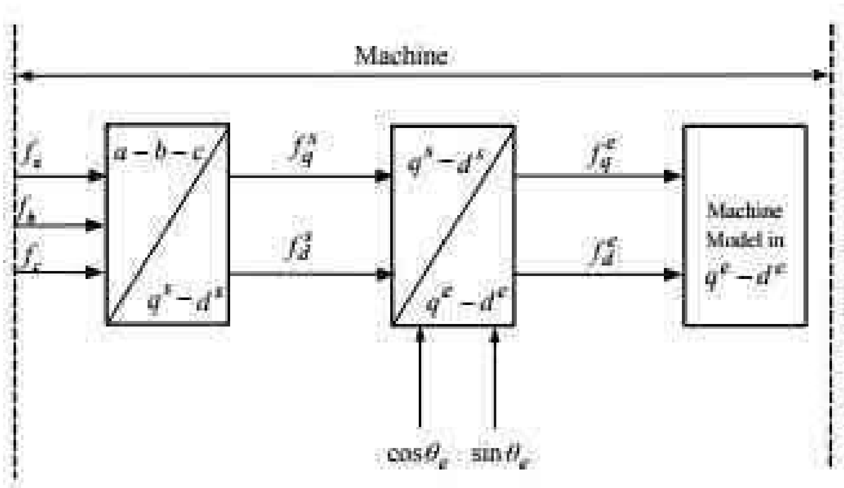
Then, the desired transformation can be expressed by the following matrix:

$$T_{dq0s}^{x\to y} = \begin{bmatrix} \cos(\theta_y - \theta_x) & -\sin(\theta_y - \theta_x) & 0 \\ \sin(\theta_y - \theta_x) & \cos(\theta_y - \theta_x) & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (6)$$

4. Compose the Field oriented control transformation with a neat block diagram.

Field Oriented Control (FOC) Transformations

2.1.1.1 Machine side transformation in field oriented control

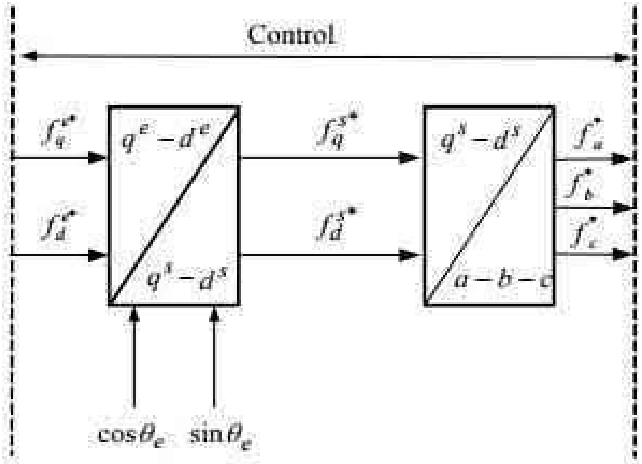


Machine side transformation in field oriented control

In the case of FOC of electric machines, control methods are performed in a two-phase reference frame fixed to the rotor (q^r -d^r) or fixed to the excitation reference frame (q^e -d^e). We want to transform all the variables from the three-phase a-b-c system to the two-phase stationary reference frame and then retransform these variables from the stationary reference frame to a rotary reference frame with arbitrary angular velocity of ω. These transformations are usually cascaded. The block diagram of this procedure is shown in Figure

2.1.1.2 Variable transformation in the field oriented control.

In this figure, f denotes the currents or voltages and q^e -d^e represents the arbitrary rotating reference frame with angular velocity θ_e and q^s -d^s represents the stationary reference frame. In the vector control method, after applying field oriented control it is necessary to transform variables to stationary a-b-c system. This can be achieved by taking the inverse transformation of variables from the arbitrary rotating reference frame to the stationary reference frame and then to the a-b-c system. In this block diagram, * is a representation of commanded or desired values of variables.



Variable transformation in the field oriented control

Commonly used reference frames

Based on speed of reference frame there are four major type of reference frames

1. **Arbitrary reference frame:** Reference frame speed is unspecified (**ω**), variables denoted by $\mathbf{f_{dqos}}$ or $\mathbf{f_{ds}}$, $\mathbf{f_{qs}}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}$.
2. **Stationary reference frame:** Reference frame speed is zero (**ω=0**), variables denoted by $\mathbf{f^s_{dqo}}$ or $\mathbf{f_d^s}$, $\mathbf{f_q^s}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s^s}$.
3. **Rotor reference frame:** Reference frame speed is equal to rotor speed (**ω= ω$_r$**), variables denoted by $\mathbf{f^r_{dqo}}$ or $\mathbf{f_d^r}$, $\mathbf{f^{qr}}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s^s}$.
4. **Synchronous reference frame:** Reference frame speed is equal to synchronous speed (**ω= ω$_e$**), variables denoted by f^e_{dqo} or $\mathbf{f_d^e}$, $\mathbf{f_q^e}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K^e}$.

The choice of reference frame is not restricted but otherwise deeply influenced by the type of analysis that is to be performed so as to expedite the solution of the system equations or to satisfy system constraints. The best suited choice of reference frame for simulation of induction machine for various cases of analysis is listed here under:

- **Stationary reference frame** is best suited for studying stator variables only, for example variable speed stator fed IM drives, because stator d-axis variables are exactly identical to stator phase a-variable.
- **Rotor reference frame** is best suited when analysis is restricted to rotor variables as rotor d-axis variable is identical to phase-a rotor variable.
- **Synchronously rotating reference frame** is suitable when analog computer is employed because both stator and rotor d-q quantities becomes steady DC quantities. It is also best suited for studying multi-machine system.

It is worthwhile to note that all three types of reference frame can be obtained from arbitrary reference frame by simply changing ω. Modeling in arbitrary reference frame is therefore beneficial when a wide range of analysis is to be done.

Induction Machine Model in the Park Reference Frame

The induction machine was modeled using two separate frames. The first one is used to express stator quantities; the second one is used to express rotor quantities. Since these two frames are linked with angle θ, a model of the machine in a common frame named d, q can be obtained using the two rotation matrices. At a certain point, the position of the magnetic field rotating in the air gap is pinpointed by angle θ_s; in relation to stationary axis $\vec{O}_{sa}$: For the development of the machine model, a Park reference frame is assumed to be lined up with this magnetic field and to rotate at the same speed (ω_s): Angle θ_s corresponds to the angle of axes $\vec{O}_{sx}$ and θ_r; angle θ_r corresponds to the angle of axes $\vec{O}_{rx}$ and $\vec{O}_d$: Transforming angle θ_s is necessary to bring the stator quantities back to the Park rotating reference frame. Transforming angle θ_r is necessary to bring the rotor quantities back. The figure indicates that the angles are linked by a relation in order to express the rotor and stator quantities in the same Park reference frame (; $\vec{O}_d$; $\vec{O}_q$). This relation is:

$$\theta_s = \theta + \theta_r \qquad (1)$$

The same situation happens between the frame speeds in each frame and the mechanical speed, that is:

$$\omega_s = \omega + \omega_r \qquad (2)$$

$$\omega_s = \frac{d\theta_s}{dt}, = \omega_r = \frac{d\theta_r}{dt}, \omega = p\Omega = \frac{d\theta}{dt} \qquad (3)$$

where Ω is mechanical speed and ω is very speed viewed in the electrical space.

The speed of the rotor quantities is ω_r in relation to rotor speed ω. In relation to the stator frame, the rotor quantities consequently rotate at the same speed xs as the stator quantities. Using the Park transform will allow the conception of an induction machine model independent from the rotor position. Two transformations are used. One [P(θ_s)]is applied to the stator quantities; the other [P(θ_r)]is applied to the rotor quantities.

$$[X_{s\_dqo}] = [\mathrm{P}(\theta_s)][X_{s_{abc}}][X_{r_{dqo}}] = [\mathrm{P}(\theta_r)][X_{r_{abc}}] \qquad (4)$$

Direct and squared components x_d, x_q represent coordinates x_a, x_b,x_c in an orthogonal frame of reference rotating in the same plane. Term x_o represents the homopolar component, which is orthogonal to the plane constituted by the system x_a, x_b, x_c.

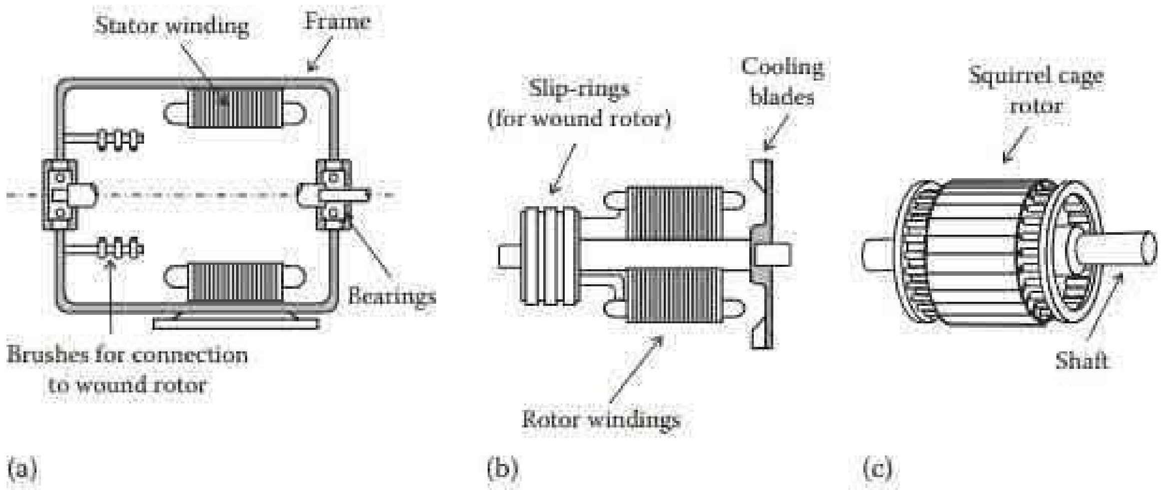
2.2 INDUCTION GENERATORS (IG)

2.2.1 Introduction

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

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

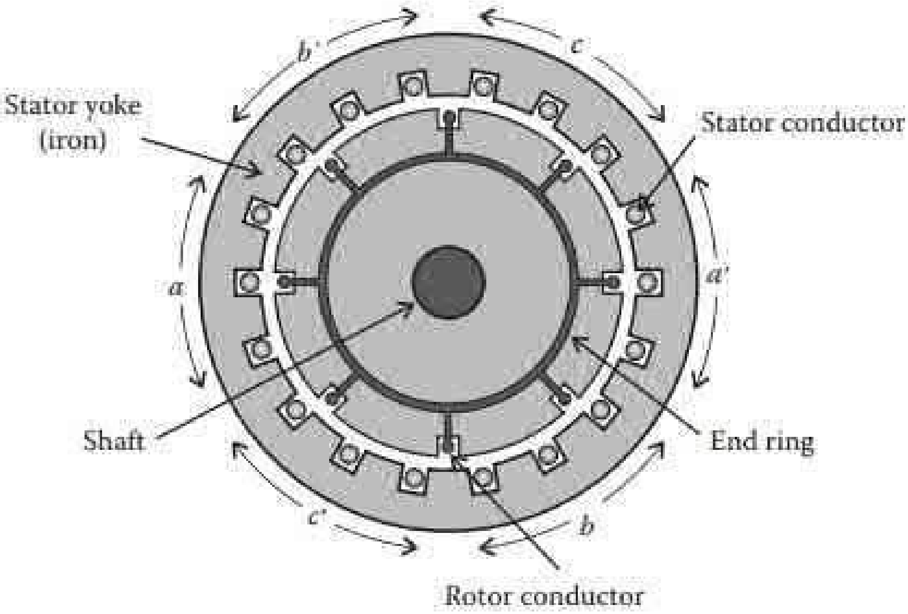
2.2.2 Construction



Induction machine longitudinal cut: (a) stator, (b) wound rotor, and (c) cage rotor

An induction generator is made up of two major components: the stator, which consists of steel laminations mounted on a frame so that slots are formed on the inside diameter of the assembly as in a synchronous machine, and the rotor, which consists of a structure of steel laminations mounted on a shaft with two possible configurations:

Wound rotor or cage rotor. Figure shows a schematic cut along the longitudinal axis of a typical wound-rotor induction machine. Figure (a) shows the external case with the stator yoke internally providing the magnetic path for the three-phase stator circuits. Bearings provide mechanical support for the shaft clearance (the air gap) between the rotor and stator cores. For a wound rotor, a group of brush holders and carbon brushes, indicated on the left side of Figure (a), allow for connection to the rotor windings. A schematic diagram of a wound rotor is shown in Figure (b). The winding of the wound rotor is of the three-phase type with the same number of poles as the stator, generally connected in Y.



Cross-sectional cut for an induction machine

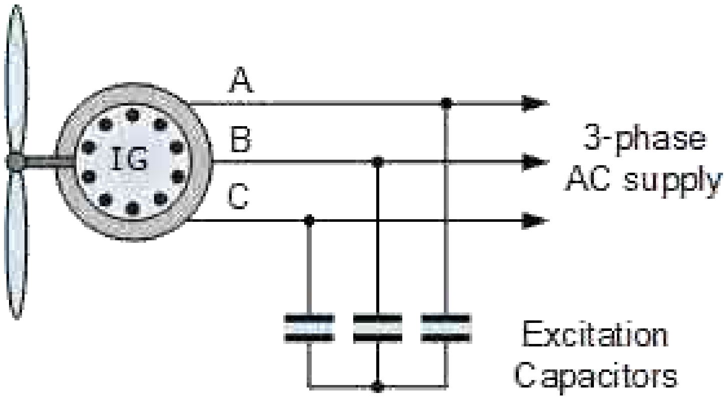
Three terminal leads are connected to the slip rings by means of carbon brushes. Wound rotors are usually available for very large power machines (>500 kW). External converters in the rotor circuit, rated with slip power, control the secondary currents providing the rated frequency at the stator. For most medium power applications, squirrel cage rotors, as in Figure (c), are used. Squirrel cage rotor windings consist of solid bars of conducting material embedded in the rotor slots and shorted at the two ends by conducting rings. In large machines, the rotor bars may be of copper alloy brazed to the end rings. Rotors sized up to about 20 inches in diameter are usually stacked in a mold made by aluminum casting, enabling a very economical structure combining the rotor bars, end rings, and cooling fan. Figure shows a cross-sectional cut indicating the distributed windings for three-phase stator excitation. Each winding (a, b, or c) occupies the contiguous slots within a 120° spatial distribution.

The stator: It is built up from silicon steel laminations punched and assembled so that it has a number of uniformly spaced identical slots, in integral multiples of six (such as 48 or 72 slots), roughly parallel to the machine shaft. Sometimes, the slots are slightly twisted or skewed in relation to the longitudinal axis, to reduce cogging torque, noise, and vibration, and to smooth up the generated voltage. Machines up to a few hundreds of KW rating and low voltage have semi closed slots, while larger machines with medium voltage have open slots.

2.2.3 Off-grid Induction Generator

We have seen above that an induction generator requires the stator to be magnetized from the utility grid before it can generate electricity. But you can also run an induction generator in a stand alone, off-grid system by supplying the necessary out-of-phase exciting or magnetizing current from excitation capacitors connected across the stator terminals of the machine. This also requires that there is some residual magnetism in the rotors iron laminations when you start the turbine. The excitation capacitors are shown in a star (wye) connection but can also be connected a delta (triangular) arrangement.

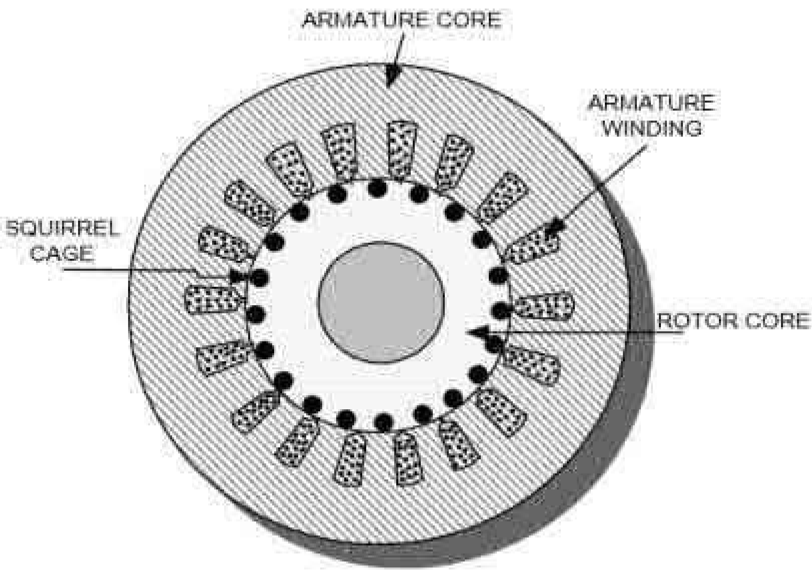
2.2.4 Capacitor Start Induction Generator



Capacitor Start Induction Generator

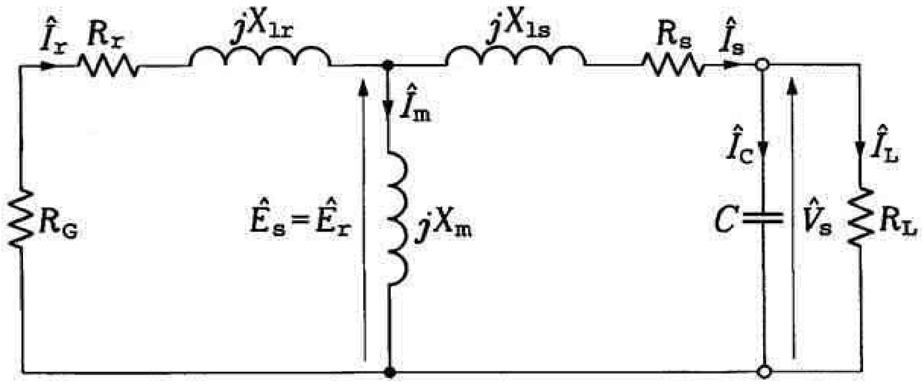
The excitation capacitors are standard motor-starting capacitors that are used to provide the required reactive power for excitation which would otherwise be supplied by the utility grid. The induction generator will self-excite using these external capacitors only if the rotor has sufficient residual magnetism. In the self-excited mode, the generator output frequency and voltage are affected by the rotational speed, the turbine load, and the capacitance value in farads of the capacitors. Then in order for self-excitation of the generator to occur, there needs to be a minimum rotational speed for the value of capacitance used across the stator windings. The ―Self-excited induction generator‖, (SEIG) is a good candidate for wind powered electric generation applications especially in variable wind speed and remote areas, because they do not need external power supply to produce the magnetic field. A three-phase induction generator can be converted into a variable speed single-phase induction generator by connecting two excitation capacitors across the three-phase windings. One of value C amount of capacitance on one phase and the other of value 2C amount of capacitance across the other phase.

2.2.5 Principle of operation



An induction generator produces electrical power when its rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, the synchronous speed is 1800 rotations per minute (rpm). The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM. The motor normally turns slightly slower than the synchronous speed; the difference between synchronous and operating speed is called "slip" and is usually expressed as per cent of the synchronous speed. For example, a motor operating at 1450 RPM that has a synchronous speed of 1500 RPM is running at a slip of +3.3%. In normal motor operation, the stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, with the currents in the rotor induced at the slip frequency. In generator operation, a prime mover (turbine or engine) drives the rotor above the synchronous speed (negative slip). The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils and the motor now operates as a generator, sending power back to the electrical grid.

2.2.5.1 Excitation



Per-phase equivalent circuit of the stand-alone induction generator

An induction machine requires externally supplied armature current. Because the rotor field always lags behind the stator field, the induction machine always "consumes" reactive power, regardless of whether it is operating as a generator or a motor. A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself. An induction machine can be started by charging the capacitors, with a DC source, while the generator is turning typically at or above generating speeds. Once the DC source is removed the capacitors will provide the magnetization current required beginning producing voltage. An induction machine that has recently been operating may also spontaneously produce voltage and current due to residual magnetism left in the core.

2.2.5.2 Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm (typical example), full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

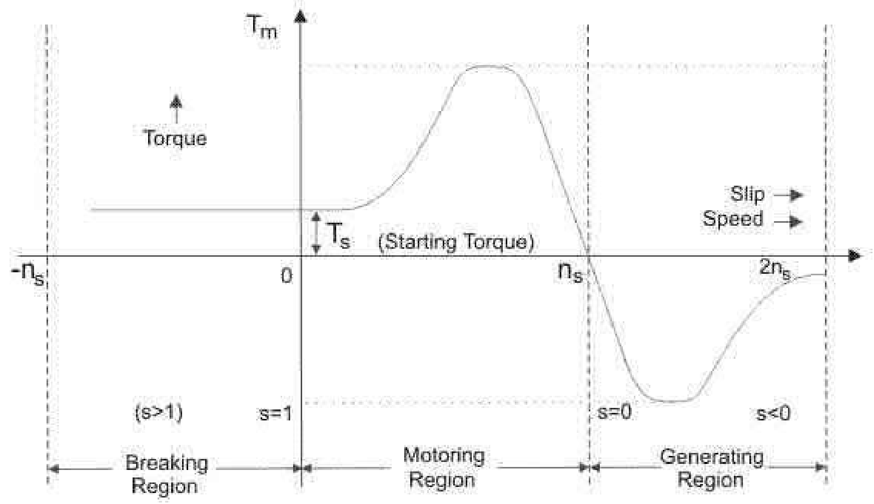
2.2.5.3 Required capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor. Consider, an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the stator pulls the rotor to run behind it (the machine is acting as a motor). Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.

If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field. This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).

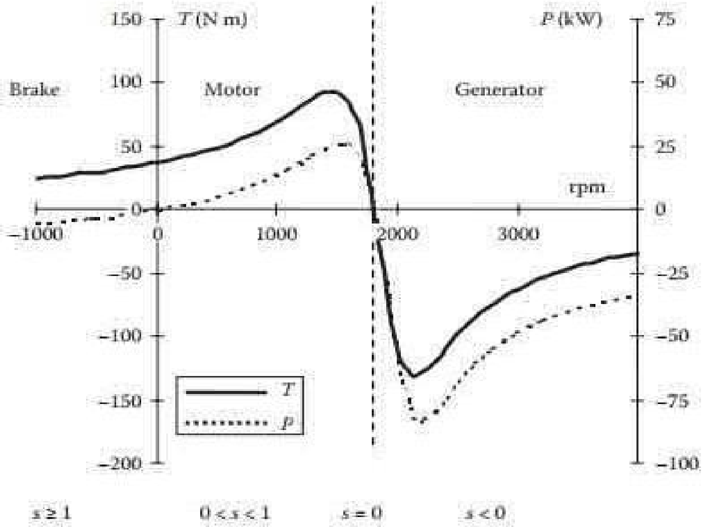
2.2.6 Torque-Slip characteristics

The basic fundamental of induction generators is the conversion between mechanical energy to electrical energy. This requires an external torque applied to the rotor to turn it faster than the synchronous speed. However, indefinitely increasing torque doesn't lead to an indefinite increase in power generation. The rotating magnetic field torque excited from the armature works to counter the motion of the rotor and prevent over speed because of induced motion in the opposite direction.



As the speed of the motor increases the counter torque reaches a max value of torque (breakdown torque) that it can operate until before the operating conditions become unstable. Ideally, induction generators work best in the stable region between the no-load condition and maximum torque region.

2.2.7 Torque–Speed characteristics



It can be observed that there is no torque at the synchronous speed. Both the torque–speed and the power–speed curves are almost linear since from no load to full load the machine's rotor resistance is much larger than its reactance. The resistance is predominant in this range, current and the rotor field as well as the induced torque increase almost linearly with the increase of the slip factors. The rotor torque varies as the square of the voltage across the terminals of the generator if the speed slows down close to the synchronous speed, the generator motorizes that is, it works as a motor; as we will show, the generated power has a maximum value for a given current drained from the generator in the same way, there is a maximum possible induced generator torque called pullout or breakdown torque, and from this torque value on, there will be over speed. The peak power supplied by the IG happens at a speed slightly different from the maximum torque, and, naturally, no electric power is converted into mechanical power when the rotor is at rest (zero speed). In the same way, in spite of the same rotation, the frequency of the IG varies with the load variation.

2.3 HIGH-EFFICIENCY INDUCTION GENERATOR

A high-efficiency induction generator is commercially available as a high-efficiency induction motor, except for some peculiarities. Therefore, the same care must be taken in design, materials selection, and manufacturing processes for building a high-efficiency generator. The main advantages of the high-efficiency induction generator compared with the conventional induction generator are better voltage regulation, less loss of efficiency. Steady-state model of Induction Generators with smaller loads, less over sizing when generators of lower power cannot be used, reduced internal losses, and, therefore, lower temperatures, less internal electric and mechanical stress, and, thus, increased useful life.

The constraints are the need for larger capacitors for self-excitation. High-efficiency induction generators should not be used for self-excited applications. The efficiency of the high-efficiency generator compared with the standard ones differs by more than about 10% for small power ratings (up to 50 kW) and about 2% for higher powers (above 100 kW). It is therefore highly recommended for micro power plants. Rated efficiencies are normalized, and they should have guaranteed minimum values stated by the manufacturer on the plate of the machine for each combination of power versus synchronous speed. High-efficiency generators are better suited to stand the harmful effects of the harmonic generated by nonlinear loads (power converters) because they have higher thermal margin and smaller losses.

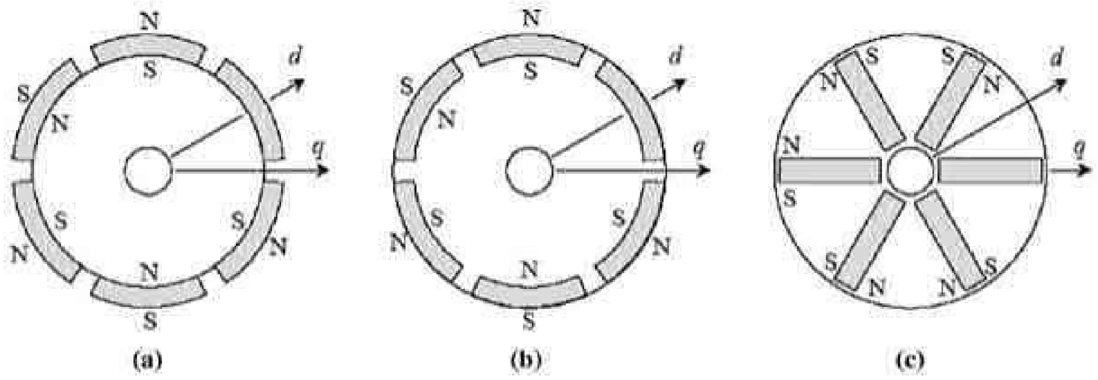
5.Describe the construction and working principle of PMSG with a neat diagram. Specify its advantages and disadvantages.

PERMANENT MAGNET SYNCHRONOUS GENERATORS (PMSG)

2.3.1 Introduction

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid. Some designs of Wind turbines also use this generator type.

2.3.2 Construction

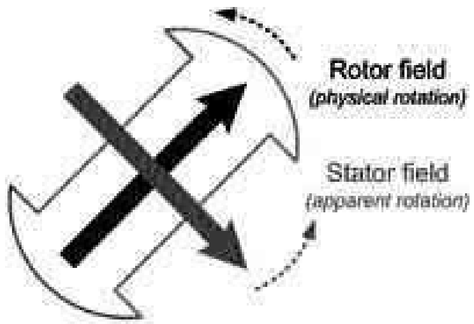


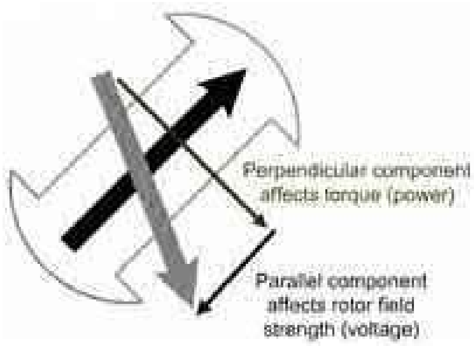
Types of PMSG rotor construction

(a) Surface mounted; (b) inset; (c) Interior PM motor

A Permanent Magnet Synchronous Generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The rotor contains the permanent magnet and the stator is the stationary armature that is electrically connected to a load. A set of 3 conductors make up the armature winding in standard utility equipment, placed 120^0 apart in space, this provides for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic field resulting from the currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single rotating magnet. The stator magnetic field appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in ‗synchronicity‘ and maintain a fixed position with respect to each other as they rotate. The armature MMF combines vectorically with the persistent flux of the permanent magnets, which leads to higher air-gap flux density and eventually core saturation. In PMSG, the output voltage is proportional to the speed.

2.3.3 Operation





In the majority of designs the rotating assembly in the center of the generator called "rotor" contains the magnet, and the "stator" is the stationary armature that is electrically connected to a load. As shown in the diagram, the perpendicular component of the stator field affects the torque while the parallel component affects the voltage. The load supplied by the generator determines the voltage. If the load is inductive, then the angle between the rotor and stator fields will be greater than 90 degrees which corresponds to an increased generator voltage. This is known as an overexcited generator.

The opposite is true for a generator supplying a capacitive load which is known as an under excited generator. A set of three conductors make up the armature winding in standard utility equipment, constituting three phases of a power circuit that correspond to the three wires we are accustomed to see on transmission lines. The phases are wound such that they are 120 degrees apart spatially on the stator, providing for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic fields resulting from the induced currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single, rotating magnet. This stator magnetic field or "stator field" appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in "synchronicity" and maintain a fixed position relative to each other as they spin.

2.3.4 Advantages and disadvantages of PMSG

Advantages

- Light weight and small size in construction.
- Low losses and high efficiency
- No need of external excitation current.
- No need of gearbox.

Disadvantages

- It is useful for small wind turbines, but for large wind turbines the size of the magnet has to be increased.
- Demagnetization of permanent magnet due to atmospheric conditions is a big problem

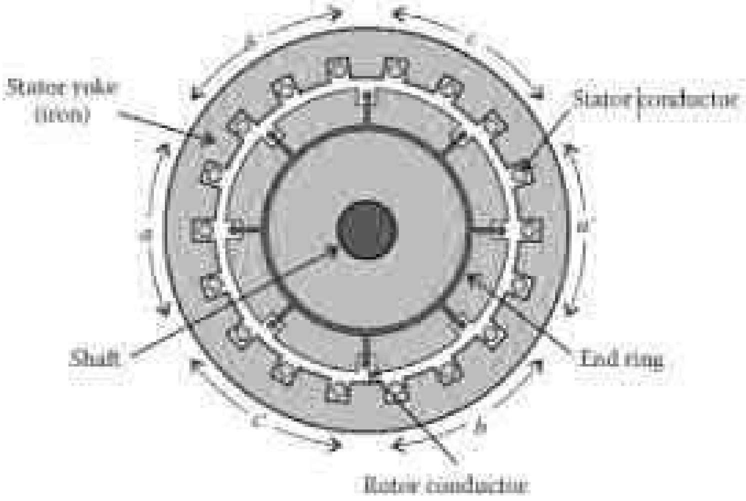
6. Explain the construction and working principle of SCIG with a neat diagram. Specify its advantages and disadvantages.

SQUIRREL CAGE INDUCTION GENERATORS (SCIG)

2.3.5 Constructional features

Asynchronous Induction generators are widely used in wind mills due to the several advantages, such as robustness, mechanical simplicity and low price. Induction machines operate in the generating and motoring modes fundamentally in the same manner except for the reversal power flow. Therefore, the equivalent circuit and the associated performance are valid for different slip. If the rotor is driven by a prime mover above the synchronous speed, the mechanical power of the prime mover is converted into electrical power to the utility grid via stator winding. The SCIG is a self-excited induction generator where a three-phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load. When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings. This

EMF is applied to the capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine.

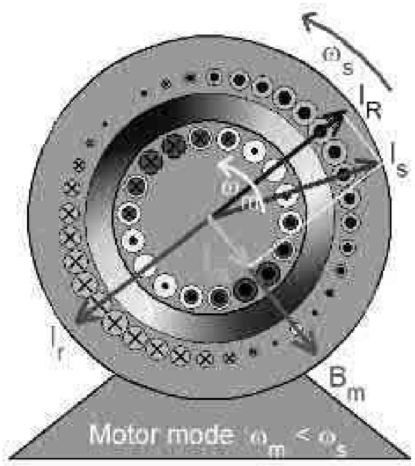


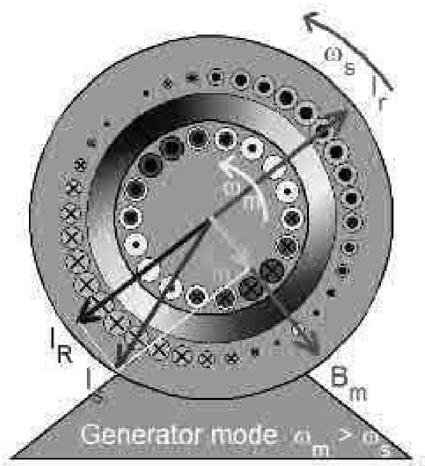
An induction generator connected and excited in this manner is capable of acting as a standalone generator supplying real and reactive power to a load. SCIG have a steep torque speed characteristic and therefore fluctuations in wind power are transmitted directly to the grid. SCIG feed only through the stator and generally operate at low negative slip, approximately 1 to 2 percent. The slip, and hence the rotor speed of a SCIG varies with the amount of power generated. The generator will always draw the reactive power from the grid. Reactive power consumption is partly or fully compensated by capacitors in order to achieve a power factor close to unity and make the induction machine to self-excite. The speed varies over a very small range above synchronous speed as it is coupled with the grid, hence commonly known as a fixed-speed generator. SCIG drives have bulky construction, low efficiency, low reliability and need of maintenance, also the existing of slip ring, brush and three-stage gearbox increases the system mass and cost, also electrical and mechanical loss. Recently, squirrel-cage induction generators are dropping in this application.

2.3.6 Principle of operation

Initially, the induction machine is connected in motoring command 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. The rotating magnetizing field represented by the space vector $\mathbf{B_m}$ (or, equivalently by the magnetizing current $\mathbf{I_m}$) moves at the synchronous speed $\boldsymbol{\omega_s}$ with respect to a stator (or stationary) observer and at the slip speed $\boldsymbol{\omega_{sl} = \omega_s - \omega_m}$ with respect to a rotor observer. In the motor mode of operation where $\boldsymbol{\omega_m < \omega_s}$, the rotor effectively moves backwards (clockwise) with respect to the field, inducing in each bar a voltage having the polarity indicated and a magnitude proportional to slip velocity u and to the field strength acting on the bar (in accordance with the flux-cutting rule **v = Blu**). Since the magnetic field is sinusoidally distributed in space, so will the induced voltages in the rotor bars. Ignoring the effects of rotor leakage, the resulting rotor currents are in phase with the induced voltages and are thus sinusoidally distributed in space varying sinusoidally in time at slip frequency; they may then be represented by the space vector $\mathbf{I_r}$ which rotate at the slip speed $\boldsymbol{\omega_{sl}}$ with respect to the rotor and at synchronous speed $\boldsymbol{\omega_s}$ with respect to the stator. Because $\mathbf{B_m}$ cannot change with a fixed stator input voltage (in accordance with Faraday's law), a stator space vector $\mathbf{I_R}$ is created in order to compensate for the rotor effects so that the resultant stator current becomes $\mathbf{I_s = I_R + I_m}$.

The electromagnetic force exerted on rotor bar acting in the positive or anticlockwise direction (same as rotor speed) in the present case of a motor. The resultant torque developed on the rotor also acts in the same direction. Follow the path taken by one rotor bar as it travels around, observing the polarity and magnitude (described by the size) of the bar current. In the case of a generator where $\boldsymbol{\omega_m > \omega_s}$, all polarities and directions are reversed as can be observed in the right figure (except for the magnetizing component).

2.3.7 Modelling of Squirrel Cage Induction Generator (SCIG)

A three-phase voltage system may be expressed, with obvious meaning of the notation, as follows

$$V_a(t) = V\cos(\omega t + \varphi)$$

$$V_b(t) = V\cos\left(\omega t + \varphi - \left(\frac{2}{3}\right)\pi\right)$$

$$V_c(t) = V\cos\left(\omega t + \varphi - \left(\frac{4}{3}\right)\pi\right) \qquad (1)$$

The corresponding space-vector is calculated in (2). Notice that the amplitude of the defined voltage space-vector is equal to the peak amplitude of the instantaneous voltage:

$$V_s(t) = \frac{2}{3}\left(v_a(t) + a v_b(t) + a^2 v_c(t)\right) = v e^{j\varphi} e^{j\omega t} \qquad (2)$$

where

$$a = e^{j(2/3)\pi}$$

$$a^2 = e^{-j(2/3)\pi}$$

$$V = Ve^{j\omega}$$

The phasor V is defined in such a way that its magnitude is equal to the peak-value of the voltage. The first part of (2) is valid also if the three-phase quantities do not form a balanced system. In this case, the space vector becomes:

$$V_s(t) = V_1 e^{j\varphi 1} e^{j\omega t} + V_2 v e^{-j\varphi 2} e^{-j\omega t} = V_1 e^{j\omega t} + V_2 e^{-j\omega t} \qquad (3)$$

Similar expressions can be obtained for currents and fluxes. The zero-sequence is not considered here, since commonly an induction generator is not grounded and therefore no zero-sequence current can flow. If no zero-sequence component is present, the instantaneous values of the currents in the three phases can be obtained from the corresponding space-vector as:

$$i_a(t) = Re(i_s)$$

$$i_b(t) = Re(a^2 i_s)$$

$$i_c(t) = Re(a i_s) \qquad (4)$$

Using the introduced space-vector notation and using a stationary reference frame, the equations describing the electrical dynamics of a squirrel-cage induction machine are given by :

$$v_s = R_s i_s + \frac{d\psi_s}{dt}$$

$$0 = R_r i_r + \frac{d\psi_r}{dt} - j\psi_r \psi_r \quad (5)$$

$$\psi_s = L_s I_s + L_m I_r$$

$$\psi_r = L_m I_s + L_r I_r \quad (6)$$

where

$$L_s = L_{sl} + L_m \; and \; L_r + L_{rl} + L_m$$

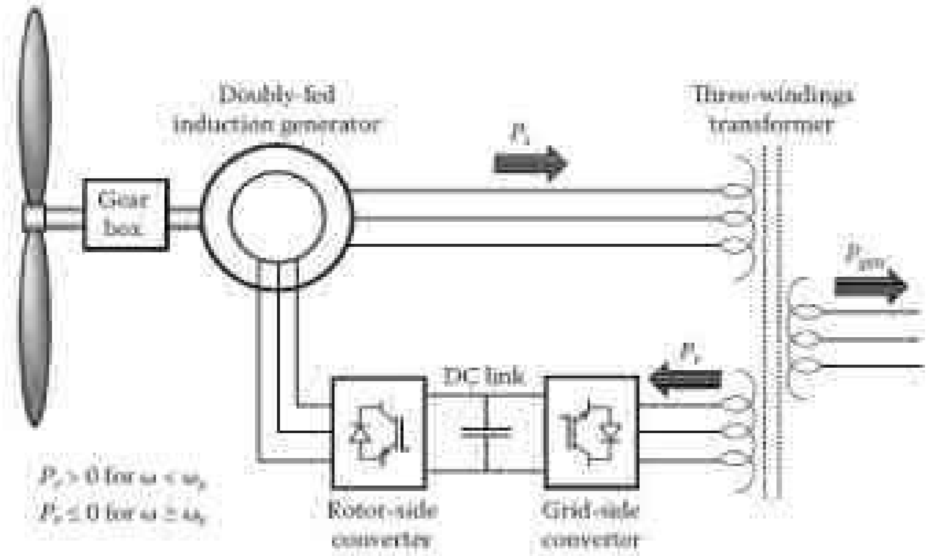
7. Discuss in detail the construction of DFIG with a neat sketch. Also mention the advantages and disadvantages.

DOUBLY FED INDUCTION GENERATORS (DFIG)

2.3.8 Constructional features

Doubly fed electrical generators are similar to AC electrical generators, but have additional features which allow them to run at speeds slightly above or below their natural synchronous speed. This is useful for large variable speed wind turbines, because wind speed can change suddenly. When a gust of wind hits a wind turbine, the blades try to speed up, but a synchronous generator is locked to the speed of the power grid and cannot speed up. Therefore large forces are developed in the hub, gearbox, and generator as the power grid pushes back. This causes wear and damage to the mechanism.

If the turbine is allowed to speed up immediately when hit by a wind gust, the stresses are lower and the power from the wind gust is converted to useful electricity. One approach to allowing wind turbine speed to vary is to accept whatever frequency the generator produces, convert it to DC, and then convert it to AC at the desired output frequency using an inverter. This is common for small house and farm wind turbines. But the inverters required for megawatt-scale wind turbines are large and expensive. Doubly fed generators are one solution to this problem. Instead of the usual field winding fed with DC, and an armature winding where the generated electricity comes out, there are two three-phase windings, one stationary and one rotating, both separately connected to equipment outside the generator. Thus the term "doubly fed". One winding is directly connected to the output, and produces 3-phase AC power at the desired grid frequency. The other winding (traditionally called the field, but here both windings can be outputs) is connected to 3-phase AC power at variable frequency. This input power is adjusted in frequency and phase to compensate for changes in speed of the turbine.



Wind turbine–powered DFIG with transformer-based utility connection

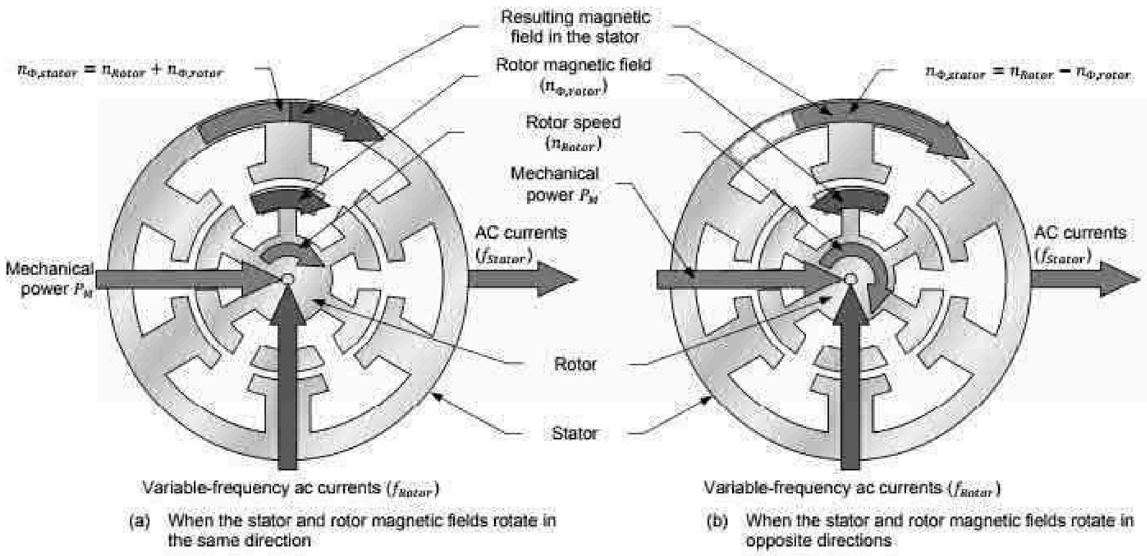
The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance when the remaining voltage stays above 15% of the nominal voltage. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. For zero voltage ride through it is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the reactive current should be injected.

2.3.9 Principle of operation

The principle of the Doubly-Fed Induction Generator (referred to as DFIG) is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converters that control both the rotor and the grid currents. Thus, rotor frequency can freely differ from the grid frequency (50 or 60 Hz). 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 but there are problems with efficiency, cost and size.

A doubly-fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances. Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason. Doubly-fed electric machine is connected to a selection of resistors via multiphase slip rings for starting. However, the slip power was lost in the resistors. Thus means to increase the efficiency in variable speed operation by recovering the slip power were developed.



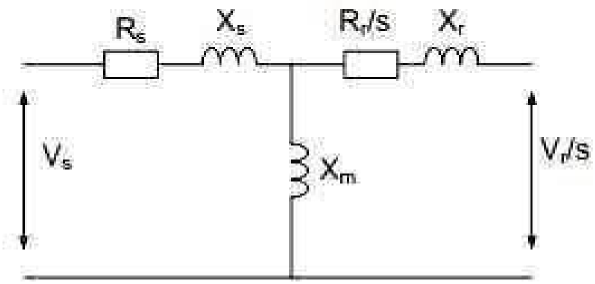
Interaction between the rotor speed and the frequency of the rotating magnetic field created in the rotor windings of a doubly-fed induction generator.

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. The control principle used is either the two-axis current vector control or direct torque control. Direct torque control has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

2.3.10 Equivalent Circuit of DFIG

A doubly fed induction generator is basically a wound rotor induction generator fed by both stator and rotor, in which the stator winding is directly connected to the grid and the rotor winding is connected to the grid through AC/DC/AC converters. These converters are divided into two components: the rotor side converter and the grid side converter. A capacitor between the converters plays a role of a DC voltage source. A coupling inductor is used to link the grid side converter to the grid.

The operation principle of DFIG is fundamentally the same as that of a transformer. Thus, DFIG can be represented as a transformer‘s per phase equivalent circuit, where R_r and X_r represent rotor resistance and reactance referred to the stator side. But the equivalent circuit of induction machine differs from a transformer‘s primarily with respect to varying rotor frequency on the rotor voltage. In case of DFIG, there is a voltage injected to the rotor winding, so an equivalent circuit of classic induction machine needs to be modified by adding a rotor injected voltage as shown in Figure. In this figure, *s* is the rotor slip, *V* the voltage, *I* the current, *R* and *X* represent resistance and reactance, respectively. The subscripts *r; s* and *m* stand for rotor, stator and mutual, respectively.



The Equivalent Circuit of DFIG

Real and reactive power in the stator side like P_s and Q_s delivered to the connected grid can be derived from I_s and *Vs* as in (1):

$$P_s = 3Re(V_s I_s^*)$$

$$Q_s = 3Im(V_s I_s^*) \qquad (1)$$

Real and reactive power in the rotor side, P_r , Q_r , referred to stator side is derived from I_r and V_r/s, as in (2):

$$P_r = 3Re\left(\frac{V_r}{s} I_r^*\right)$$

$$Q_r = 3Im\left(\frac{V_r}{s}I_r^*\right) \quad (2)$$

It is possible to express the electromechanical torque, T_e , as in (3):

$$T_e = \frac{3}{2}\frac{p}{2}Re(j\Psi_s I_s^*) = \frac{3}{2}\frac{p}{2}Re(j\Psi_r I_r^*) \quad (3)$$

where

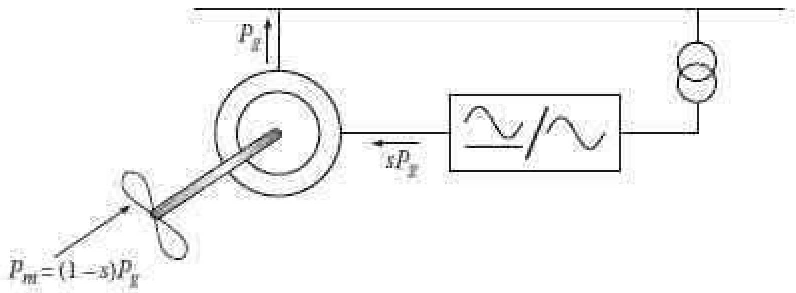
$$\Psi_s = \frac{X_s I_s + X_m I_r}{\omega_s};\ \Psi_r = \frac{X_r I_r + X_m I_s}{\omega_S}$$

❤$_s$ and ❤$_r$: the stator and the rotor flux, respectively. p: the number of poles per phase.

I_s^*, I_r^* : the complex conjugates of the stator and the rotor current, respectively.

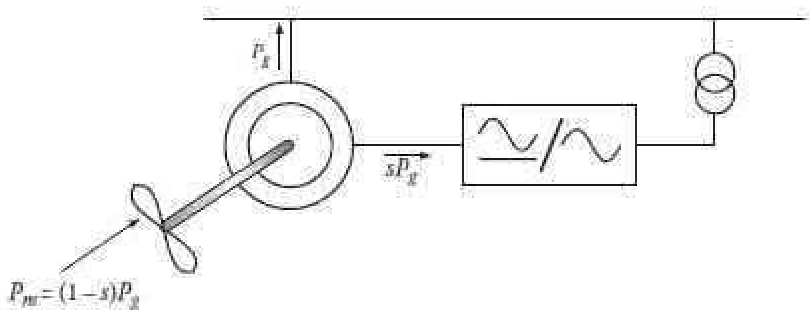
2.8.5 Sub- and Super-synchronous modes

Figure (a) shows the power balance in a DFIG at sub-synchronous generation where $s > 0$ and the power flow into the rotor by a current-controlled inverter. A step-up transformer is usually connected between the low-frequency low-voltage requirements and the grid in order to alleviate the rotor converter ratings.

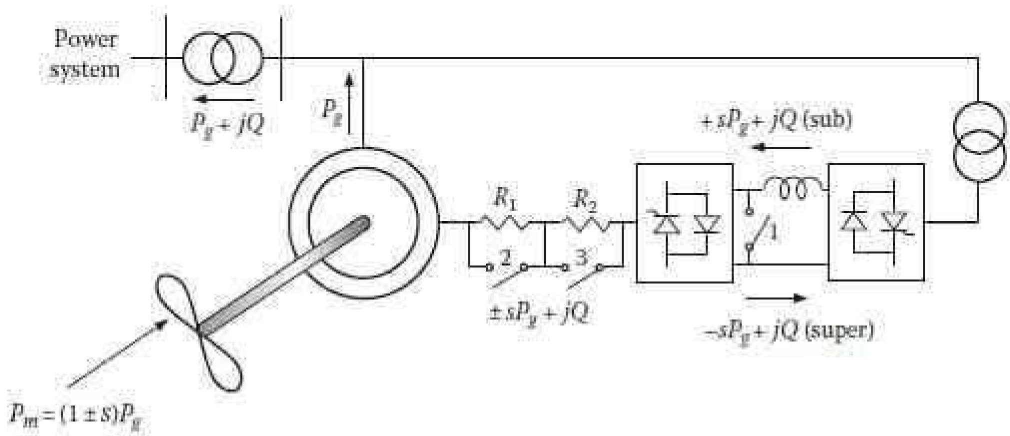


(a) Sub-synchronous generating mode ($s > 0$).

Figure (b) shows the super-synchronous generating mode where the mechanical speed is greater than the electrical synchronous speed, so the slip is negative ($s < 0$). The rotor voltages will have their phase sequence reversed; since $Pg < 0$ and $Pr < 0$, the rotor circuit contributes in generating power to the line with improved efficiency.



(b) Super-synchronous generating mode ($s < 0$).

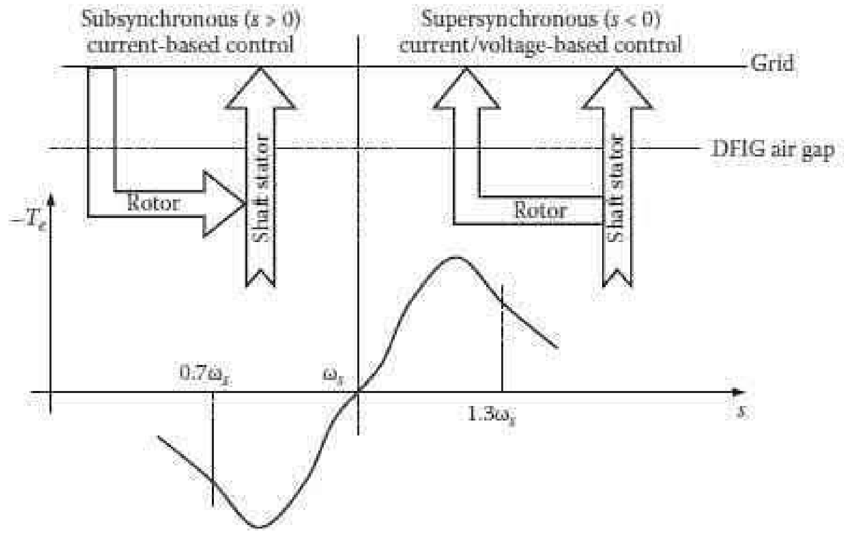


(c) Sub-synchronous mode back-to-back double converter.

It is important to note that the shaft incoming power indicates $Pm = (1 + s)Pg$ to show the extra capability of the power conversion, but the slip is actually negative. Thus, very efficient generating systems can be achieved using the super-synchronous region. Because the operating region is limited, the main drawback is the starting-up sequence of the system. One possible way around this is to use auxiliary resistors in the rotor circuit as indicated in Figure (c), then drive the machine in motoring mode, and, just after the cut-in speed, plug in the controller, which imposes regenerative operation.

2.8.6 Torque-slip curve for DFIG in sub- and super-synchronous modes.

For high-power machines, the stator resistance is neglected, and the stator terminal power is *Pg*. Considering that the power flowing out of the machine is negative (generating mode), the induction generator has a power balance in accordance with the torque-slip curve indicated in Figure. The power distribution for the generator operating at sub-synchronous and super-synchronous regions is indicated in the operating region from $0.7\omega s$ to $1.3\omega s$. For operation at the sub-synchronous region, the slip is positive, and therefore, the rotor circuit receives power from the line, whereas for the super-synchronous region, the slip is negative, and the rotor power supplements extra generating power to the grid.



2.8.7 Advantages and disadvantages of DFIG

Advantages

- DFIG is a variable speed generator and therefore has the variable speed advantages compared to fixed speed generators.
- It more fully converts the available wind power over a wider range of wind speeds with less mechanical complexity but more electrical and electronic complexity.
- DFIG provides variable speed with a smaller power converter compared to other variable-speed generators.
- Only the rotor power needs to be converted. That is typically about 30% of the total power.
- Reduced power conversion means reduced losses and increased efficiency. However the converter must be designed to transfer power in either direction, making it more complex than power converters for other types of variable-speed generators.
- The overall equipment, installation and maintenance cost is apparently lower for DFIG systems for some range of power levels.

Disadvantages

- A disadvantage of the DFIG compared to the permanent magnet synchronous generator is that the DFIG requires a speed increasing gearbox between the wind turbine and the generator whereas the PMSG can be constructed with a sufficient number of poles to allow direct drive.

PART C

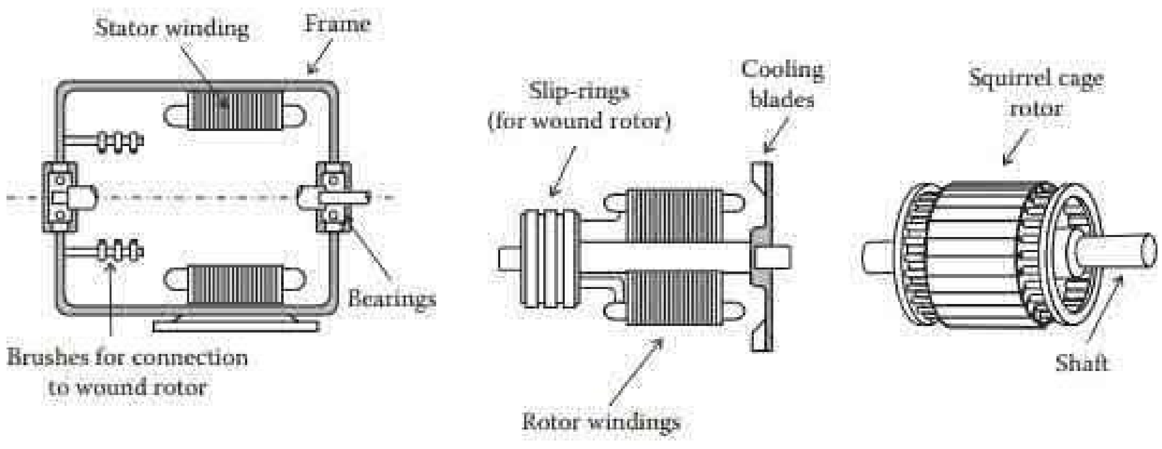
1. Develop the equivalent circuit of DFIG with necessary equations.

2.1.1 Introduction

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

Induction generator is not a self excited machine therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizng current and reactive power from the various sources like the supply mains or it may be another synchronous generator. The induction generator can't work in isolation because it continuously requires reactive power from the supply system. However we can have a self excited or isolated induction generation in one case if we will use capacitor bank for reactive power supply instead of AC supply system.

2.1.2 Construction

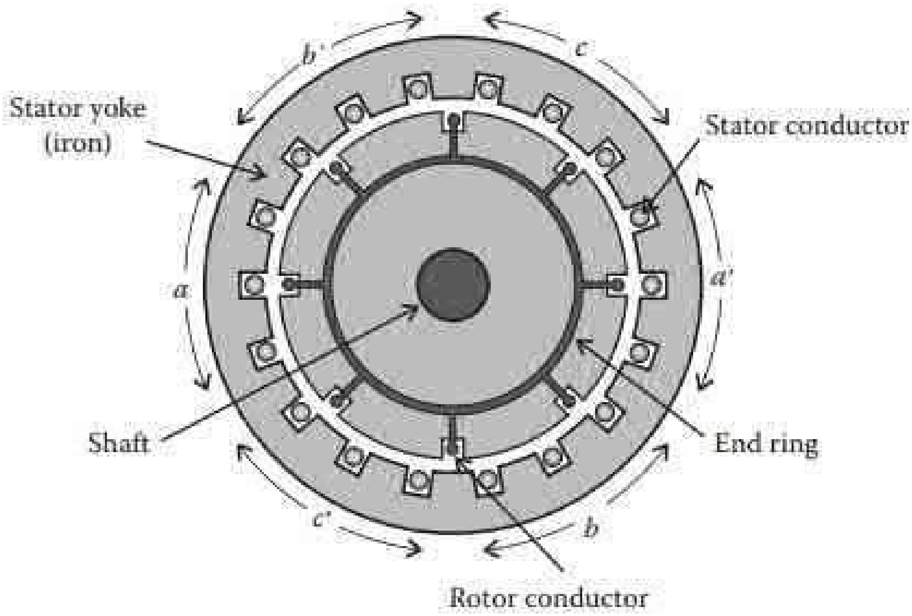


(a) (b) (c)

Induction machine longitudinal cut: (a) stator, (b) wound rotor, and (c) cage rotor

An induction generator is made up of two major components: the stator, which consists of steel laminations mounted on a frame so that slots are formed on the inside diameter of the assembly as in a synchronous machine, and the rotor, which consists of a structure of steel laminations mounted on a shaft with two possible configurations:

Wound rotor or cage rotor. Figure shows a schematic cut along the longitudinal axis of a typical wound-rotor induction machine. Figure (a) shows the external case with the stator yoke internally providing the magnetic path for the three-phase stator circuits. Bearings provide mechanical support for the shaft clearance (the air gap) between the rotor and stator cores. For a wound rotor, a group of brush holders and carbon brushes, indicated on the left side of Figure (a), allow for connection to the rotor windings. A schematic diagram of a wound rotor is shown in Figure (b). The winding of the wound rotor is of the three-phase type with the same number of poles as the stator, generally connected in Y.



Cross-sectional cut for an induction machine

Three terminal leads are connected to the slip rings by means of carbon brushes. Wound rotors are usually available for very large power machines (>500 kW). External converters in the rotor circuit, rated with slip power, control the secondary currents providing the rated frequency at the stator. For most medium power applications, squirrel cage rotors, as in Figure (c), are used.

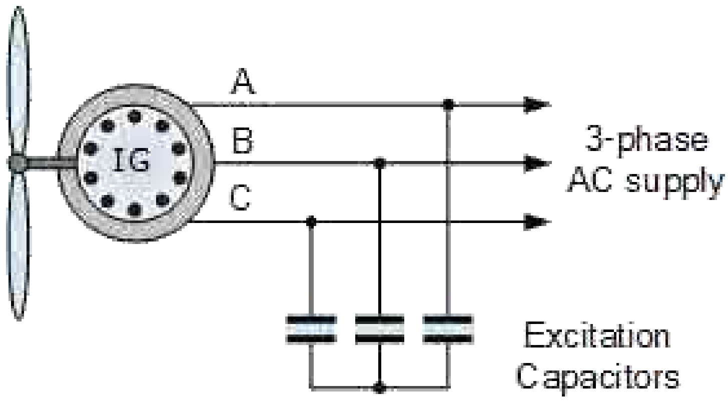
Squirrel cage rotor windings consist of solid bars of conducting material embedded in the rotor slots and shorted at the two ends by conducting rings. In large machines, the rotor bars may be of copper alloy brazed to the end rings. Rotors sized up to about 20 inches in diameter are usually stacked in a mold made by aluminum casting, enabling a very economical structure combining the rotor bars, end rings, and cooling fan. Figure shows a cross-sectional cut indicating the distributed windings for three-phase stator excitation. Each winding (a, b, or c) occupies the contiguous slots within a 120° spatial distribution.

The stator: It is built up from silicon steel laminations punched and assembled so that it has a number of uniformly spaced identical slots, in integral multiples of six (such as 48 or 72 slots), roughly parallel to the machine shaft. Sometimes, the slots are slightly twisted or skewed in relation to the longitudinal axis, to reduce cogging torque, noise, and vibration, and to smooth up the generated voltage. Machines up to a few hundreds of KW rating and low voltage have semi closed slots, while larger machines with medium voltage have open slots.

2.1.3 Off-grid Induction Generator

We have seen above that an induction generator requires the stator to be magnetized from the utility grid before it can generate electricity. But you can also run an induction generator in a stand alone, off-grid system by supplying the necessary out-of-phase exciting or magnetizing current from excitation capacitors connected across the stator terminals of the machine. This also requires that there is some residual magnetism in the rotors iron laminations when you start the turbine. The excitation capacitors are shown in a star (wye) connection but can also be connected a delta (triangular) arrangement.

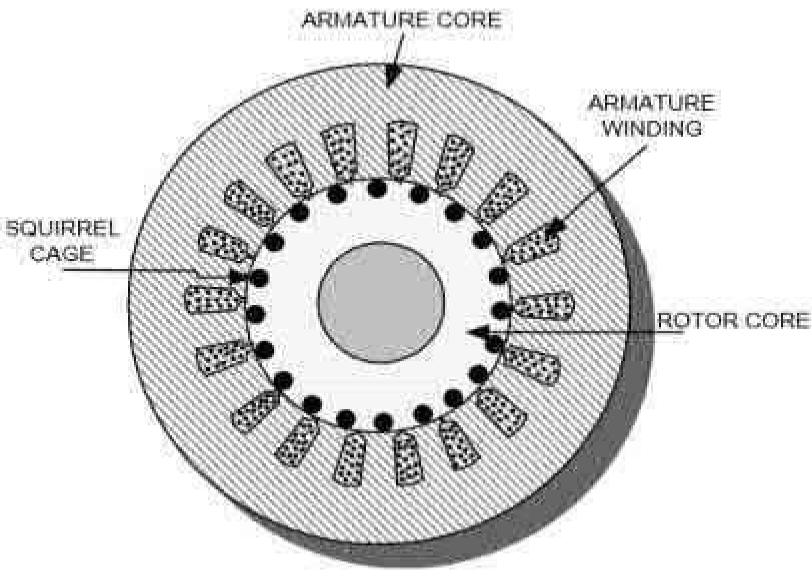
2.1.4 Capacitor Start Induction Generator



Capacitor Start Induction Generator

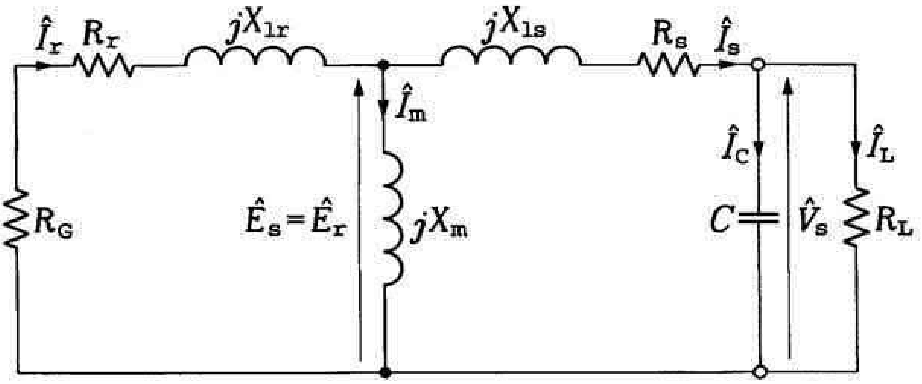
The excitation capacitors are standard motor-starting capacitors that are used to provide the required reactive power for excitation which would otherwise be supplied by the utility grid. The induction generator will self-excite using these external capacitors only if the rotor has sufficient residual magnetism. In the self-excited mode, the generator output frequency and voltage are affected by the rotational speed, the turbine load, and the capacitance value in farads of the capacitors. Then in order for self-excitation of the generator to occur, there needs to be a minimum rotational speed for the value of capacitance used across the stator windings. The ―Self-excited induction generator‖, (SEIG) is a good candidate for wind powered electric generation applications especially in variable wind speed and remote areas, because they do not need external power supply to produce the magnetic field. A three-phase induction generator can be converted into a variable speed single-phase induction generator by connecting two excitation capacitors across the three-phase windings. One of value C amount of capacitance on one phase and the other of value 2C amount of capacitance across the other phase.

2.1.5 Principle of operation



An induction generator produces electrical power when its rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, the synchronous speed is 1800 rotations per minute (rpm). The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM. The motor normally turns slightly slower than the synchronous speed; the difference between synchronous and operating speed is called "slip" and is usually expressed as per cent of the synchronous speed. For example, a motor operating at 1450 RPM that has a synchronous speed of 1500 RPM is running at a slip of +3.3%. In normal motor operation, the stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, with the currents in the rotor induced at the slip frequency. In generator operation, a prime mover (turbine or engine) drives the rotor above the synchronous speed (negative slip). The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils and the motor now operates as a generator, sending power back to the electrical grid.

2.1.5.1 Excitation



Per-phase equivalent circuit of the stand-alone induction generator

An induction machine requires externally supplied armature current. Because the rotor field always lags behind the stator field, the induction machine always "consumes" reactive power, regardless of whether it is operating as a generator or a motor. A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself. An induction machine can be started by charging the capacitors, with a DC source, while the generator is turning typically at or above generating speeds. Once the DC source is removed the capacitors will provide the magnetization current required beginning producing voltage. An induction machine that has recently been operating may also spontaneously produce voltage and current due to residual magnetism left in the core.

2.1.5.2 Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm (typical example), full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

2.1.5.3 Required capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor. Consider, an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the stator pulls the rotor to run behind it (the machine is acting as a motor). Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.

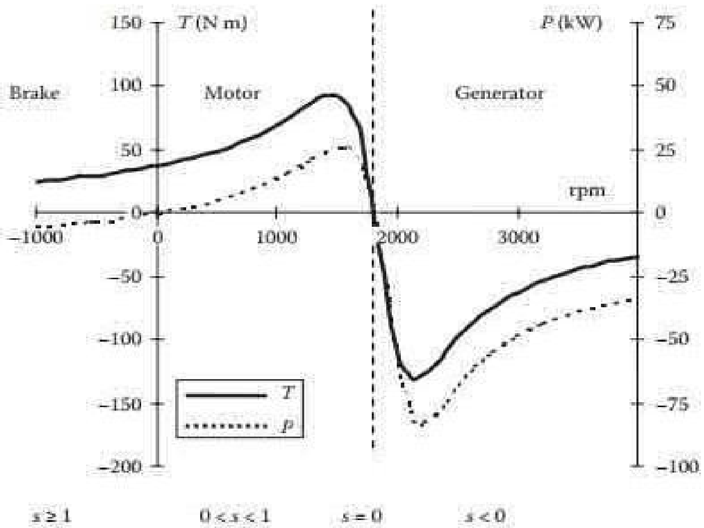
If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field. This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).

2.1.6 Torque-Slip characteristics

The basic fundamental of induction generators is the conversion between mechanical energy to electrical energy. This requires an external torque applied to the rotor to turn it faster than the synchronous speed. However, indefinitely increasing torque doesn't lead to an indefinite increase in power generation. The rotating magnetic field torque excited from the armature works to counter the motion of the rotor and prevent over speed because of induced motion in the opposite direction.

As the speed of the motor increases the counter torque reaches a max value of torque (breakdown torque) that it can operate until before the operating conditions become unstable. Ideally, induction generators work best in the stable region between the no-load condition and maximum torque region.

2.1.7 Torque–Speed characteristics



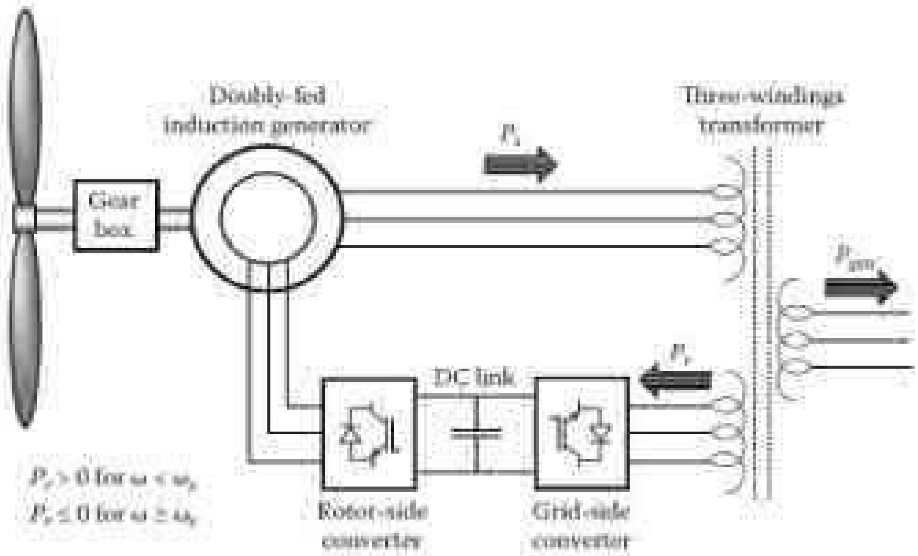
It can be observed that there is no torque at the synchronous speed. Both the torque–speed and the power–speed curves are almost linear since from no load to full load the machine‘s rotor resistance is much larger than its reactance. The resistance is predominant in this range, current and the rotor field as well as the induced torque increase almost linearly with the increase of the slip factors. The rotor torque varies as the square of the voltage across the terminals of the generator if the speed slows down close to the synchronous speed, the generator motorizes that is, it works as a motor; as we will show, the generated power has a maximum value for a given current drained from the generator in the same way, there is a maximum possible induced generator torque called pullout or breakdown torque, and from this torque value on, there will be over speed. The peak power supplied by the IG happens at a speed slightly different from the maximum torque, and, naturally, no electric power is converted into mechanical power when the rotor is at rest (zero speed). In the same way, in spite of the same rotation, the frequency of the IG varies with the load variation.

2. Construct the modelling of Squirrel cage Induction Generator with necessary equations.

Constructional features

Doubly fed electrical generators are similar to AC electrical generators, but have additional features which allow them to run at speeds slightly above or below their natural synchronous speed. This is useful for large variable speed wind turbines, because wind speed can change suddenly. When a gust of wind hits a wind turbine, the blades try to speed up, but a synchronous generator is locked to the speed of the power grid and cannot speed up. Therefore large forces are developed in the hub, gearbox, and generator as the power grid pushes back. This causes wear and damage to the mechanism.

If the turbine is allowed to speed up immediately when hit by a wind gust, the stresses are lower and the power from the wind gust is converted to useful electricity. One approach to allowing wind turbine speed to vary is to accept whatever frequency the generator produces, convert it to DC, and then convert it to AC at the desired output frequency using an inverter. This is common for small house and farm wind turbines. But the inverters required for megawatt-scale wind turbines are large and expensive. Doubly fed generators are one solution to this problem. Instead of the usual field winding fed with DC, and an armature winding where the generated electricity comes out, there are two three-phase windings, one stationary and one rotating, both separately connected to equipment outside the generator. Thus the term "doubly fed". One winding is directly connected to the output, and produces 3-phase AC power at the desired grid frequency. The other winding (traditionally called the field, but here both windings can be outputs) is connected to 3-phase AC power at variable frequency. This input power is adjusted in frequency and phase to compensate for changes in speed of the turbine.



Wind turbine–powered DFIG with transformer-based utility connection

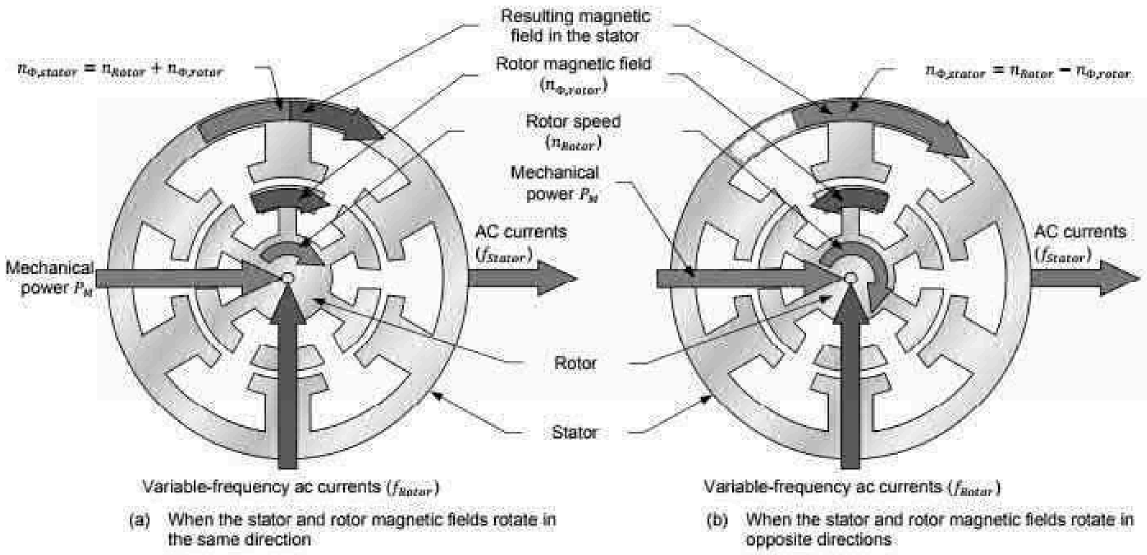
The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance when the remaining voltage stays above 15% of the nominal voltage. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. For zero voltage ride through it is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the reactive current should be injected.

2.1.1 Principle of operation

The principle of the Doubly-Fed Induction Generator (referred to as DFIG) is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converters that control both the rotor and the grid currents. Thus, rotor frequency can freely differ from the grid frequency (50 or 60 Hz). 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 but there are problems with efficiency, cost and size.

A doubly-fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances. Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason. Doubly-fed electric machine is connected to a selection of resistors via multiphase slip rings for starting. However, the slip power was lost in the resistors. Thus means to increase the efficiency in variable speed operation by recovering the slip power were developed.



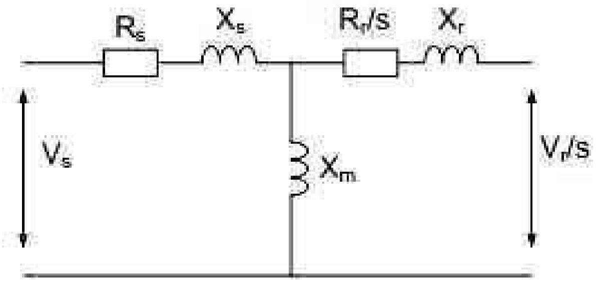
Interaction between the rotor speed and the frequency of the rotating magnetic field created in the rotor windings of a doubly-fed induction generator.

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. The control principle used is either the two-axis current vector control or direct torque control. Direct
torque control has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

2.1.2 Equivalent Circuit of DFIG

A doubly fed induction generator is basically a wound rotor induction generator fed by both stator and rotor, in which the stator winding is directly connected to the grid and the rotor winding is connected to the grid through AC/DC/AC converters. These converters are divided into two components: the rotor side converter and the grid side converter. A capacitor between the converters plays a role of a DC voltage source. A coupling inductor is used to link the grid side converter to the grid.

The operation principle of DFIG is fundamentally the same as that of a transformer. Thus, DFIG can be represented as a transformer‘s per phase equivalent circuit, where R_r and X_r represent rotor resistance and reactance referred to the stator side. But the equivalent circuit of induction machine differs from a transformer's primarily with respect to varying rotor frequency on the rotor voltage. In case of DFIG, there is a voltage injected to the rotor winding, so an equivalent circuit of classic induction machine needs to be modified by adding a rotor injected voltage as shown in Figure. In this figure, *s* is the rotor slip, *V* the voltage, *I* the current, *R* and *X* represent resistance and reactance, respectively. The subscripts *r; s* and *m* stand for rotor, stator and mutual, respectively.



The Equivalent Circuit of DFIG

Real and reactive power in the stator side like P_s and Q_s delivered to the connected grid can be derived from I_s and *Vs* as in (1):

$$P_s = 3Re(V_s I_s^*)$$

$$Q_s = 3Im(V_s I_s^*) \qquad (1)$$

Real and reactive power in the rotor side, P_r , Q_r , referred to stator side is derived from I_r and V_r/s, as in (2):

$$P_r = 3Re\left(\frac{V_r}{s} I_r^*\right)$$

$$Q_r = 3Im\left(\frac{V_r}{s} I_r^*\right) \qquad (2)$$

It is possible to express the electromechanical torque, T_e , as in (3):

$$T_e = \frac{3}{2}\frac{p}{2} Re(j\Psi_s I_s^*) = \frac{3}{2}\frac{p}{2} Re(j\Psi_r I_r^*) \qquad (3)$$

where

$$\Psi_s = \frac{X_s I_s + X_m I_r}{\omega_s};\ \Psi_r = \frac{X_r I_r + X_m I_s}{\omega_S}$$

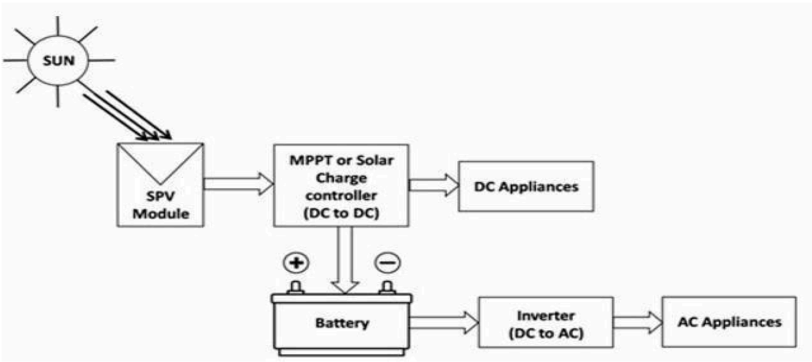
♥$_s$ and ♥$_r$: the stator and the rotor flux, respectively. p: the number of poles per phase.

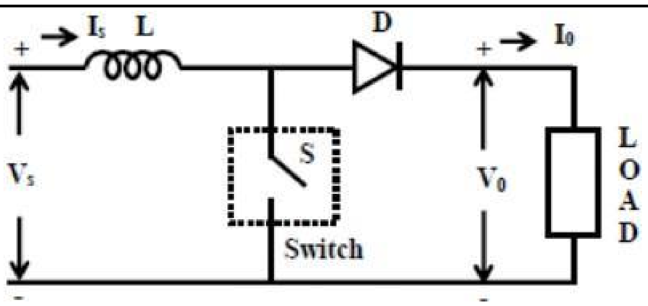
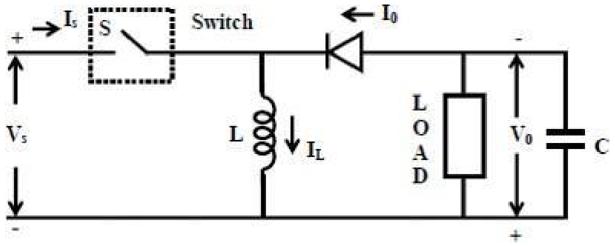
I_s^* I_r^* , : the complex conjugates of the stator and the rotor current, respectively.

UNIT III-
POWER CONVERTERS AND ANALYSIS OF SOLAR PV SYSTEMS

Part A

1.	**State the principle of PV effect. Mention some of the application.** Photovoltaic effect is the process of converting sunlight (photons) to electricity (voltage). Some of the application are calculators, wrist watches, satellites, water pumps, traffic signals, lights appliances etc.

2.	**Classify the types of solar PV 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.
3.	**Draw the block diagram of standalone PV system.**  Fig 1 Simple Block Diagram of Standalone SPV system
4.	**Specify the function of "dual function" inverter?**
	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.
5.	**Specify the function of charge controller?** 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.	**What is called "phase controlled Converter"** 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 controlledconverters".
7.	**What is called Line Commutated inverter?** 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".
8.	**What is called Load Commutated inverter?** The thyristors in the converter circuit while operating in the inverter mode requires load side counter emf for commutation and is referred to as the "Load commutated inverter".
9.	**Define firing angle.** It is defined as angle measured from the instant that gives maximum output voltage to the one at which it is actually triggered.
10.	**Draw the circuit of Boost converter.**

	
11	**Define duty ratio in power converter. How it is expressed?** Duty cycle or power cycle is the fraction of one period in which a signal or system is active. It is commonly expressed as a percentage or a ratio. It is denoted by 'K'. It ranges between 0 and 1.
	K=Ton/T
12.	**Draw the circuit of Buck-Boost converter.** 
13.	**What is sizing in solar electrical system?** Sizing is about calculating the number of solar modules and batteries that are needed to run the required number of appliances.
14.	**Predict the limitation of sizing?** 1. The weather records for the site may not be detailed enough to do an accuratecalculation of the module output. **2.** It is difficult to predict accurately how much electricity will be used each day.
15.	**Express the formula for calculating the daily requirements of one appliance?** **Power of Appliance (W) × Expected daily use of appliance (hours per day) = Daily requirement of one appliance (W h per day)**

Part B

1..Construct the block diagram of solar PV system and explain each component in brief.

<u>Photovoltaic (PV) Systems</u>

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 wristwatches. 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 (as when rays of sunlight are perpendicular to the PV modules). 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.

3.1 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.

3.2 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.

3.3.1 Introduction

A Solar PV panel produces DC electrical power, which is different from AC power that we receive from our electrical grid supply. There are appliances that use either DC power or AC power for their operation. Most of the equipment used in our homes use AC power. Therefore it is often required to convert DC power into AC power. The conversion of DC power to AC power can be achieved using a device called inverter (or DC to AC converter). It is also possible to convert AC power into DC power using a rectifier.

3.3.2 Block Diagram

Figure 1 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.

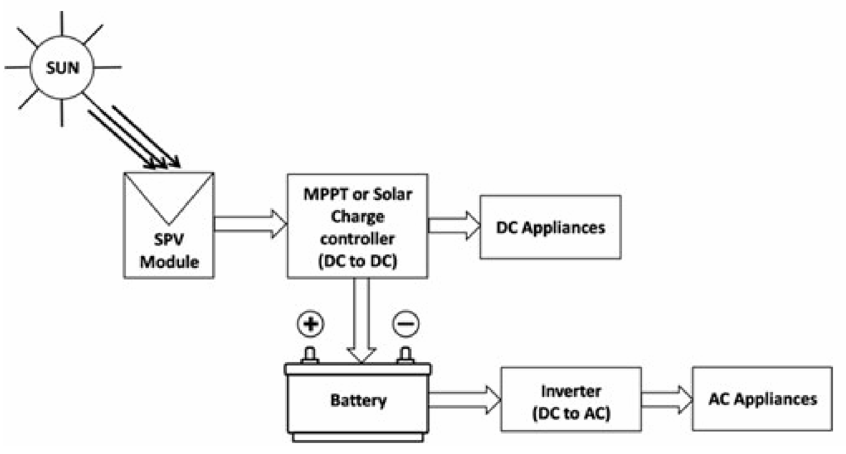
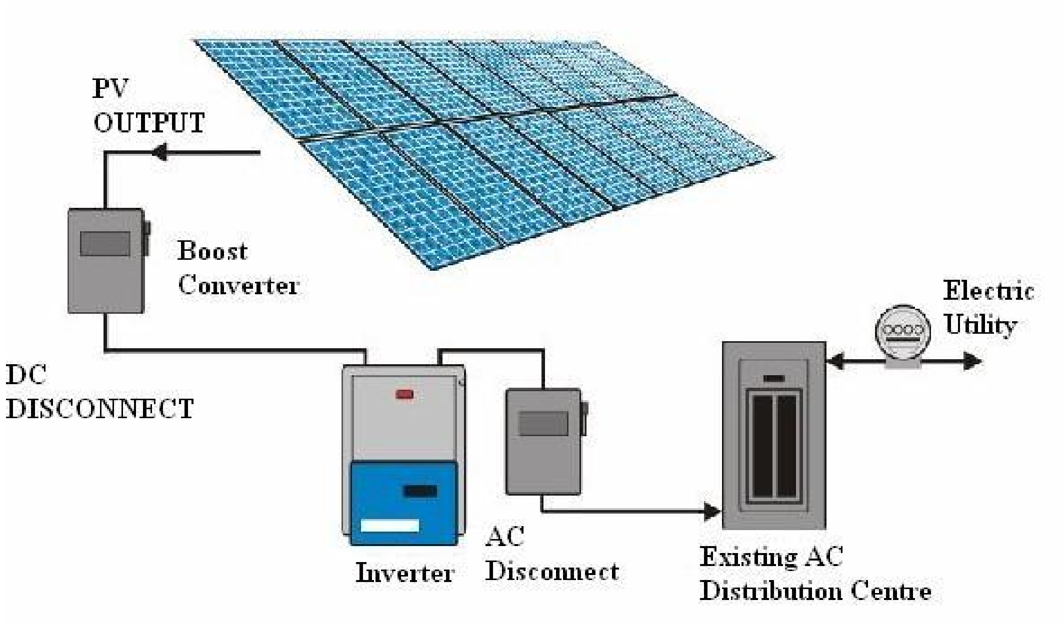


Fig 1 Simple Block Diagram of Standalone SPV system

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

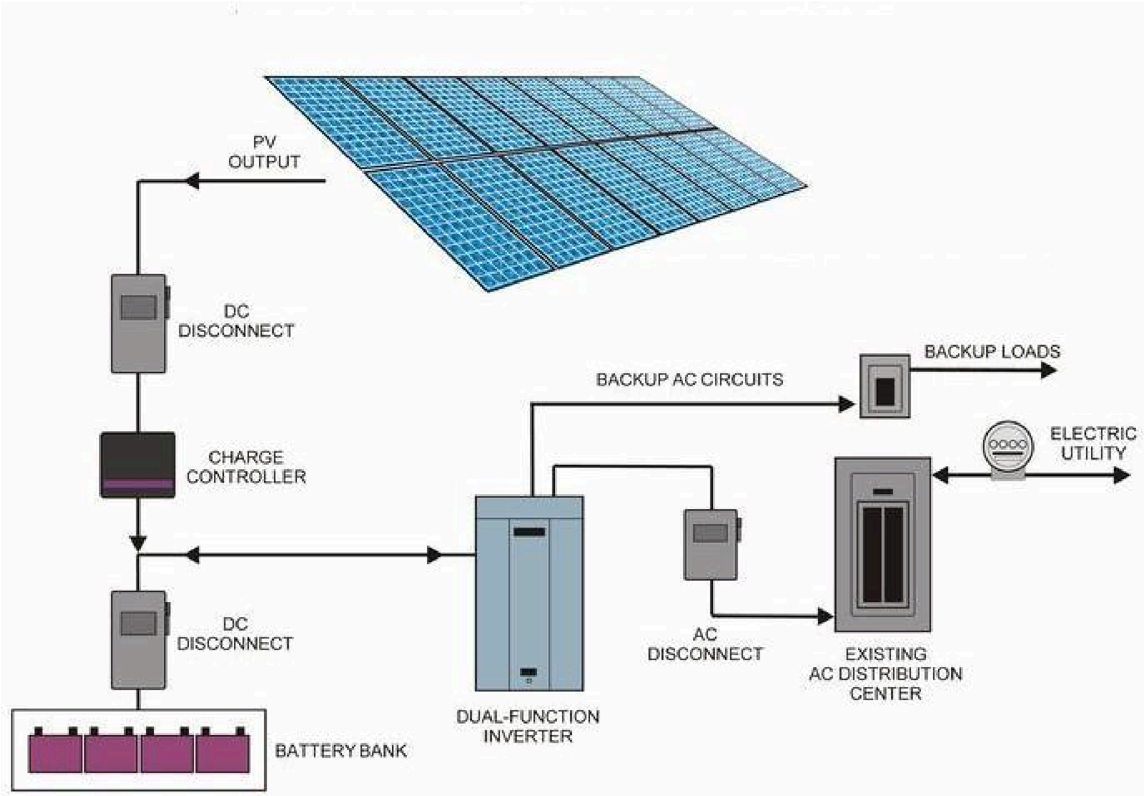
3.3 Typical Grid Tied System (Battery less)

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.



3.4 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.



Part C

1. Produce the line commutated converter with suitable waveform and explain the operating principle of inverting mode by necessary analysis and phasor diagram.

3.5 Line Commutated
Converters 3.6.1 Introduction

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".

In phase controlled rectifiers though the output voltage can be varied continuously the load harmonic voltage increases considerably as the average value goes down. Of course the magnitude of harmonic voltage is lower in three phase converter compared to the single phase circuit. Since the frequency of the harmonic voltage is higher smaller load inductance leads to continuous conduction. Input current wave shape become rectangular and contain 5th and higher order odd harmonics. The displacement angle of the input current increases with firing angle. The frequency of the harmonic voltage and current can be increased by increasing the pulse number of the converter which can be achieved by series and parallel connection of basic 6 pulse converters. The control circuit become considerably complicated and the use of coupling transformer and / or inter phase reactors become mandatory.

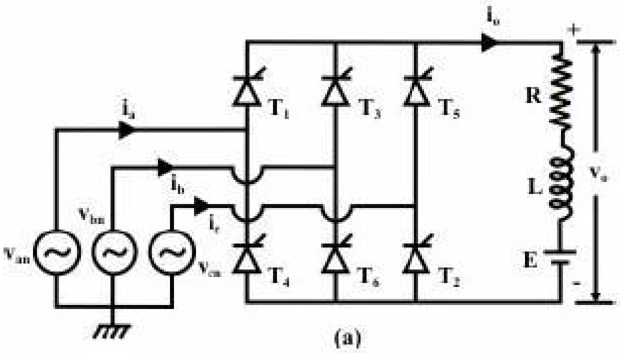
With the introduction of high power IGBTs the three phase bridge converter has all but been replaced by dc link voltage source converters in the medium to moderately high power range. However in very high power application (such as HV dc transmission system, cycloconverter drives, load commutated inverter synchronous motor drives, static scherbius drives etc.) the basic B phase bridge converter block is still used. In this lesson the operating principle and characteristic of this very important converter topology will be discussed in source depth.

3.6.2 Operating principle of 3 phase fully controlled bridge converter

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig. 4 (a)

For any current to flow in the load at least one device from the top group (T_1, T_3, T_5) and one from the bottom group (T_2, T_4, T_6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct.

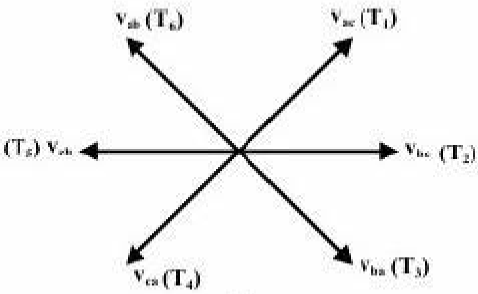
Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence $T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5 \rightarrow T_6 \rightarrow T_1$ with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T_1T_2, T_2T_3, T_3T_4, T_4T_5, T_5T_6, T_6T_1. Each conduction mode is of 60° duration and appears in the sequence mentioned. The conduction table of Fig. 4 (b) shows voltage across different devices and the dc output voltage for each conduction interval. The phasor diagram of the line voltages appear in Fig. 4 (c). Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T_1 is fired at the end of T_5T_6 conduction interval. During this period the voltage across T_1 was v_{ac}. Therefore T_1 is fired α angle after the positive going zero crossing of v_{ac}. Similar observation can be made about other thyristors. The phasor diagram of Fig. 4 (c) also confirms that all the thyristors are fired in the correct sequence with 60° interval between each firing.



(a)

Device / Mode	v_{T1}	v_{T2}	v_{T3}	v_{T4}	v_{T5}	v_{T6}	v_o
T_1T_2	0	0	v_{ba}	v_{ca}	v_{ca}	v_{cb}	v_{ac}
T_2T_3	v_{ab}	0	0	v_{ca}	v_{cb}	v_{cb}	v_{bc}
T_3T_4	v_{ab}	v_{ac}	0	0	v_{cb}	v_{ab}	v_{ba}
T_4T_5	v_{ac}	v_{ac}	v_{bc}	0	0	v_{ab}	v_{ca}
T_5T_6	v_{ac}	v_{bc}	v_{bc}	v_{ba}	0	0	v_{cb}
T_6T_1	0	v_{bc}	v_{ba}	v_{ba}	v_{ca}	0	v_{ab}
NONE	-	-	-	-	-	-	E

(b)



(c)

Fig 4: Operation of Fully Controlled Bridge Converter (a) Circuit Diagram (b) Conduction Table

(a) Phasor Diagram of Line Voltages

Fig. 5 shows the waveforms of different variables (shown in Fig. 4.1 (a)). To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 4.1 (c). If the converter firing angle is α each thyristor is fired "α" angle after the positive going zero crossing of the line voltage with which it's firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 4.1 (b). Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the "six pulse" converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.

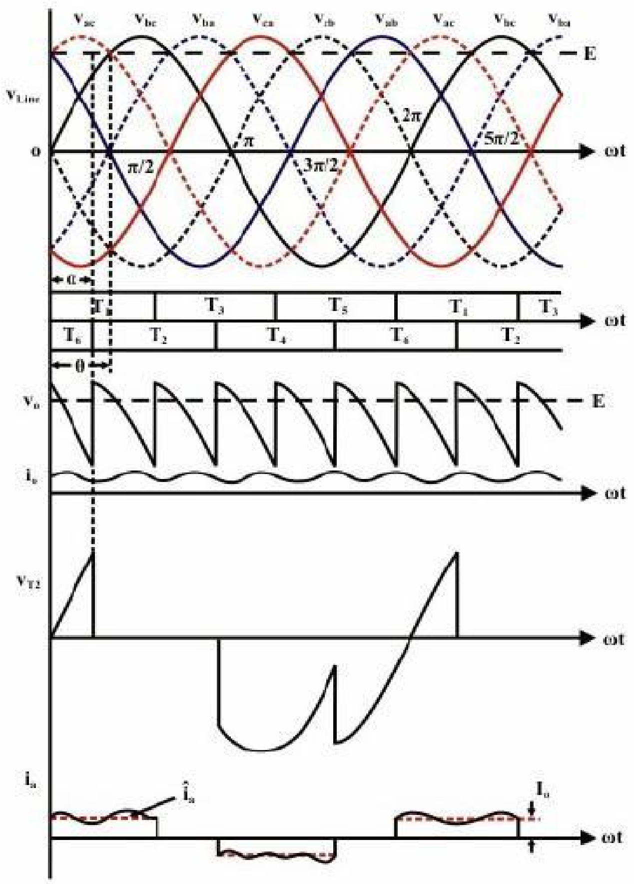


Fig 5 Waveforms of Three Phase Fully Controlled Converters in rectifier mode

3.6.3 ANALYSIS OF CONVERTER IN THE RECTIFIER MODE

The output voltage waveform can be written as

$$v_0 = V_0 + \sum_{K=1,2}^{\alpha} V_{AK} \cos 6K\omega t + \sum_{K=1,2}^{\alpha} V_{BK} \sin 6K\omega t \qquad (4.1)$$

$$V_0 = \frac{3}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \, d\omega t = \frac{3\sqrt{2}}{\pi} V_L \int_{\alpha}^{\alpha+\frac{\pi}{3}} \sin\left(\omega t + \frac{\pi}{3}\right) d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \qquad (4.2)$$

$$V_{AK} = \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \cos 6K\omega t \, d\omega t$$

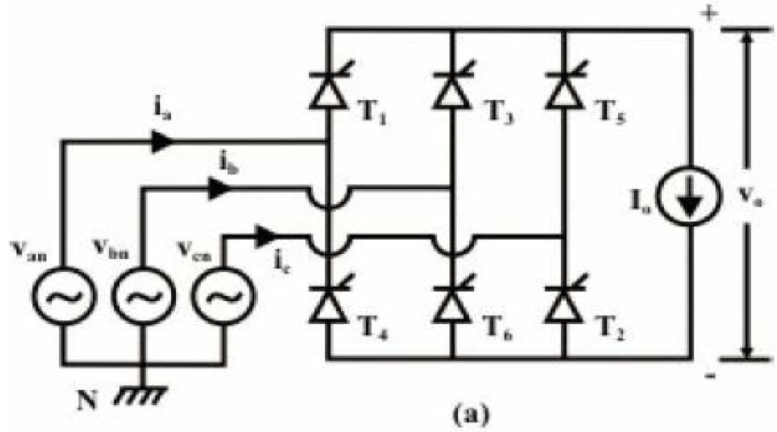
$$= \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} \sqrt{2}\, V_L \sin\left(\omega t + \frac{\pi}{3}\right) \cos 6\,\omega t \, d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \left[\frac{\cos(6K+1)\alpha}{6K+1} - \frac{\cos(6K-1)\alpha}{6K-1}\right] \qquad (4.3)$$

$$V_{BK} = \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \sin 6K\omega t \, d\omega t$$
$$= \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} \sqrt{2}\, V_L \sin\left(\omega t + \frac{\pi}{3}\right) \sin 6\omega t \, d\omega t$$
$$= \frac{3\sqrt{2}}{\pi} V_L \left[\frac{\sin(6K+1)\alpha}{6K+1} - \frac{\sin(6K-1)\alpha}{6K-1}\right] \qquad (4.4)$$
$$V_{0RMS} = \sqrt{\frac{3}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0^2 \, d\omega t} = V_L \left[1 + \frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right]^{\frac{1}{2}}$$

3.6.4 Analysis of the converter in the inverting mode.

In all the analysis presented so far it has been assumed that α < 90°. It follows from equation 4.2 that the output dc voltage will be positive in this case and power will be flowing from the three phase ac side to the dc side. This is the rectifier mode of operation of the converter. However 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 [Fig. 4 (a)] would have to be reversed for inverter mode of operator. Fig. 6 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.



(a)

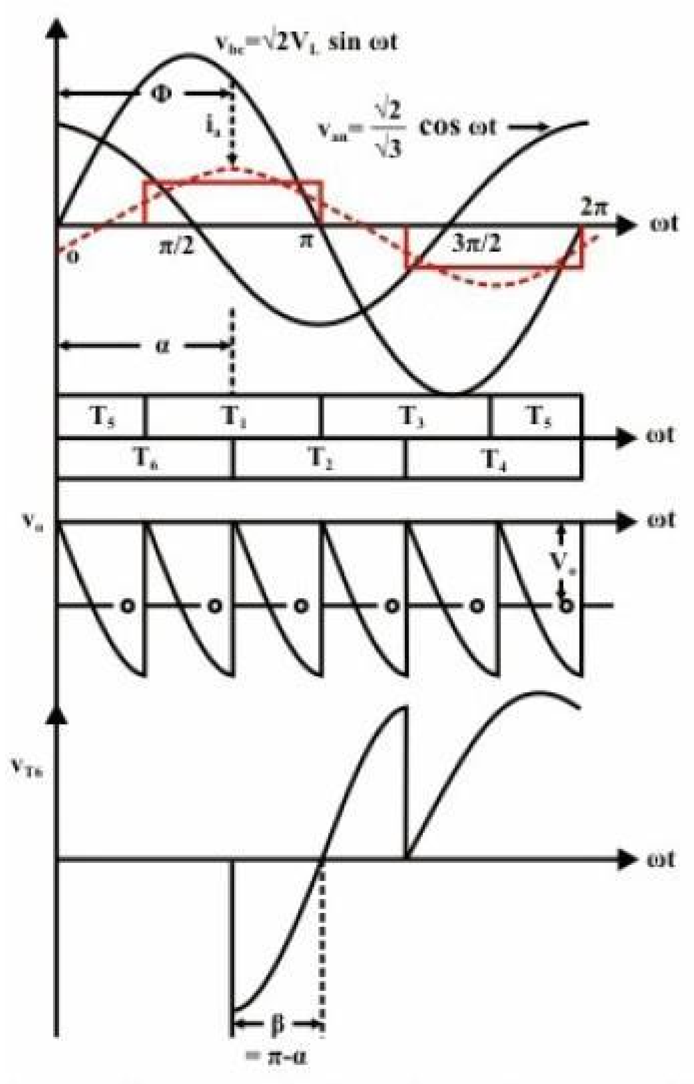


Fig 6: Invertering Mode of Operation of Three Phase Fully Controlled Converter (a) Circuit Diagram (b) Waveforms

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

$$V_0 = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \qquad (4.5)$$

$$i_{a1} = \frac{2\sqrt{3}}{\pi} I_0 \cos(\omega t - \alpha) \qquad (4.6)$$

For values of α in the range 90° < α < 180° it is observed from Fig. 6 (b) 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 Fig. 6 (b) that an outgoing thyristor (thyristor T_6 in Fig. 6(b)) 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.,

$\beta \geq \omega tq$, tq is the thyristor turn off time Therefore $\pi-\alpha \geq \omega tq$ or $\alpha \leq \pi-\omega tq$.

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

7. Design and operate the boost converter by constructing the circuit and waveform. Also model the analysis of boost converter.

<u>BOOST CONVERTER</u>

The boost converter, also known as the step-up converter, is another switching converter that has the same components as the buck converter, but this converter produces an output voltage greater than the source. The ideal boost converter has the five basic components, namely a power semiconductor switch, a diode, an inductor, a capacitor and a PWM controller. The placement of the inductor, the switch and the diode in the boost converter is different from that of the buck converter. The basic circuit of the boost converter is shown in Fig. 7.

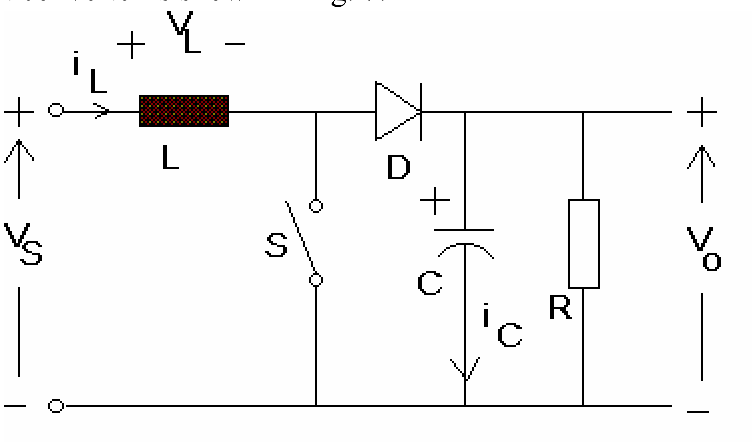


Fig 7 Boost Converter

The operation of the circuit is explained now. The essential control mechanism of the circuit in Fig. 7 is turning the power semiconductor switch on and off. When the switch is ON, the current through the inductor increases and the energy stored in the inductor builds up. When the switch is off, current through the inductor continues to flow via the diode D, the RC network and back to the source. The inductor is discharging its energy and the polarity of inductor voltage is such that its terminal connected to the diode is positive with respect to its other terminal connected to the source. It can be seen then the capacitor voltage has to be higher than the source voltage and hence this converter is known as the boost converter. It can be seen that the inductor acts like a pump, receiving energy when the switch is closed and transferring it to the RC network when the switch is open.

When the switch is closed, the diode does not conduct and the capacitor sustains the output voltage. The circuit can be split into two parts, as shown in Fig. 8. As long as the RC time constant is very much larger than the on-period of the switch, the output voltage would remain more or less constant.

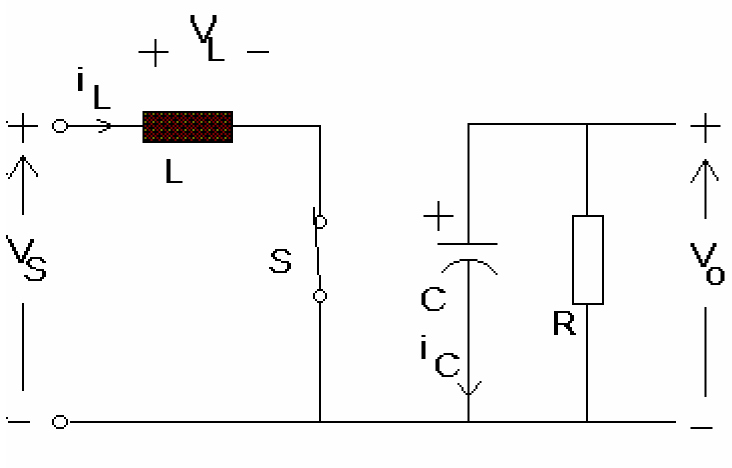


Fig 8 When Switch S is closed

When the switch is open, the equivalent circuit that is applicable is shown in Fig. 9. There is a single connected circuit in this case.

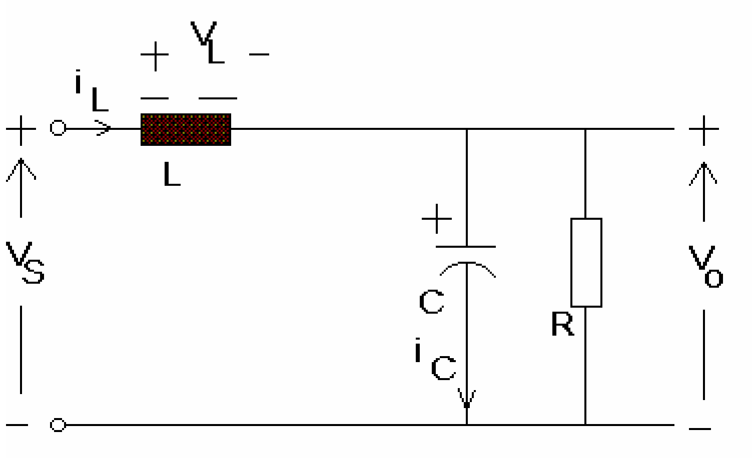


Fig 9 When Switch S is open

3.7.1 ANALYSIS OF THE IDEAL CIRCUIT

Analysis of the circuit is carried out based on the following assumptions. The circuit is ideal. It means when the switch is ON, the drop across it is zero and the current through it is zero when it is open. The diode has zero voltages drop in the conducting state and zero current in the reverse-bias mode. The time delays in switching on and off the switch and the diode are assumed to be negligible. The inductor and the capacitor are assumed to be lossless.

1. The responses in the circuit are periodic. It means especially that the inductor current is periodic. Its value at the start and end of a switching cycle is the same. The net increase in inductor current over a cycle is zero. If it is non-zero, it would mean that the average inductor current should either be gradually increasing or decreasing and then the inductor current is in a transient state and has not become periodic.
2. It is assumed that the switch is made ON and OFF at a fixed frequency and let the period corresponding to the switching frequency be T. Given that the duty cycle is D, the switch is on for a period equal to DT, and the switch is off for a time interval equal to (1 - D)T.
3. The inductor current is continuous and is greater than zero.
4. The capacitor is relatively large. The RC time constant is so large, that the changes in capacitor voltage when the switch is ON or OFF can be neglected for calculating the change in inductor current and the average output voltage. The

average output voltage is assumed to remain steady, excepting when the change in output voltage is calculated.

5. The source voltage V_S remains constant.

3.7.2 Inductor Current with Switch Closed

When the switch is closed, the equivalent circuit that is applicable is shown in Fig. 8. The source voltage is applied across the inductor and the rate of rise of inductor current is dependent on the source voltage V_S and inductance L. The differential equation describing this condition is:

If the source voltage remains constant, the rate of rise of inductor current is positive and remains fixed, so long as the inductor is not saturated. Then equation (1) can be

$$L\frac{di_L}{dt} = v_S(t) \quad (1)$$

expressed as :

$$\frac{\Delta i_L}{\Delta t} = \frac{V_S}{L} \quad (2)$$

The switch remains ON for a time interval of DT in one switching cycle and hence DT can be used for T. The net increase in inductor current when the switch is ON can be obtained from equation (2) to be:

3.7.3 Inductor Current with Switch Open

When the switch is open, the circuit that is applicable is shown in Fig. 9. Now the

$$\Delta I_L = \frac{V_S}{L} \times (DT) \quad (3)$$

$$v_L = V_S - V_o \quad (4)$$

voltage across the inductor is:

Given that the output voltage is larger than the source voltage, the voltage across the inductor is negative and the rate of rise of inductor current, described by equation (5), is negative. Hence if the switch is held OFF for a time interval equal to (1 - D) T, the change in inductor current can be computed as shown in equation (6)

$$\frac{di_L}{dt} = \frac{V_S - V_o}{L} \quad (5)$$

$$\Delta I_L = \frac{V_S - V_o}{L} \times (1 - D)T \quad (6)$$

The change in inductor current reflected by equation (6) is a negative value, since $V_o > V_S$. Since the net change in inductor current over a cycle period is zero when the response $i_L(t)$ is periodic, the sum of changes in inductor current expressed by (4) and (6) should be zero. That is,
On simplifying equation (7), we get that

$$V_o = \frac{V_S}{1 - D} \quad (8)$$

$$\frac{V_S}{L} \times DT + \frac{-V_o}{L} \quad T = 0 \quad (7)$$

It has been stated that when $i_L(t)$ is periodic, the net change in inductor current over a cycle is zero. Since change in inductor current is related to its volt-seconds, the net volt- seconds of the inductor has to be zero. The expression for the net volt-seconds can be obtained from equation (7) and it can be seen that the numerator of equation (7) should be zero. That is,
The value of D varies such that $0 < D < 1$ and it can be seen from equation (8) that output voltage is greater than the source voltage, and hence this circuit is called the

$$V_S \times DT + (V_S - V_o) \times (1 - D)T = 0 \quad (9)$$

boost converter. The output voltage has its lowest value when D = 0 and then the output voltage equals the source voltage. When D approaches unity, output voltage tends to infinity. Usually D is varied such that $0.1 < D < 0.9$.

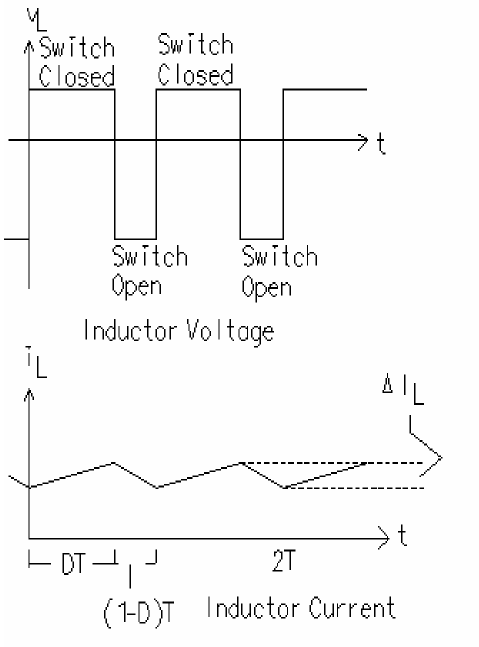


Fig 10

The waveforms of inductor voltage and inductor current are shown in Fig. 10. These waveforms are drawn assuming that both the output and the source voltage remain steady. These waveforms illustrate how the inductor voltage is related to its current.

3.7.4 Output Voltage Ripple with Switch Closed

In this sub-section, the change in output voltage is calculated. It needs to be emphasized that the peak-to-peak ripple in output voltage is quite small for a well-designed circuit. For the inductor, the net change in inductor current over a cycle is zero when $i_L(t)$ is periodic. For the capacitor, the net change in capacitor voltage over a cycle is zero when it is periodic. When the switch is closed, the equivalent circuit in Fig. 8 shows that the boost converter is split into two sub-circuits, with the loop currents decoupled from each other. When the switch is closed, the output voltage is sustained by the capacitor. During this period, the capacitor discharges part of its stored energy and it re-acquires this energy when the switch is open. When the switch is open, part of the inductor current charges the capacitor since the inductor current usually remains larger than the current through the load resistor. From Fig. 8,

$$i_C(t) = C\frac{dv_o(t)}{dt} \quad (10)$$

When current through a capacitor charges it up, its rate of rise of capacitor voltage is positive since the capacitor voltage is increasing. When the switch is open, the capacitor is discharging its energy with its voltage falling and the current through the capacitor is then a negative value. The output voltage remains positive and hence the output current is positive and it is the negative of the capacitor current, as can be seen from Fig. 8. Since the change in output voltage is quite small, it can be assumed that the load current remains constant at its average value and equation (10) can be now expressed as:

When the capacitor current is constant, its voltage changes linearly with time. Here the period for which the switch is closed is DT and the DT can be used in place of Δ T. The peak-to-peak ripple in output voltage expressed as Δ V_o and it is then expressed

$$i_C(t) \approx -\frac{V_o}{R} \quad (11)$$

as:

$$\Delta v_o = i_C \times (DT) = -\frac{V_o}{R} \times (DT) = -\frac{DV_o}{fR} \quad (12)$$

Equation (12) yields the value of the peak-to-peak ripple in output voltage. In equation (12), 1/f replaces T since T is the reciprocal of switching frequency.

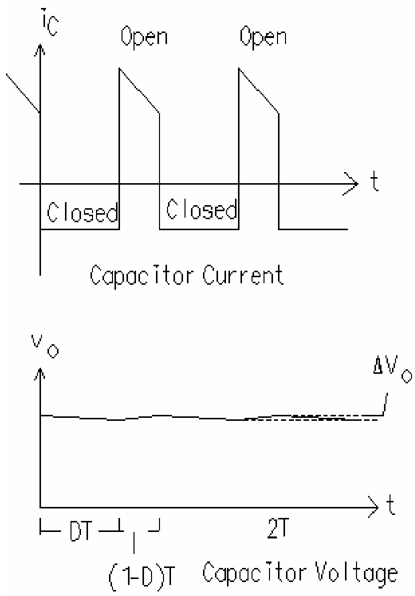


Fig 11

Figure 11 shows how the capacitor current and voltage vary over a cycle. The ripple in output voltage is exaggerated in Fig. 11, whereas in practice it would be much smaller. If the output voltage is drawn to scale, the ripple in output voltage would not be noticeable. **3.7.5 Expression for Average Inductor Current**

The average inductor current can be found out by equating the power drawn from the source to the power delivered to the load resistor. Again the ripple in output voltage is ignored and it is assumed justifiably that the output voltage remains steady at its average value. Power P_o absorbed by load resistor is then:

It can be seen from the circuit in Fig. 7 that the current drawn from the source flows through the inductor. Hence the average value of inductor current is also the average

$$P_o = \frac{(V_o)^2}{R} \quad (13)$$

value of source current. Let the average inductor current be I_L. Then power P_S supplied by the source is then:

$$P_S = V_S \times I_L \quad (14)$$

After equating equations (13) and (14), we get the average inductor current as:

$$I_L = \frac{(V_o)^2}{V_S \times R} \quad (15)$$

Since load current I_o is:

$$I_o = \frac{V_o}{R} \quad (16)$$

Using equations (8) and (16), equation (15) can be re-presented as:

$$I_L = \frac{I_o}{1-D} \quad (17)$$

Since $0 < D < 1$, it can be seen from equation (17) that $I_L > I_o$.

3.7.6 CONTINUOUS CONDUCTION

The analysis thus far is based on the assumption that the current through the inductor is continuous. The inductor current varies over a cycle, varying between a minimum value

and a maximum value. The minimum and maximum values can be expressed in terms of its mean value and its change as expressed in equation (3). That is,
and

$$I_{L,\min} = I_L - \left(\frac{\Delta I_L}{2}\right) \quad (19)$$

It is shown in Fig. 6 how the maximum and the minimum inductor current can be obtained. It is also shown that as the load resistor becomes greater, the average inductor current reduces, but the peak-to-peak ripple in inductor current does not change. It has to be so and expression for Δ I_L in equation (3) does not indicate any term reflecting the load resistor.

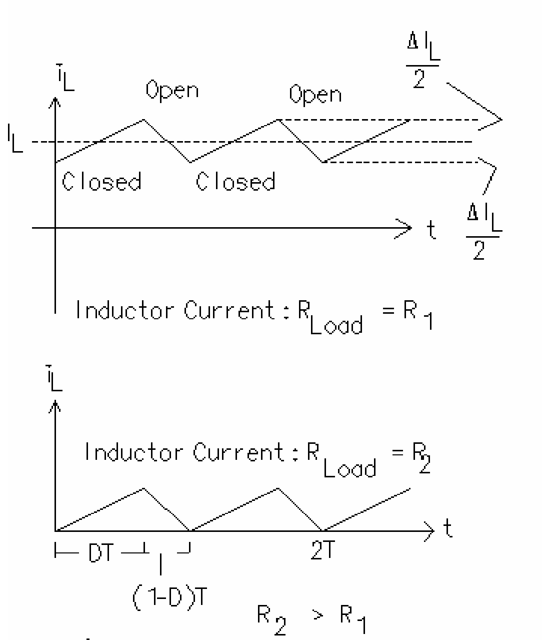


Fig 12

For continuous conduction,

$$I_L > \frac{\Delta I_L}{2} \quad (20)$$

At the boundary of continuous and discontinuous conduction,

$$I_L = \frac{\Delta I_L}{2} \quad (21)$$

Another expression for I_L is now obtained. Substituting for V_o in equation (15) the expression in equation (8), we obtain that
Substituting for I_L from the equation above and for i_L from equation (3), equation

$$I_L = \frac{V_S}{(1-D)^2 \times R} \quad (22)$$

(18) becomes:

$$I_{L,\max} = \frac{V_S}{[1-D]^2 R} + \left(\frac{(DT)V_S}{2L}\right) \quad (23)$$

and

$$I_{L,\min} = \frac{V_S}{[1-D]^2 R} - \left(\frac{(DT)V_S}{2L}\right) \quad (24)$$

From equations (23) and (24), the condition for continuous conduction is:

$$\frac{V_S}{[1-D]^2 R} > \left(\frac{(DT)V_S}{2L}\right) \quad , or$$

$$f > \frac{RD[1-D]^2}{2L}, where\ fT = 1 \quad (25)$$

Equation (25) can be interpreted as follows, assuming that only one of the four parameters is varied at a given time with the other three parameters remaining unchanged.
The circuit tends to become discontinuous,

i. if the switching frequency f is decreased, or
ii. if the duty cycle D is reduced, or
iii. if the load resistance increases, or
iv. if the inductance used has lower value.

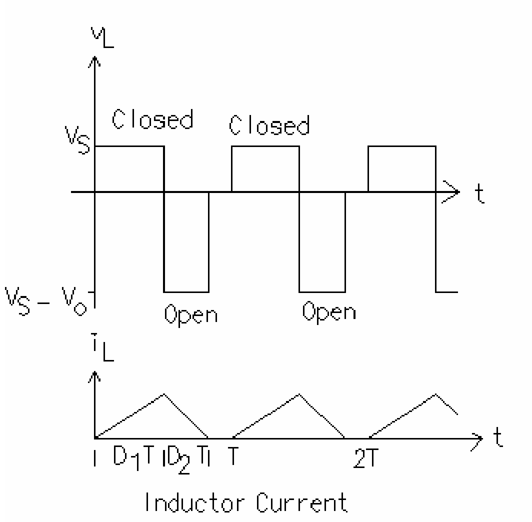


Fig 13

When the conduction is discontinuous, the voltage across the inductor is zero for part of the cycle since there is no current through the inductor. Let D_1T be the time for which the switch is ON in one cycle and let D_2T be the period for which the diode conducts. Since the conduction is discontinuous,

An expression for the output voltage can be obtained in terms of source voltage, duty cycle D_1 of the switch and duty cycle D_2 of the diode. Since the net change in inductor

$$(D_1 + D_2) < 1 \quad (26)$$

current is over a cycle, the net volt-seconds area associated with the inductor is zero. The waveforms relevant to the inductor when the conduction is discontinuous are shown in Fig. 13. From Fig. 13,

$$V_S \times D_1T + (V_S - V_o) \times D_2T \quad = 0 \quad (27)$$

On simplifying, an expression for V_o can be obtained. Then

$$V_o = V_S \times \left[\frac{D_1 + D_2}{D_2} \right] \quad (28)$$

The value of D_1, the duty cycle of the switch, is usually known, but the period for which the diode conducts is an unknown quantity depending on the other circuit parameters. The value of D_2can be determined in several ways. Here it is determined using the power balance between the input and output. When the circuit is ideal, the input power equals output power. Let the average source current be I_S and the average output current be I_o. Then

Using equation (28), we get that

$$I_S = I_0 \times \left[\frac{D_1 + D_2}{D_2}\right] = \frac{V_0}{R} \times \left[\frac{D_1 + D_2}{D_2}\right] = \frac{V_S}{R} \times \left[\frac{D_1 + D_2}{D_2}\right]^2 \quad (30)$$

The average source current be I_S can be obtained from Fig. 7. The average source current is the same as the average inductor current. Let the peak inductor current be ΔI_L and the period for which this current flows is (D_1T + D_2T). This period is the base of the triangle that defines the inductor current. The average inductor current is obtained as the area of this triangle divided by the cycle period. We have that

Equating equations (30) and (31),

$$\Delta I_L \times \left[\frac{D_1 + D_2}{2}\right] = \frac{V_S}{R} \times \left[\frac{D_1 + D_2}{D_2}\right]^2 \quad (32)$$

From equation (3),

$$\Delta I_L = \frac{D_1 T V_S}{L} = \frac{D_1 V_S}{fL} \quad (33)$$

Substituting for ΔI_L from equation (33) in equation (32), we get that

$$\frac{D_1}{2fL} = \frac{(D_1 + D_2)}{R \times (D_2)^2} \quad (34)$$

Equation (34) can be re-written as:

$$(D_2)^2 = \frac{2fL}{RD_1} \times (D_1 + D_2) \quad (35)$$

Solving for D_2,

$$D_2 = \frac{fL}{RD_1} \times \left[1 + \sqrt{1 + \frac{2RD_1^{\,2}}{fL}}\right] \quad (36)$$

Equation (36) states how D_2 varies as a function of R, D_1, f and L. Once D_2 is known, V_o can be obtained from equation (28).

It is possible to get an expression for V_o as a function of R, D_1, f and L. For this, we equate the average load current with the average diode current. The average output current can be obtained from the average output voltage and the load resistor. The average diode current is:

Using the expression for ΔI_L from equation (33), and replacing the L.H.S. by the average load current,

$$I_{D,avg} = \Delta I_L \times \frac{D_2}{2} \quad (37)$$

$$\frac{V_o}{R} = \frac{V_S D_1 D_2}{2fL}, \; where \; fT = 1 \quad (38)$$

Hence we obtain that

$$D_2 = \frac{2fL}{RD_1} \times \frac{V_o}{V_S} \quad (39)$$

By substituting for D_2 from equation (36) in the above equation, we can get an expression for V_o/V_S. Alternatively, equation (28) can be re-written as:

$$\frac{V_o}{V_S} = 1 + \frac{D_1}{D_2} \quad (40)$$

Using the expression for D_2 from equation (39) in equation (40),

$$\frac{V_o}{V_S} = 1 + \frac{RD_1^{\,2}}{2fL \times \left({V_o}/{V_S}\right)} \quad (41)$$

That is,

$$\left[\frac{V_o}{V_S}\right]^2 - \frac{V_o}{V_S} = \frac{RD_1^{\,2}}{2fL} \quad (42)$$

Solving for the ratio of output to source voltage and taking the positive root of the expression on the R.H.S. of equation (42),
Equation (43) states how (V_o/V_S) varies as a function of R, D_1, f and L

$$\frac{V_o}{V_S} = \frac{1}{2} \times \left[1 + \sqrt{1 + \frac{2RD_1^{\ 2}}{fL}} \right] \quad (43)$$

8. Design and operate the Buck-boost converter by constructing the circuit and waveform. Also model the analysis of Buck-boost converter.

3.6 BUCK BOOST CONVERTER

3.8.1 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 (if, 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.

3.8.2 Principle of Operation

The basic principle of the buck–boost converter is fairly simple (see figure 14 and 15):

- ✔ 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 ∞.

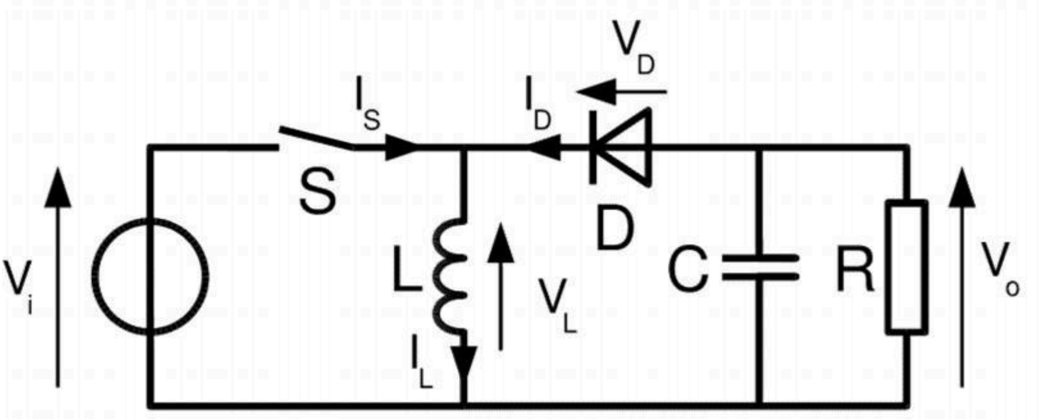


Fig 14 Buck Boost Converter

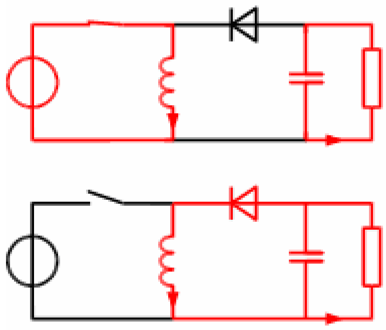


Fig. 15: The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load).
When the switch is opened, the inductor supplies current to the load via the diode D.

<u>**3.8.3** Continuous Conduction Mode</u>

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 16.
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
At the end of the On-state, the increase of I_L is therefore:

$$\frac{\mathrm{d}I_{\mathrm{L}}}{\mathrm{d}t} = \frac{V_i}{L}$$

$$\Delta I_{\mathrm{L_{On}}} = \int_0^{DT} \mathrm{d}I_{\mathrm{L}} = \int_0^{DT} \frac{V_i}{L}\,\mathrm{d}t = \frac{V_i\,DT}{L}$$

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:

$$\frac{\mathrm{d}I_{\mathrm{L}}}{\mathrm{d}t} = \frac{V_o}{L}$$

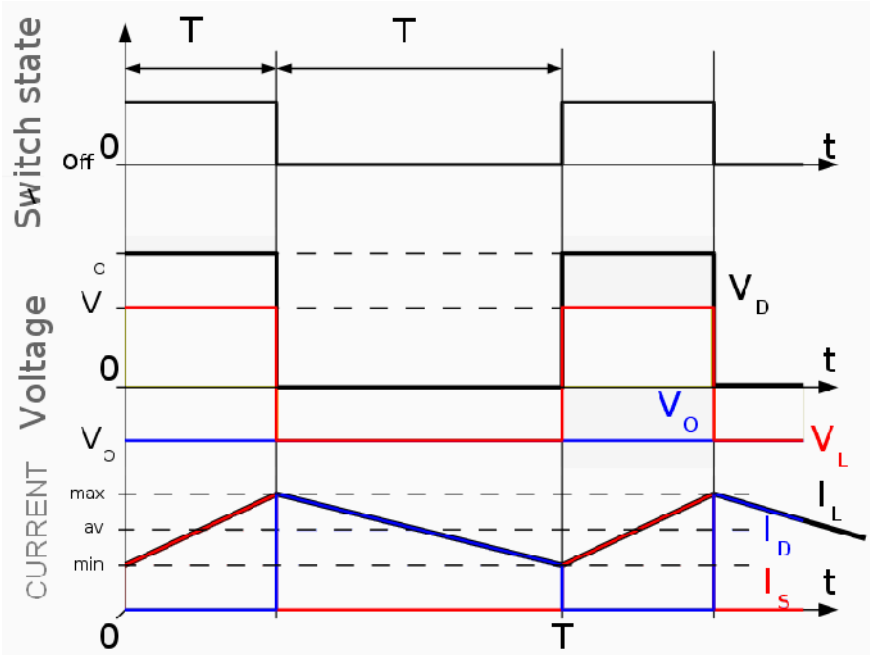


Fig 16: Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

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

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

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:

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

It is obvious that the value of I_L at the end of the off state must be the same as the value of 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:

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

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

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

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.

3.8.4 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 (see waveforms in figure 17). 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 $I_{L\max}$ (at $t = DT$) 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 17, 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:

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

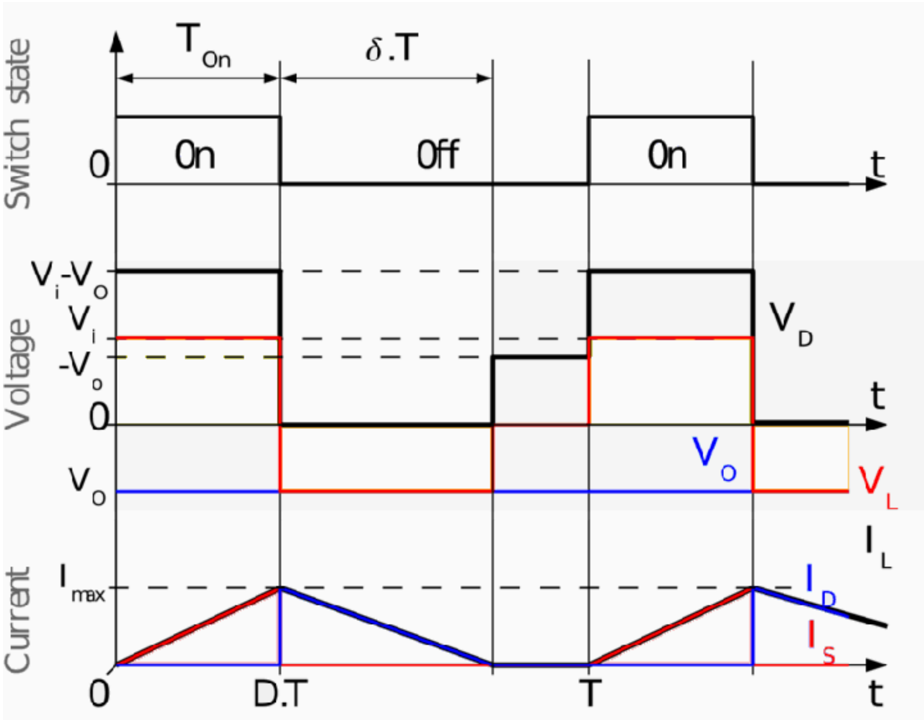


Fig 17: Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode

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.

3.Design the solar PV system based on sizing of Inverter, battery and array. Explain in detail with proper procedure.

Designing of PV system (Sizing of Inverter, Battery and Array)

It is very important for a photovoltaic designer to know how to find the suitable size of photovoltaic array to be installed in a certain building. To do this, he needs to take some factors into considerations and do some calculations.

Here are some basic principles to follow when designing a quality PV system:-

1. Select a packaged system that meets the owner's needs. Customer criteria for a system may include reduction in monthly electricity bill, environmental benefits, desire for backup power, initial budget constraints, etc. Size and orient the PV array to provide the expected electrical power and energy.
2. Ensure the roof area or other installation site is capable of handling the desired system size.
3. Specify sunlight and weather resistant materials for all outdoor equipment.
4. Locate the array to minimize shading from foliage, vent pipes, and adjacent structures.
5. Design the system in compliance with all applicable building and electrical codes.
6. Design the system with a minimum of electrical losses due to wiring, fuses, switches, and inverters.
7. Properly house and manage the battery system, should batteries be required.
8. Ensure the design meets local utility interconnection requirements.

3.9.2 Basic steps to be followed when installing a PV system:

1. Ensure the roof area or other installation site is capable of handling the desired system size.
2. If roof mounted, verify that the roof is capable of handling additional weight of PV system. Augment roof structure as necessary.
3. Properly seal any roof penetrations with roofing industry approved sealing methods.
4. Install equipment according to manufacturer's specifications, using installation requirements and procedures from the manufacturers' specifications.
5. Properly ground the system parts to reduce the threat of shock hazards and induced surges.
6. Check for proper PV system operation by following the checkout procedures on the PV System Installation Checklist.

7. Ensure the design meets local utility interconnection requirements
8. Have final inspections completed by the Authority Having Jurisdiction (AHJ) and the utility (if required).

3.9.3 Sizing of Solar Electric System

When we consider using solar electricity, we have to know exactly how many appliances have to power. Sizing is about calculating the number of solar modules and batteries that are needed to run the required number of appliances.

To do sizing, there are several steps to be followed. The first step is to add up the daily requirement for electricity of each of the appliances. This is based on the power rating of each appliances and the average length time it will be used in one day.

The next step is to calculate how much electricity will be produced by one module. This calculation uses weather records of sunshine for the site and the current output from one module. For big countries that sit on huge range of latitude (e.g. United States, Australia, China, and Africa) and countries that have 4 seasons a year, the records of sunshine will vary accordingly to the latitude and seasons. However, India sits on latitude of 6 ° 15 ' N and has only hot and humid climate. The sunshine record would be more constant. Next, the number of modules is calculated using the daily requirements of appliances and the daily output expected from one module.

Batteries are used to store electricity generated during sunny days for use during and after cloudy days. Sizing batteries are based on the daily requirement for electricity and the number of day's storage that is needed. Besides, it also depends on the recommended cycle depth for the type of battery to be used.

3.9.3.1 Limitations of Sizing

It is very important to realize that there is no sizing procedure is perfect. Therefore, the calculations that we get cannot be relied upon totally. The main problems with sizing are as follow:

1. The weather records for the site may not be detailed enough to do an accurate calculation of the module output.
2. Since the weather records are the summary of the past, they can only suggest what may happen on the future when the solar electricity will be used each day. After all, it is the law of the nature that the weather is unpredictable.

3. It is difficult to predict accurately how much electricity will be used each day.

One way of overcoming these limitations is to have extra modules and batteries which allow for periods of very bad weather. However, extra features will add on the cost of the project. Therefore, we have to balance the cost and the performance of the system in order to create the best application as possible.

3.7 Units of Consumption of Electricity

The unit that we measure for the consumption of electricity of a typical electrical appliance is kilo-watt hours (KWh) or watt hours (Wh) for small appliances. To calculate the daily requirement in Wh per day, we as the designer must first list down all the appliances that are expected to be used in the system. For each appliance, first find its power and decide the amount of time in hours that it will be used each day. The calculation of daily requirement for each appliance is as follow:-

$$\text{Power of Appliance (W)} \times \text{Expected daily use of appliance (hours per day)} = \text{Daily requirement of one appliance (W h per day)}$$

The power or wattage of an appliance can be found somewhere on the outside of the appliance, electrical tag attached to the cable or in the instruction book. Sometimes there are some appliances that has no power figure but only numbers with units of "V" and "A". Multiply these two numbers together to get the power of the appliance in W.

2. Mr. X decides to install a stand-alone PV system in his house. The first step that he has to do is to determine the total daily requirement of appliances of his house. The appliances in his house are as follow:

- **8 fluorescent tubes, 20 W each (4 hours per day)**
- **2 filament bulbs, 50 W each (2 Hours per day)**
- **One 10 W-DVD player (2 hours per day)**
- **One 80 W-color television (4 hours per day)**
- **2 cooling fans, 40 W each (6 hours per day)**
- **Refrigerator, 100 W (24 hours per day)**
- **Clothes iron, 1KW (30 minutes per day)**
- **Electric cooker, 3KW (1 hour per day)**
- **Air-conditioner 1.5hp (8 hours per day)**

Calculate the total daily electricity requirement of all the appliances in Mr. X's house.(1 hp = 0.7457 KW)

3.10.1 Calculation of Daily requirements of Appliances

Now, let us look at one example of calculation using the equation discussed above.
Mr. X decides to install a stand-alone PV system in his house. The first step that he has to do is to determine the total daily requirement of appliances of his house.
The appliances in his house are as follow:

- 8 fluorescent tubes, 20 W each (4 hours per day)
- 2 filament bulbs, 50 W each (2 Hours per day)
- One 10 W-DVD player (2 hours per day)
- One 80 W-color television (4 hours per day)
- 2 cooling fans, 40 W each (6 hours per day)

- Refrigerator, 100 W (24 hours per day)
- Clothes iron, 1KW (30 minutes per day)
- Electric cooker, 3KW (1 hour per day)
- Air-conditioner 1.5hp (8 hours per day)

Calculate the total daily electricity requirement of all the appliances in Mr. X's house. (1 hp = 0.7457 KW)

Solution

1.5 hp = 1.5 X 0.7457 K = 1.12KW

Appliance	Wattage (W)	Units	Hours per day	Total Requirement (KW h)
Fluorescent tubes	**20**	**8**	**4**	**0.640**
Filament bulbs	**50**	**2**	**2**	**0.200**
DVD player	**10**	**1**	**2**	**0.020**
Television	**80**	**1**	**4**	**0.320**
Fans	**40**	**2**	**6**	**0.480**
Refrigerator	**100**	**1**	**24**	**2.400**
Clothes iron	**1000**	**1**	**0.5**	**0.500**
Electric cooker	**3000**	**1**	**1**	**3.000**
Air-conditioner	**1120**	**1**	**8**	**8.960**
			TOTAL	**16.520**

3.10.2 Estimating the consumption for a PV system

The output from a solar cell module of 40 W peak output can reach about 150 W h per day. Recall that the total daily requirement of electricity for Mr. X's house is 16.52 KW h. Therefore at least 110 modules (16.52K / 150 = 110.1 modules) are required to meet a daily requirement of 16.52 KW h per day. This is a very large number of solar modules for just one home.

Clearly it is not economical to use solar electricity for running some of the appliances that are found in a home connected to the mains or a generator. When sizing for a solar system, the daily requirement can be significantly reduced the values in the previous example. Reductions are made by carefully decided which appliances need to be run on solar electricity and for how long they really need to be used each day.

For Mr. X's case, it is very obvious that air-conditioner is not suitable to be run using solar electricity. Therefore, we have to replace the air-conditioner by adding more low-power cooling fans. Electric cooker has to be eliminated from this system as the power consumed is too high.

Now, let us recalculate the requirement of solar electricity of Mr. X's house after considering the consumption of power for every appliances. The summary of calculation is shown below:

Table 2 after Reduction of Power Consumption

Therefore, the total daily requirement of electricity for Mr. X's house is **about 4 KW h**.

Appliance	Wattage (W)	Units	Hours per day	Total Requirement (KW h)
Fluorescent tubes	**8**	**8**	**4**	**0.256**
Filament bulbs	**10**	**2**	**2**	**0.040**
DVD player	**10**	**1**	**2**	**0.020**
Television	**20**	**1**	**4**	**0.080**
Fans	**30**	**5**	**8**	**1.200**
Refrigerator	**80**	**1**	**24**	**1.920**
Clothes iron	**900**	**1**	**0.5**	**0.450**
			TOTAL	**3.966**

The requirement has reduced about 75% from 16.52 KW h to 4 KW h. If using the solar module that can produce 150 W h per day, the minimum number of solar modules needed is about 27 (4 K / 150 = 27) for stand-alone photovoltaic system. The number of modules can be reduced if we choose modules that can produce higher power but certainly it will cost more.

In conclusion, the large reduction in requirement can be achieved by removing the high- power appliances and changing to the low-power appliances.

3.8 Average Daily Output from One Module

For a system with a generator, sizing is simple because the power output of the generator is constant. For photovoltaic system, sizing is much more complicated. This is because the amount of electricity generated each day depends on the rating solar module and on the amount of sunlight reaching the modules through the day.

3.11.1 Units of Daily Insolation

We know that the irradiance that reaching the surface of a module can be measured in units of watts per square meter (W/m^2). A different unit is used when measuring the total amount of light reaching the ground over a period of time.

For calculating the daily output of a solar module, the unit that we use is *peak-hours per day*. Peak hours are equivalent to the number of hours of sunlight at an irradiance of 1000 W/m^2. This value of irradiance is chosen because it is the same value as the Standard Test Conditions (STC) under which the electrical specifications of solar modules are measured. The value of 1000 W/m^2 also happens to be the highest irradiance that can be received on a surface facing the sun directly and when the sun is more than 45° above the horizon. Peak hours can also be given as KW/m^2 per days which are the same size.

3.11.2 Standard Test Conditions (STC)

1. Irradiance of 1000 W/m^2
2. Cell temperature of 25°C

3.11.3 Module Tilt

A solar module is always mounted at a certain angle of tilt from horizontal. The tilt angle should be at least 15° or more to ensure that the rain-water can drain off easily, and wash the dust away.

Here are 2 simple steps that can be followed to determine the tilt angle and the direction of the modules:-

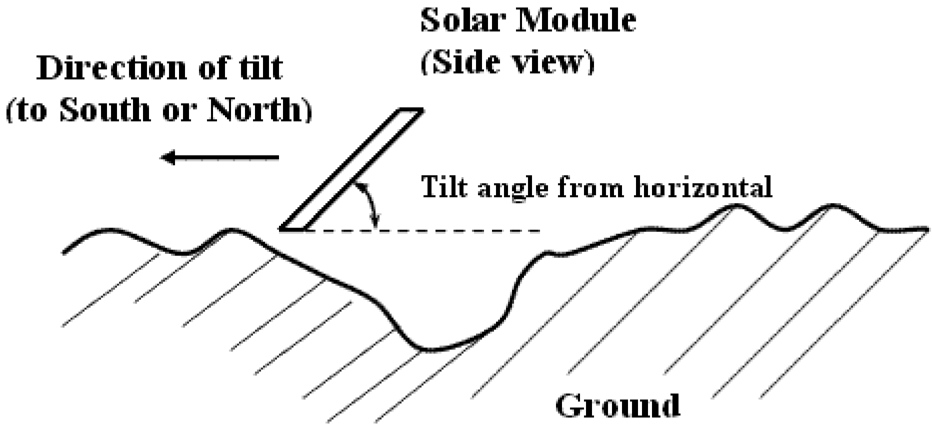
a) Set the tilt angle at the latitude angle of the site.

For sites at higher latitudes than 30°, the tilt angle can be set at the latitude angle plus 15°. This helps to even out the daily electrical output over the year by optimizing the tilt angle for the winter months.

For sites at latitudes between 15°S and 15°N (for Example, Malaysia), a tilt angle of 15° is used.

b) The direction of tilt should be set towards equator.

For countries at the North hemisphere of the earth (China, Malaysia, Japan etc.), the module should face South and for countries located at the South hemisphere of the earth (Australia, New Zealand etc.), the direction of the module should be North.



3.9 Selecting Suitable Modules for the Application

The number of cells needed in a module depends on the type of charge regulation to be used and the local temperature. Self-regulating modules with thirty o thirty-two cells are good for small solar systems. A separate charge-regulating unit is not needed, which keeps the system simple and low cost.

Modules with thirty-three or thirty-four cells and a charge regulator make better use of the available sunshine to charge batteries in the shortest time. Extra cells are needed in hot climates and in systems with large system losses to the batteries.

Table below shows a selection of a module for various types of systems and climates based on open circuit voltage in volts (V_{oc}) under Standard Test Conditions (STC) or number of cells in the module.

Application	Local Climate			
	Mild (below 30 °C at midday)		Hot (above 30 °C at midday)	
	Crystalline Silicon	Thin-film Silicon	Crystalline Silicon	Thin-film Silicon
Self-regulating, no diode	18 V (30 cells)	20 V	19 V (32 cells)	21 V
Self-regulating, with a diode	19 V (32 cells)	21 V	20 V (34 cells)	22 V
With a charge regulator	≥ 20 V (32 cells)	≥ 22 V	≥ 21 V (> 34 cells)	≥ 23 V

From the table we can find that V_{oc} for thin-film silicon is higher in each application. The number of cells for crystalline silicon is also increased in hot climate. However, both type of silicon produce higher voltages during hot weather compared to mild climate. This is because more power is absorbed during hot weather and thus higher voltage can be generated.

Besides, additional of 2 cells is needed for self-regulating crystalline-type with diode because it has to compensate voltage drop in the diode. Diode is used to avoid current from flowing back to the cells when the batteries are fully charged.

We have known that thin-film silicon cells can perform better than crystalline silicon cells. However, it is much more expensive than crystalline silicon cells. Therefore, we have to choose the suitable type of cells not only based on the performance but also our budget of the project. This section teaches us to choose suitable type of cells. The following section will teach us how to determine the daily output from the module that we have chosen here.

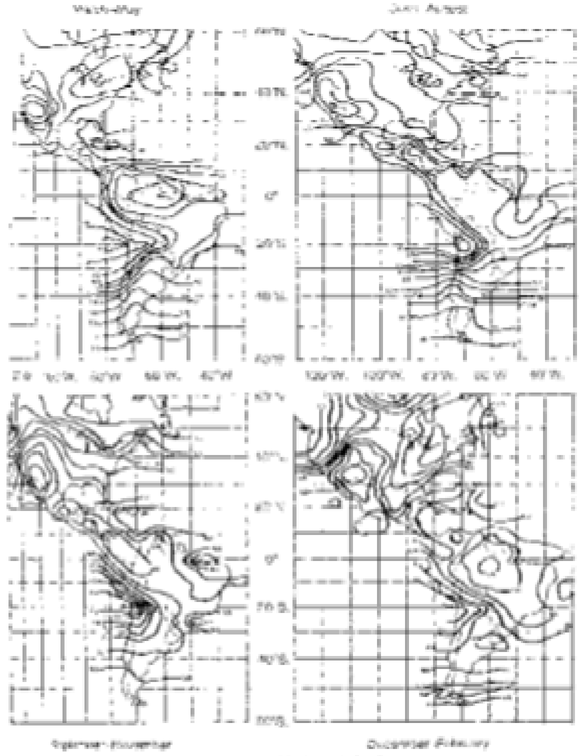
3.10 Determining the Daily Output from One Module

The maps shown below have sets of average daily insolation for most countries of the world. The averages are over three month periods and apply to modules tilted at the same angle as their angle of latitude.

For some sites, the country can be found directly on the maps. Otherwise, we can use a pencil to draw lines for the angles of latitude and longitude of the site so that the site is located where the lines cross. For each quarter of the year, choose the nearest curve of daily insolation and follow along this curve to the value of peak-hours per day. A more accurate estimate of daily insolation can be made by judging the position of the site between two curves. We will practice this method in the example on next section.

The daily electrical output from one module in units of *W h per day at 12 V* is calculated using the following formula:

Current at load or other current specification of module (A) × **Daily peak insolation (Peak-hours per day)** × **12 V** = **Daily output of one module (W h per day at 12 V)**



b. North and South America (longitudes 130°W. to 30°W.).

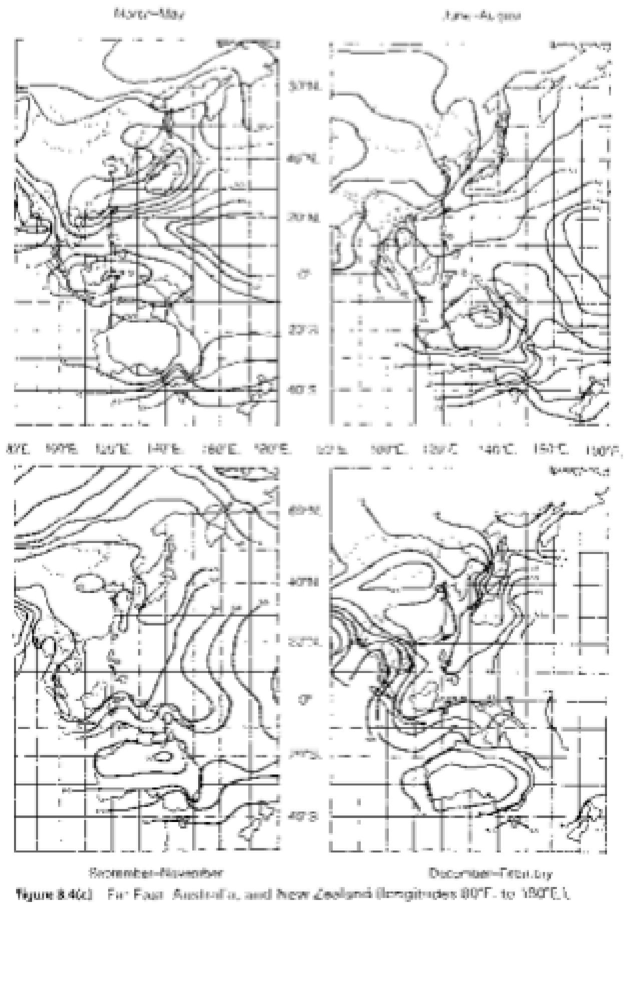


Figure 8.4(c) Far East, Australia, and New Zealand (longitudes 80°E. to 180°E.).

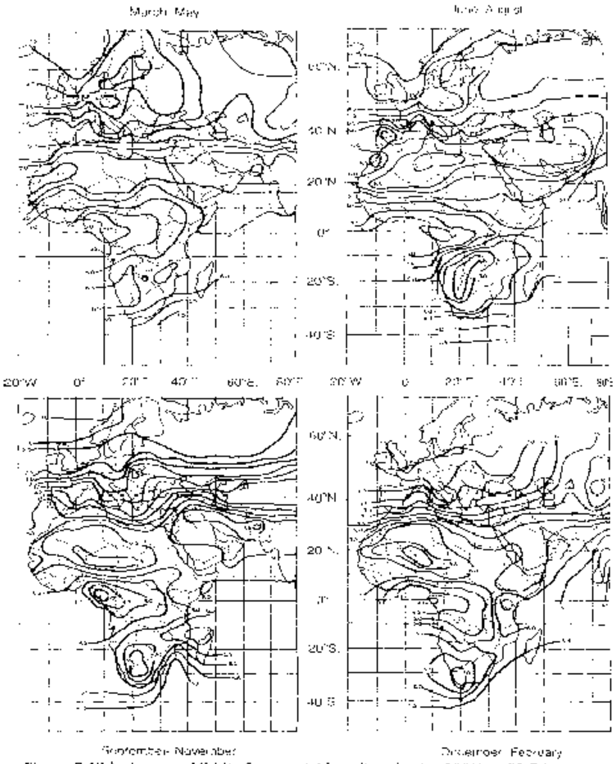


Figure 8.4(b) Europe, Middle East, and Africa (longitudes 20°W to 80°E)

The value of 12 V is chosen because it is the voltage at which the electricity is actually used by the appliances. For 24 V systems, 12 is still used because allowance for the higher voltage is made later when sizing the number of modules.

Example

From previous example, Mr. X has decided to install modules with a current at load of 4.5 A under STC in his house. His house is located in Kuala Lumpur. What will be the lowest daily electrical output of one module averaged over a three-month period?

Solution

Kuala Lumpur is at latitude of 3 ° 8 ' N. Based on the map, we can calculate the average output of a module over a three-month period using above Equation. The calculations are as follow:-

March - May

Average output = 4.5 X 5.5 X 12 = 297 W h per day at 12

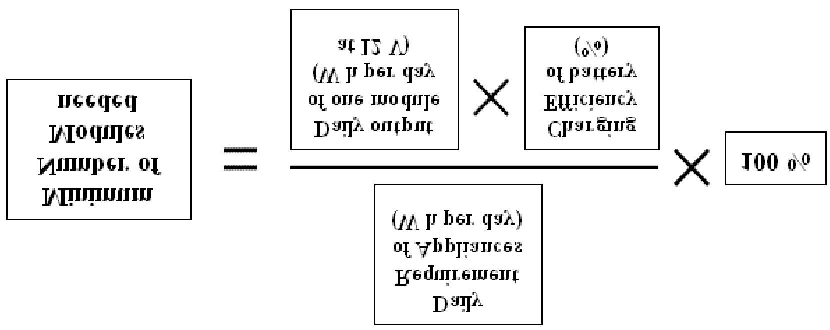
V. June - August

Average output = 4.5 X 4.6 X 12 = 248.4 W h per day at 12 V.
September - November
Average output = 4.5 X 5.0 X 12 = 270 W h per day at 12 V.
December - February
Average output = 4.5 X 5.4 X 12 = 294.6 W h per day at 12 V.
Therefore, we have determined that the lowest average daily output for Mr. X's module is 248.4 W h per day at 12 V for June to August. As Kuala Lumpur is located at latitude of 3 ° 8 ' N, the modules should be tilted at 15° from horizontal and facing South to generate electrical output.
There are some weaknesses to determine the average output of a module using the maps of daily insolation. The information given from the maps only gives an approximate indication of daily insolation. The values on the curves are averaged over three-month periods. There is no indication of how long the daily electrical output might get for one month.
Besides, setting the tilt angle of the module at the same angle as the latitude of the site may not be the optimum. On the small scale of the maps, they cannot take into account local variations which can be significant for some sites.
The suggestion to overcome the limitation is determine the average daily insolation for every month at the site. If meteorological records are available for the area of interest, they can be used to give a better estimate of daily electrical output expected from a module.

4. Estimate the number of modules needed for sizing with an example.

Sizing the Number of Modules Needed

Most appliances are used at night. Therefore they draw power from the batteries in stead of directly from the solar modules. When sizing the number of modules that are needed, the small loss of electricity when charging the batteries must be included. This is the current or A h charging efficiency. Typical values to use are 80% for lead-acid batteries and 70% for nickel-cadmium batteries.
The formula for sizing the minimum number of modules is as follow:



Example
Calculate the minimum number of modules needed by Mr. X from the values that we have determined from previous examples if he uses lead-acid batteries.
Solution
Daily requirement of appliances = 3.966 K
W h Daily output of one module = 248.4 W
h
Therefore, minimum number of solar modules needed by Mr. Lee is
= (3.966 K X 100) / (248.4 X 80)
= 19.96
That is 20 modules

3.14 Choosing the Right Battery

The first step in choosing a battery is to find out which ones are available. Then their details, specifications and price should be listed in a table. The price should include the cost of delivery to the site and all other incidental costs for each battery. The voltage supplied by a battery depends on the number and type of cells from which it is made. Batteries should be compared at the same voltage of 12 V. Below shows two tables we have to make and equations to help us to determine certain parameters in the table.

Number	Make and Model	[1]Nominal Capacity (A h)	Voltage (V)	Cost for One Battery			Cost for a 12 V battery
				Price	Transport and others	Total	
1							
2							
3							
.							
.							
.							

[1]At C/100 or C_{100} (measured for a full discharge over 100 hours)

Where
+

$$\text{Cost for a 12 V battery (Local Currency)} = \frac{\text{Total Cost of one battery (Local Currency)} \times 12\text{ V}}{\text{Nominal Voltage of one battery (V)}}$$

We can also use the following table to compare batteries by value for money of various aspects.

Number	Nominal Capacity (A h)	Cost for a 12 V battery	Usable cycle depth (%)	Cycle Life (Cycles)	Capacity (A h)		Relative value for money		
					Usable	Total Usable	One cycle	Cycle Life	Life
1									
2									
3									
.									
.									
.									

Table 5 comparing batteries by value for money of various aspects

Where

$$\text{Usable Capacity (A h)} = \text{Nominal Capacity (A h)} \times \frac{\text{Usable depth (\%)}}{100\ \%}$$

$$\text{Total usable capacity over cycle life (A h)} = \text{Usable capacity (A h)} \times \text{Cycle Life at usable depth (Cycle)}$$

At the last column of Table 5, each capacity figures is divided by price and to give a number which is "value for money". The higher the answer, the better value for money of battery.

Often the full specifications are not given to enable Table 5 to be completed. Table 6 lists typical specifications of various types of rechargeable batteries. This can be used a guide to complete the calculation of capacity figures. However, when comparing individual brands of batteries, always use the specifications for that brand provided by the supplier.

Table 6 Specifications for various types of rechargeable batteries that can be used in

Type of Battery	Usable depth (%)	Cycle Life (Cycles)	Calendar life (years)	[1]Self-discharge (capacity % per month)
Lead Acid				
Low antimony (for solar and stationary use)	50 80	3000 1200	8 4	3
Antimony-free: calcium Pure lead	20 50 80	1000 300	5 5 [2]15	3 3
High antimony: SLI for cars SLI for trucks Traction	20 80 50 80	 10 500 1500	1-3 5 6	30 10 7
Sealed: galled Starve electrolyte	50 [3]100 [3]100	400 200 250	8 8 8	3 10
Nickel-Cadmium				
Vented (pocket plate)	100	1200-2000	200	3
Sealed (sintered plate)	100	500-1000	4	30

[1] At 20 °C (68 °F) [2] Only applies when used on standby at float voltage
[3] Should recharge immediately

solar electric systems. The values are given for the purpose of comparison only.
Please refer to the specifications from individual suppliers where possible

There are two approaches to balancing the starting and running costs of a system:

1. To minimize the system cost at the start, aim for high usable capacity. However, the battery may have a short life.
2. To minimize the cost over the life of the battery, aim for a high value of total usable capacity over cycle life.

5.Estimate the number of batteries required for sizing by applying the required formula.

Sizing the Number of Batteries Needed

Batteries charge up during the day and ready to use at night. They also smooth out the variations of insolation. They do this by storing the excess charge received during sunny days and ready for use during cloudy days that follow. Therefore, the period of storage
required should be based on the maximum number of consecutive days with rain or heavy cloud.

Another purpose of batteries can be to provide seasonal storage and smooth out variations of daily insolation between months. A battery with low rate of self-discharge is essential for this purpose.

The usable capacity required is calculated from the daily electrical requirement and period of storage as follow:-

$$\text{Total Usable capacity needed (A h at 12 V)} = \frac{\text{Daily requirement of appliances (W h per day)} \times \text{Period of storage required (days)}}{12\ \text{V}}$$

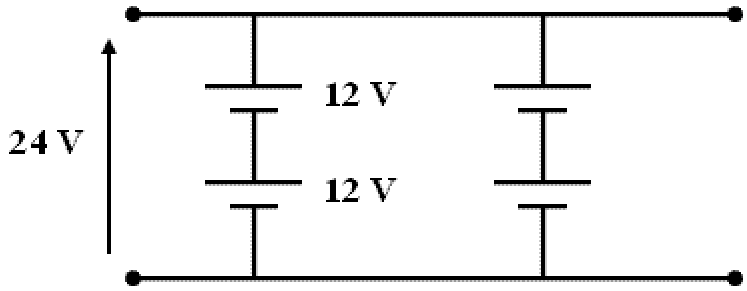
We have learnt how to select a rechargeable battery from those that are available at the previous section. For sizing, two specifications are required about the battery which we have selected. The specifications are:-

1. The full capacity in A h units.
2. The usable depth of discharge recommended for that type of battery, in percentage. The full capacity of a battery is measured as it is discharged to a specified voltage. However, most types of lead-acid battery should not be cycled over their full capacity or else their life is severely shortened. The percentage of charge used on each cycle of a battery is called cycle depth. To obtain the full life of a battery, the cycle depth should not exceed the depth recommended for that type of battery.

The number of batteries that are needed is calculated from the usable capacity and cycle depth as shown in equation below:-

$$\text{Minimum number of 12 V batteries needed} = \frac{\text{Total Usable capacity needed (A h in 12 V)}}{\text{Maximum depth of cycles (\%)} \times \text{Full Capacity specified for one 12 V battery (A h)}} \times 100\ \%$$

This calculation is based on nominal 12 V batteries. When batteries have a lower nominal voltage, they are connected in series to form 12 V batteries. Their voltages add for series connection while the over all capacity in A h is the same as for one battery.
For systems operating at 24 V, the wiring arrangement is to connect 12 V batteries in series pairs. The circuit is as shown bellow:-



In these 24 V systems, equation 7.8 still applies but the nearest even number above the answer should be used.

Example

We know that the daily requirement of appliances for Mr. Lee house is 4 KW h per day. Mr. Lee has decided to choose batteries which have a capacity of 500 A h. They are lead-acid batteries intended for deep-cycle operation and can be discharged to a depth of 65 %. What is the smallest number of batteries that can be used?

Solution

Since the estimate of period for storage is not given, we assume that 4 days of storage is adequate in Kuala Lumpur. Using Equation 7.7, the total usable battery capacity needed is:

(4 K X 4) / 12 = 1333.33A h at 12 V

Thus using Equation 7.8, the minimum number of batteries needed is:- (1333.33 X 100) / (500 X 65) = 4.103

Therefore, the minimum number of batteries that are needed is 5. If the system is running on 24 V, we take 6 batteries for the storage of the electricity for the system.

6..Select the suitable specification of inverter for AC and DC voltages Summarize it in brief.

SELECTION OF INVERTER

AC Voltage:

In the US, we can face a multitude of AC operating voltages as well as single or three-phase systems;

1. 120/240- single phase is used in residential applications. Inverters would connect to 240VAC in this application.
2. 240- three-phase is used for power loads in commercial and industrial buildings. This is a delta configuration. Across any one (of 3 transformers) there's 240V. On one side (only) of the delta. There is a center-tapped transformer which is connected to neutral. Thus providing 2x 120VAC for outlets.
3. 208Y/120-V three-phase four wire distribution is commonly used in commercial buildings with limited electrical loads. 120V is available between a pole and ground, while 208V is available between any two poles.
4. 480- Three phase delta is commonly used in commercial and industrial buildings with substantial motor loads.
5. 480Y/277- is used to supply commercial and industrial buildings. Between any two poles there's 480V, and between any pole and neutral there's 277V. The 277V is used for ballasted lighting. Local step-down transformers are typically inserted to provide 208Y/120-V power for lighting, appliances and outlets.

DC Voltage:

For inverters we have the following parameters when considering DC voltages;

1. The Maximum Power Point Transfer (MPPT or MPP) voltage range. This is the voltage range where the inverter employs its software algorithm to adjust its DC input impedance to that of the solar system. A solar PV string should be sized such that the inverter can normally operate within this range.
2. Maximum DC voltage; a solar PV string with no load (Vo) must under no circumstance ever exceed an inverters maximum DV voltage. When considering this factor, one must assume the lowest possible solar PV panel temperature while exposed to bright sunlight. This usually happens on a winter day with cumulus clouds. Here in Los Altos California, it is safe to assume a T (min) of -10C.

3. Minimum DC voltage; for tracking systems, the minimum DC voltage at which the inverter remains on-line is particularly critical to concentrated solar PV tracker performance. During cloud cover, a solar PV string's DC voltage can drop to a very low level. At some point, the inverter will decide to all-together stop production, and proceed with shutdown. Upon cloud clearing, a shut-down inverter, must now go through a start-up procedure during which it must monitor the AC voltage and frequency for a given time interval before going on-line.

String sizing:

Solar PV panels or receivers should be connected in series to form "strings". Strings should be connected in parallel to match an inverters power rating. A 10KW inverter should not be used together with a 1KW solar PV plant, because the inverter will never operate at its peak efficiency level. Inversely, a 10KW solar PV string should not be used to power a 1KW inverter. In this case, assuming VDC is not being violated, the inverter will simply produce 1KW.

String considerations for tracker operations:

A single tracker in an open field has no special requirements to string layout. On the other hand, as more trackers are added to a field, and the spacing between trackers become denser, trackers will inevitably shade their partners during early morning and late afternoons. This is a particularly important time because is happens to be at the time of day where;

1) The largest gain is made by using tracking vs. non-tracking
2) In the late afternoon, the energy costs are at their highest

While shading ultimately is inevitable, designing the proper string layout can mitigate the shading issue. Consider a simple heliostat, ie. a solar PV-panel-equipped-plane with 3 rows, which is pointed perpendicular to the sun. Rather than having a given solar PV string run zigzag between top, middle and bottom rows, it would be better to have a top, middle and bottom string. For commercial fields where 3-phase wiring is used, one may even consider installing 3 distinct inverters for each of the rows, where each inverter feeding 1 of 3 phases. Thus affording a dedicated MPP unit for each string.

UNIT IV - ANALYSIS OF POWER CONVERTERS FOR HYBRID ENERGY SYSTEMS

Part A

1. **What do you mean by power converter?**
   A power converter is an electrical circuit that changes the electric energy from one form into the desired form optimized for the specific load. There are several kings of converters based on the source input voltage and the output voltage and these falls into four categories namely the AC to DC converter known as the rectifier, the AC to AC clycloconverter or frequency changer, the DC to DC voltage or current converter, and the DC to AC inverter.
2. **State the principle of power converter.**
   The principle of operation of a converter is based on the switch mode action of its switches. Commutations of the switches generate very fast current and/or voltage transients so that the transient behavior of the sources is fundamental for converter design.
3. **Classify the main types of converter?**
   - AC-DC converter (rectifier)
   - AC-AC converter (cyclo converter or frequency converter)
   - DC-DC Voltage or current converter
   - DC-AC converter (Inverter)
4. **Specify the function of back-to back converter?**
   An important property of the back-to-back converter is the possibility of fast control of the power flow. By controlling the power flow to the grid, the dc-link voltage can be held constant.

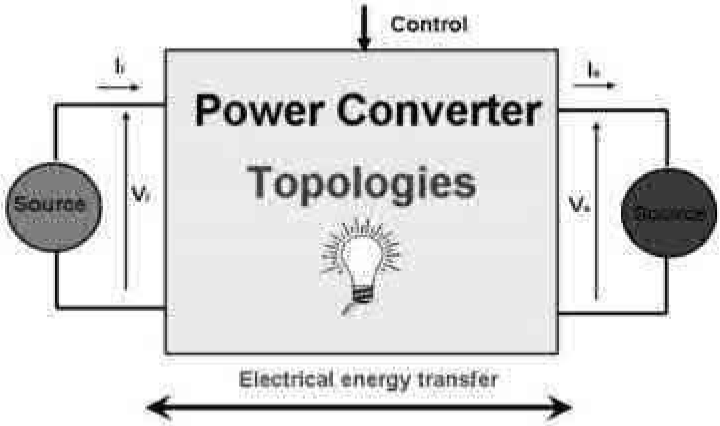
5. **Encounter the issues associated with a small DC- link capacitor?**
   - Smallest size of the dc-link capacitor is governed by the need to keep the switch-frequent ripple at acceptable (i.e. small) levels.
   - Fluctuations in the load cannot be smoothed in the converter, but must be accommodated by other means.
6. **How to overcome the issues associated with a small DC link capacitor?**
   - One alternative is to simply transfer such fluctuations to the power grid.
   - Another alternative is to use the load itself.
7. **What is rectifier?**
   A rectifier is a device that changes alternating current (AC) into direct current (DC).
8. **What is meant by uncontrolled rectifier?**
   The rectifier which uses uncontrolled power electronic devices as their power converting devices are known as uncontrolled rectifier.
9. **List the advantages of PWM techniques.**
   - Reduces harmonic distortion
   - Reduce noise in the output waveform
   - Improve the power quality
   - Reduce Electromagnetic interference
10. **Mention the function of PWM inverter.**
    It provide the fine control over the output voltage waveform in VSIs enabling accurate voltage and current regulation.
11. **List the various PWM techniques used.**
    - Single pulse width Modulation(SPWM)
    - Multiple pulse widt Modulation(MPWM)
    - Sinusoidal pulse width Modulation
    - Modified Sinusoidal oulse width Modulation
12. **Mention some of the application of PWM inverters.**
    - It is utilized in the speed AC drives where the speed of the drive is dependent on the variation in the frequency of the applied voltage.
    - Majorly the circuits in power electronics can be controlled by using PWM signals.
    - To generate the signals in analog form from digital devices like microcontrollers, the PWM technique is beneficial.
13. **Predict the function of soft start circuit?**
    It is used to delay the charging for 8 to 10 seconds after resuming the power. It is to protect the MOSFETs from the high currents. This is also referred to as Mains delay.
14. **Specify the function of change over circuit?**
    Based on the mains availability this circuit switches the operation of the inverter between the battery and the charging modes.
15. **Articulate the function of shut down circuit?**
    This circuit is to monitor the inverter closely and shut it down whenever any abnormality incurred.

Part B

1. Summarize the performance of power converter.

INTRODUCTION TO POWER CONVERTERS

The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for the user loads. Energy was initially converted in electromechanical converters (mostly rotating machines). Today, with the development and the mass production of power semiconductors, static power converters find applications in numerous domains and especially in particle accelerators. They are smaller and lighter and their static and dynamic performances are better. A static converter is a meshed network of electrical components that acts as a linking, adapting or transforming stage between two sources, generally between a generator and a load.



Power converter definition

An ideal static converter controls the flow of power between the two sources with 100% efficiency. Power converter design aims at improving the efficiency. But in a first approach and to define basic topologies, it is interesting to assume that no loss occurs in the converter process of a power converter.

A converter is an electrical circuit which accepts a DC input and generates a DC output of a different voltage, usually achieved by high frequency switching action employing inductive and capacitive filter elements.

A power converter is an electrical circuit that changes the electric energy from one form into the desired form optimized for the specific load. A converter may do one or more functions and give an output that differs from the input. It is used to increase or decrease the magnitude of the input voltage, invert polarity, or produce several output voltages of either the same polarity with the input, different polarity, or mixed polarities such as in the computer power supply unit.

The DC to DC converters are used in a wide range of applications including computer power supplies, board level power conver sion and regulation, dc motor control circuits and much more.

The converter acts as the link or the transforming stage between the power source and the power supply output. There are several kings of converters based on the source input voltage and the output voltage and these falls into four categories namely the AC to DC converter known as the rectifier, the AC to AC clyclo converter or frequency changer, the DC to DC voltage or current converter, and the DC to AC inverter.

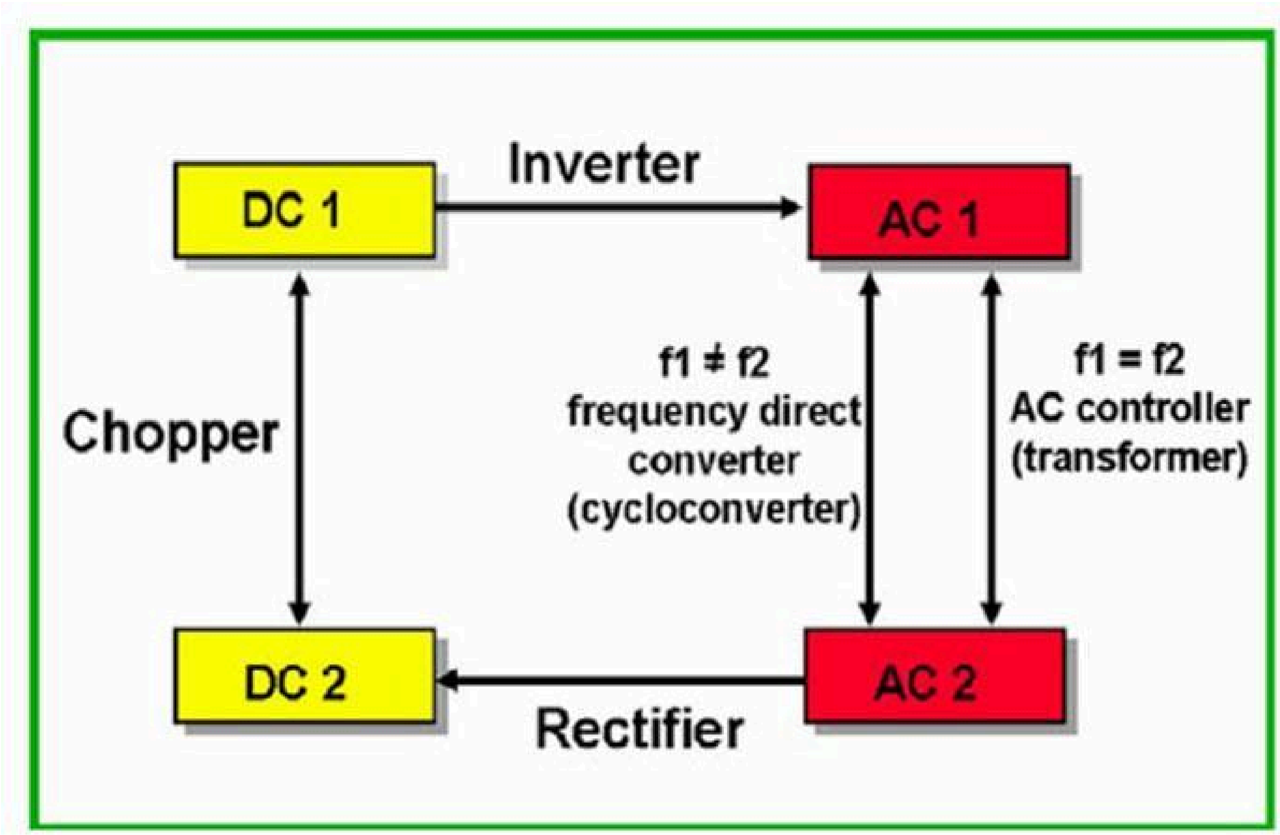


Fig 1 Power converter specifications

The converter uses non linear components such as the semiconductor switches, and linear reactive components such as the inductors, transformers and capacitors for intermediate energy storage as well as current and voltage filtering. The size, weight and cost of the converter are largely determined by these components.

There three basic converter circuits that are widely used in DC to DC converters are the buck, boost, and the buck and boost. These configurations are the most used topologies due to their simplicity and use of fewer components. Each has its advantages and drawbacks which determines the suitability for any specific application.

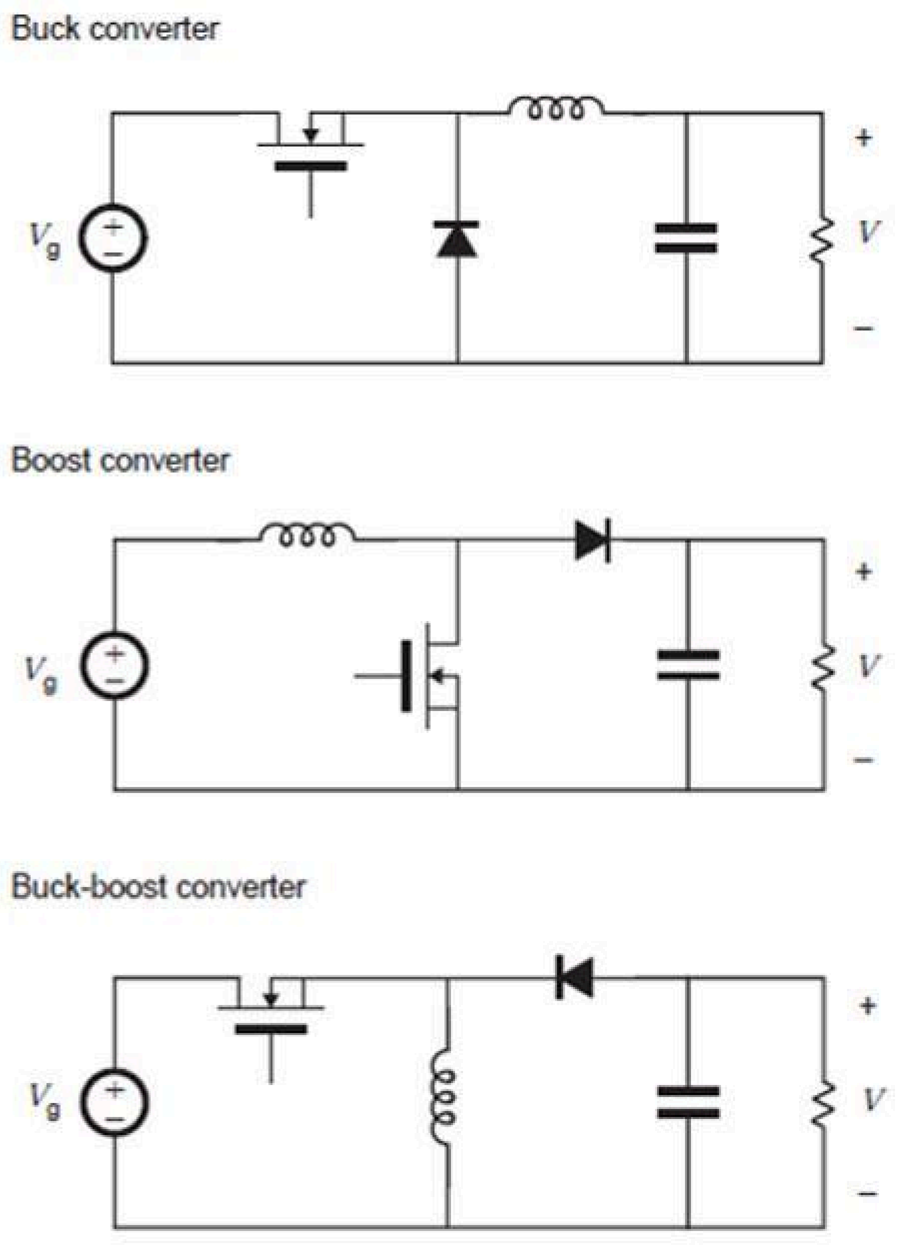


Figure 2 non-isolated converter circuit arrangements

The buck converter is a step-down, the boost a step-up while the buck-boost is both step-up and step-down. All these are non-isolated and use the inductor as the energy transfer element and are mostly used in board level power conversion and regulation.

The isolated dc to dc converters use a transformer to provide the isolation, multiple outputs, a different voltage level, or polarity depending on the turns ratios and directions of the windings.

They are based on the non-isolated topologies but with the inclusion of a transformer. The commonly used types are, the full bridge, the half bridge, forward and the push pull converters, which are the isolated versions of the buck; and the flyback which is the isolated version of the buck-boost converter.

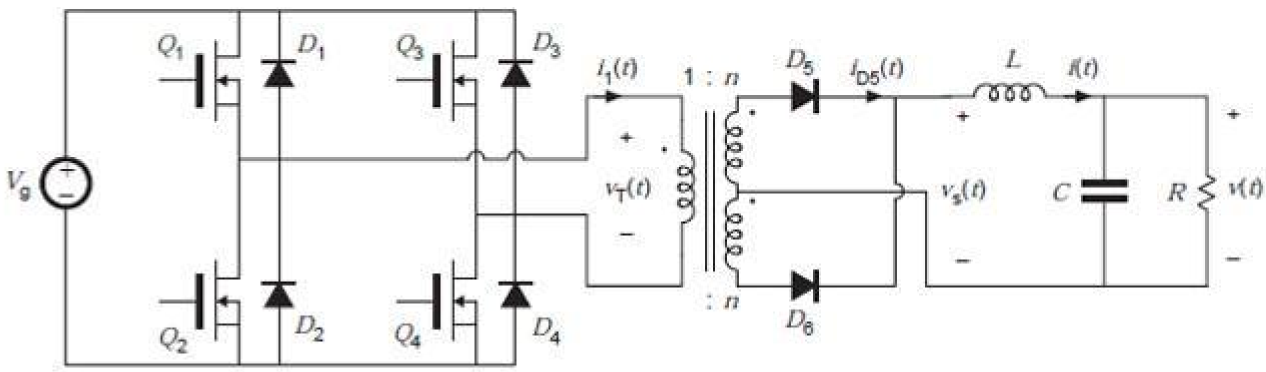


Figure 3 Full Bridge isolated buck converter

To improve performance, high frequencies and fast switching power semiconductor devices are used. The high frequencies increase the efficiency while reducing the physical sizes of the supplies since they allow the use of smaller components. The frequencies are usually above the audible range and in the range of between 20 KHz and 200 KHz. A feedback and duty cycle control circuit is usually used to adjust the turn-on and turn-off conditions to maintain a constant voltage at the output regardless of the load current or variations in the supply voltage.

Converters are widely used in the electronic equipment, in power supplies and other circuits requiring specific voltage and current levels other than the available raw supply energy. The converters provide any type of the required voltage at the desired magnitude. With a proper design and use of the almost ideal components, the available methods of conversion offer variety of reliable and efficient energy to power most of the electronic devices and components.

3.1 SOLAR PHOTO-VOLTAIC SYSTEM

3.1.1 Introduction

A photovoltaic system, also PV system or solar power system is a power system designed to supply usable solar power by means of photo-voltaic. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling and other electrical accessories to set up a working system. It may also use a solar tracking system to improve the system's overall performance and include an integrated battery solution, as prices for storage devices are expected to decline. Strictly speaking, a solar array only encompasses the ensemble of solar panels, the visible part of the PV system, and does not include all the other hardware, often summarized as balance of system . Moreover, PV systems convert light directly into electricity and shouldn't be confused with other technologies, such as concentrated solar power or solar thermal, used for heating and cooling.

PV systems range from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market. Operating silently and without any moving parts or environmental emissions, PV systems have developed from being niche market applications into a mature technology used for mainstream electricity generation.

3.1.2 Working and components of a PV system

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. For large-scale generation of solar electricity the solar panels are connected together into a solar array. The solar panels are only a part of a complete PV solar system. Solar modules are the heart of the system and are usually called the power generators. One must have also mounting structures to which PV modules are fixed and directed towards the sun.

For PV systems that have to operate at night or during the period of bad weather the storage of energy are required, the batteries for electricity storage are needed. The output of a PV module depends on sunlight intensity and cell temperature; therefore components that condition the DC (direct current) output and deliver it to batteries, grid, and/or load are required for a smooth operation of the PV system. These components are referred to as charge regulators. For applications requiring AC (alternating current) the DC/AC inverters are implemented in PV systems. These additional components form that part of a PV system that is called balance of system. The elements of a PV system are schematically presented in Figure 1.

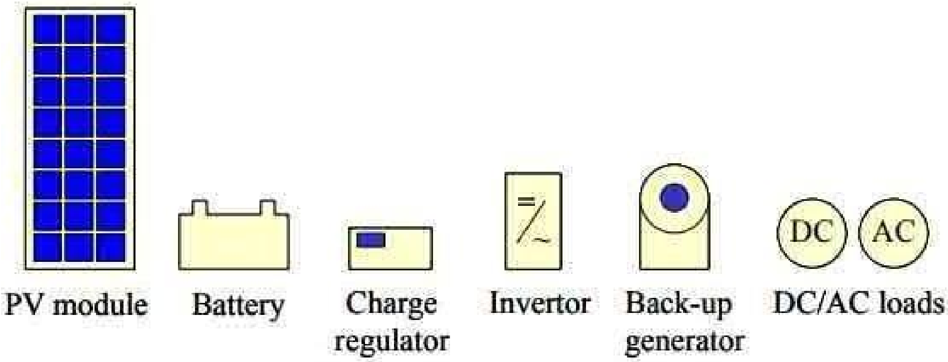


Figure 1: Components of a PV system

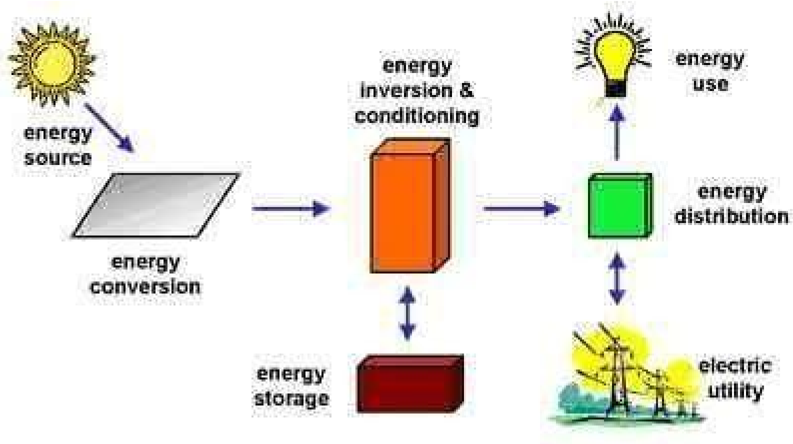
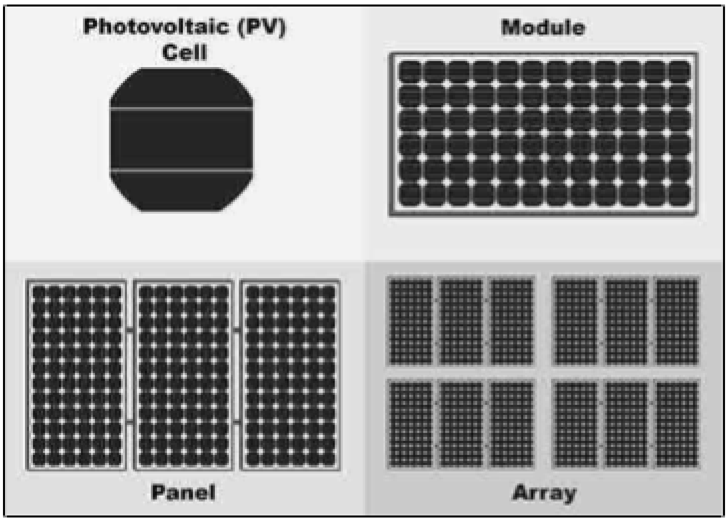


Figure 2: Major photovoltaic system components

Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances). In addition, an assortment of balance of system hardware, including wiring, over current, surge protection and disconnect devices, and other power processing equipment. Figure 2 show a basic diagram of a photovoltaic system and the relationship of individual components. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over discharge.

3.1.3 PV module and Array

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field- installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.



Photovoltaic cells, modules, panels and arrays

3.1.4 Mounting structures

The principal aim of the mounting structures is to hold the PV modules securely in place, which usually means that they have to resist local wind forces. When placed in a public area the structures should prevent stealing the modules. The further common requirements are not to cause shading of the modules and to be arranged so that there is an easy access to the modules for the maintenance or repair. The cost of the structures should be low. For integration in buildings, special mounting structures are being developed that together with the modules serve as building elements.

3.1.5 Energy storage

The simplest means of electricity storage is to use the electric rechargeable batteries, especially when PV modules produce the DC current required for charging the batteries. Most of batteries used in PV systems are lead-acid batteries. In some applications, for example when used in locations with extreme climate conditions or where high reliability is essential, nickel-cadmium batteries are used. The major difficulty with this form of storage is the relative high cost of the batteries and a large amount required for large-scale application.

3.1.6 Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge. Charge and discharge voltage limits should be carefully selected to suit the battery type and the operating temperature. These settings can significantly affect maximum operational life of a battery. High temperatures tend to reduce battery life because they accelerate corrosion and self-discharge. High temperatures may also increase out gassing during charging and therefore should be controlled. PV modules that are used to charge batteries usually operate at an approximately constant voltage, which is selected to suit the local temperature. However some PV systems regulators employ a maximum power point tracker (MPPT), which automatically permits the PV modules to operate at the voltage that produces maximum power output. Such regulators employ an electronic DC-DC converter to maintain their output at the required system voltage. The benefit of using an MPPT depends on the application and should be weighed against its additional cost and reliability risks. For many applications, it may be equally or more cost effective to operate the system at a fixed voltage.

3.1.7 Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage. The most important features of an inverter for PV applications are its reliability and its efficiency characteristics. They are designed to operate a PV system continuously near its maximum power point. The technology for high-switching-frequency inverters (typically 20 kHz or higher) is made possible by switch-mode semiconductor power devices. The efficiency of an inverter is normally quoted at its design operating power, but inverters in PV systems typically operate for much of their life at partial loads. For grid-connected operation, inverters must meet the requirements of the utilities concerning acceptable levels of harmonic distortion (quality of voltage and current output waveforms), and should not emit electrical noise, which could interfere with the reception of television or radio. They must also switch off when there is a grid failure for the safety of the engineers who have to repair the grid.

3.2 TYPES OF PV SYSTEMS

PV systems can be very simple, just a PV module and load, as in the direct powering of a water pump motor, or more complex, as in a system to power a house. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid.

3.2.1 Stand-alone systems

Stand-alone systems depend on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather. Figure 1 shows schematically examples of stand-alone systems.

3.2.2 Grid-connected systems

Grid-connected PV systems have become increasingly popular as building integrated application. They are connected to the grid through inverters, and do not require batteries because the grid can accept all of the electricity that a PV generator can supply. Alternatively they are used as power stations. A grid-connected PV system is schematically presented in Figure 2.

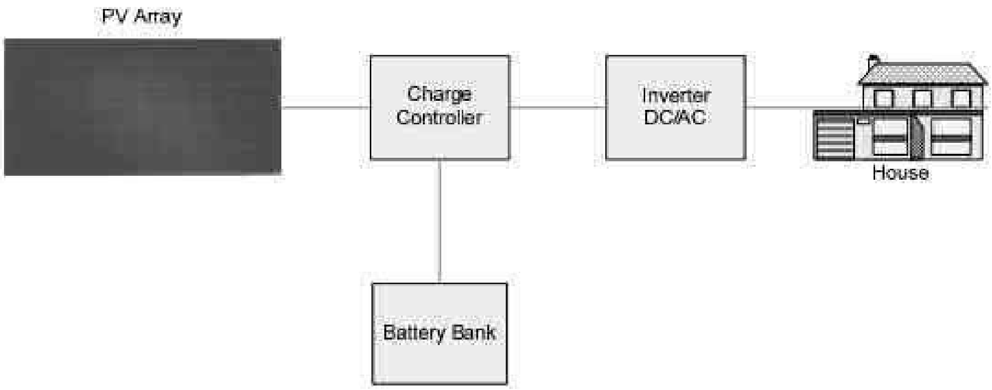


Figure 1: Stand-alone systems

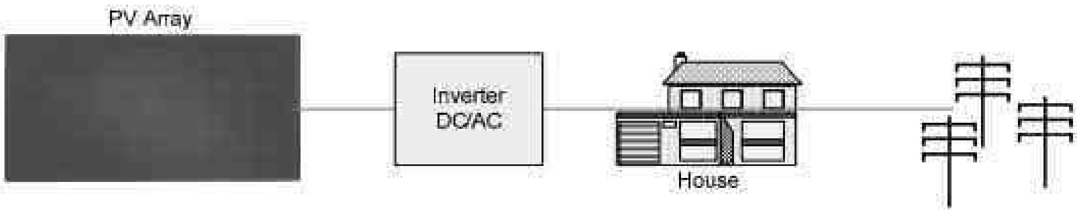


Figure 2: Grid-connected systems

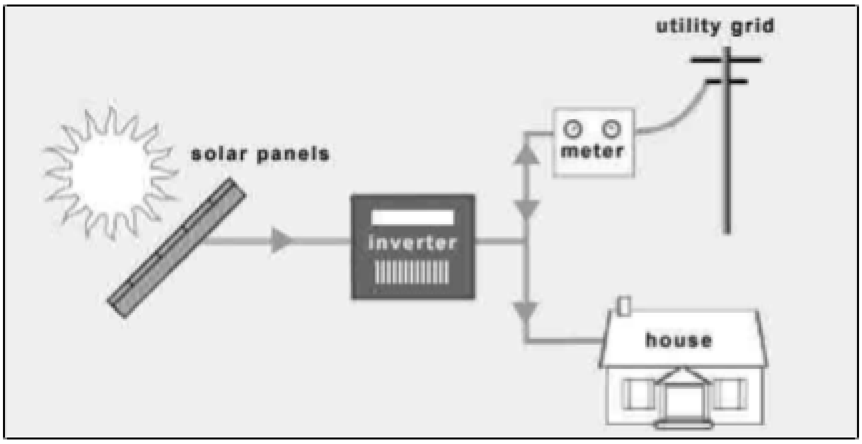


Figure 3: Hybrid PV-Diesel systems

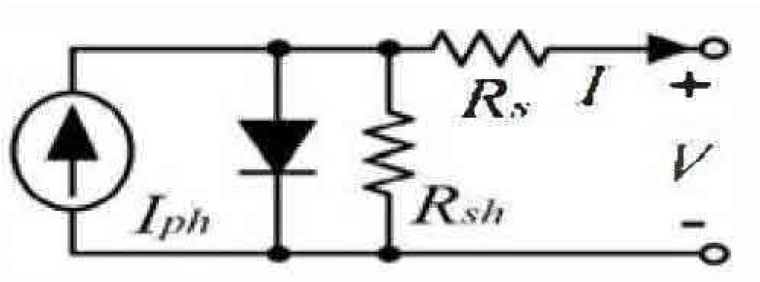
3.2.3 Hybrid systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand- alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well. A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy, which could be produced by the PV generator, is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected if a PV generator is added to an existing diesel engine without installing an automatic system for starting the engine and controlling its output.

3.2.4 Equivalent circuit diagram of solar PV cell

Now a days, different semiconductor materials i.e. mono crystal polycrystalline and formless silicon are used. The single diode circuit configuration for PV cells is shown in Figure 1 and equation (1) shows the current expression. The double diode circuit configuration for PV cell is shown in Fig.2 and equation (2) shows the current expression.

Figure 1: Single diode configuration for PV cell



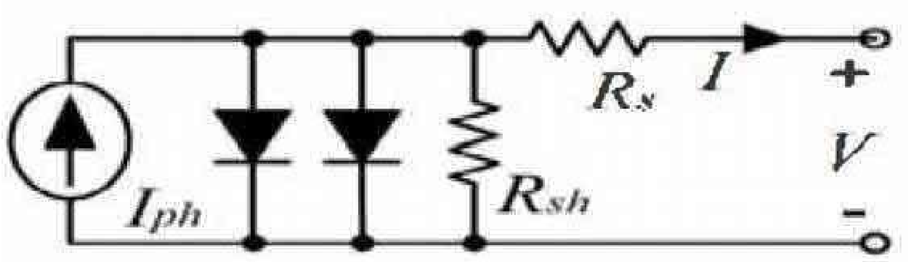


Figure 2: Double diode configuration for PV cell

For temperature dependence I_{ph} will be as shown in equation (3) for maximum power in case of single diode model.

$$I = I_{ph} - I_s\left[e^{\frac{q(V+IR_s)}{N_s K T_0 A}} - 1\right] - \frac{V+IR_s}{R_{sh}} \qquad (1)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{A_1 KT}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{A_2 KT}} - 1\right]\frac{V+IR_s}{R_{sh}} \qquad (2)$$

$$I_{ph} = I_{ph(T=298K)}\left[1 + \left(T - 298K(5\times10^{-4})\right)\right] \qquad (3)$$

$$I_{S1} = K_1 T^3 e^{\frac{-E_S}{KT}} \qquad (4a)$$

$$I_{S2} = K_2 T^{\frac{5}{2}} e^{\frac{E_S}{KT}} \qquad (4b)$$

Where

q	=	electron charge = 1.6 x 10^{-19} V
I_s	=	diode saturation current
Iph	=	Photon Current
K_1	=	12000 A/m^2K^3
K_2	=	2.9 x 10^9 $A/m^2K^{5/2}$
R_s	=	Series Resistance
Rsh	=	Shunt Resistance
A	=	Diode ideality Factor
T_o	=	Operating temperature
N_s	=	No. of cells in series
K	=	Boltzmann constant = 1.38 x 10^{-23}J/K

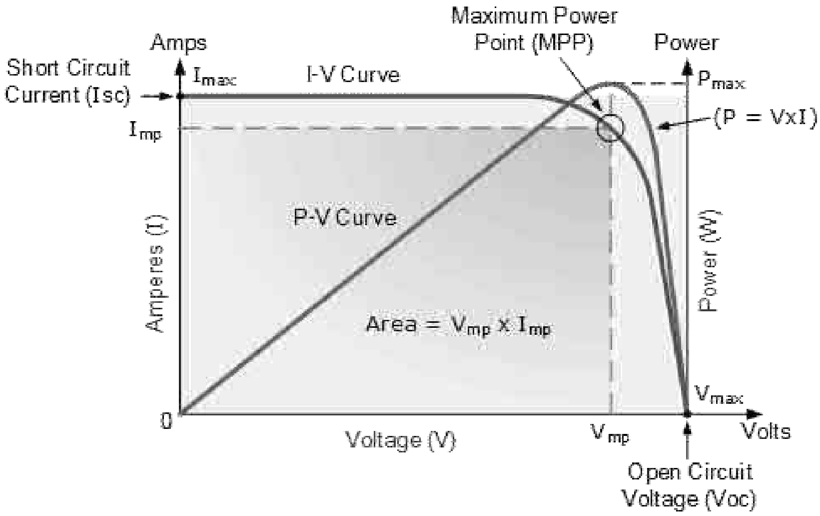
Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly more at low irradiance, since there will be less magnitude of current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large. For the rise of series resistance the voltage and current density will be reduced and vice versa. For ideal solar plate R_s will be zero and the R_{sh} will be infinite. Therefore, for the maximum power from the solar PV cell Rs will be negligible value and the R_{sh} must have a higher value.

For maximum power in case of single diode model

$$\frac{dP_m}{dP_m} = \left[I_{ph} - I_{rs}\left[e^{\frac{q(V+qIR_s)}{N_s K T_0 A}} - 1 \right] - \left[\frac{V + IR_s}{R_{sh}} \right] + V_m \left[-\frac{q}{N_s K T_0 A} I_{rs} \left[e^{\frac{q(V+IR_s)}{N_s K T_0 A}} \right] - \frac{1}{R_{sh}} \right] \right] = 0 \quad (5)$$

3.2.5 Characteristics of PV array and MPP

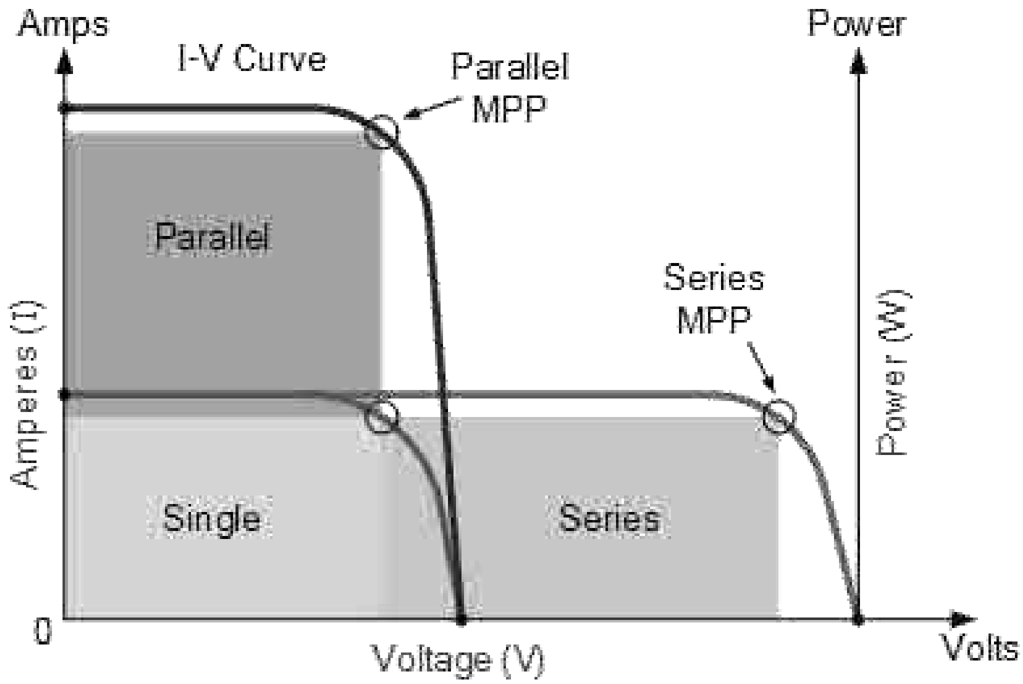
Solar Cell V-I Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature. *V-I* curves provide the information required to configure a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



The above graph shows the *V-I* characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a solar cell is the product of current and voltage. If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level. With the solar cell open-circuited that is not connected to any load the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells **open circuit voltage**, or $\mathbf{V_{oc}}$. At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together, the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells **short circuit current**, or $\mathbf{I_{sc}}$.

Solar Panel I-V Characteristic Curves

Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array. If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallels then the current increases.



The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current, (P = V x I). However the solar panels are connected together, the upper right hand corner will always be the maximum power point (MPP) of the array.

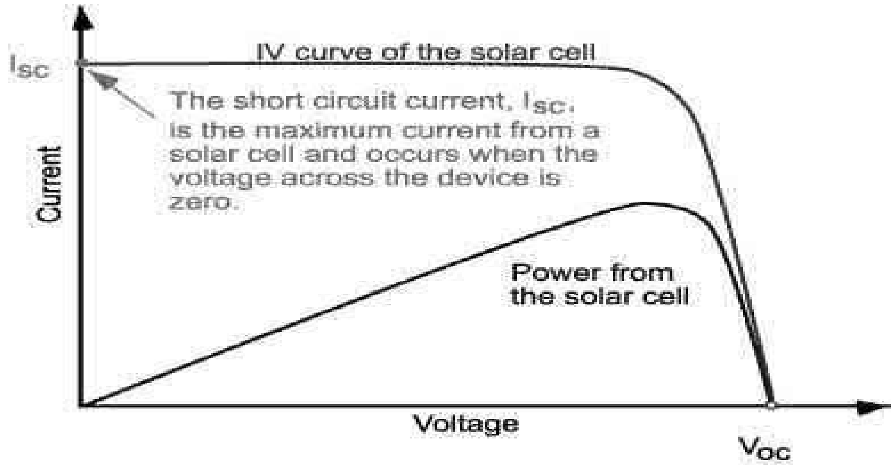
3.2.6 Open circuit voltage and short circuit current of PV system

Open-Circuit Voltage

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

Short-Circuit Current

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



Short-Circuit Current

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

3.2.7 MPPT

Maximum power point tracking is often called as MPPT. This is an electronic system which commands a solar panel or a set of solar panels to generate the maximum amount of power. The MPPT is not a physical system strapped with solar trackers that position the panels so that they remain under the sun at all times. Although they can be used along with solar trackers, you must know that both are different systems. This fully electronic system varies the electrical operating point of the panels which enables them to deliver the maximum power. The Extra power generated by the panels is made available to the modules in the form of increased battery charging current.

3.3 PV POWER CONDITIONING SYSTEM

This is a power converter which interfaces the PV to utility grid and converts the DC supply from the PV plant to AC supply as requirement by the utility grid. Based on the galvanic connection between PV plant and grid, the power conditioning system (PCS) can be broadly classified into two types such as **isolated power conditioning system** and **non isolated power conditioning system**.

3.3.1 Isolated PV Power Conditioning System

In isolated type PV system the isolation between PV plant and grid is achieved by using a line frequency transformer at the output of the inverter (AC side) or by using high frequency transformer DC-DC converter at the input side of the inverter. In low frequency (power frequency) transformer system involves huge size, increasing magnetic loss and low efficiency than high frequency transformer based DC-DC converter system. This high frequency transformer involves complex control resonant problems and which increase the cost of the PV system.

3.3.2 Non Isolated PV Power Conditioning System

The non isolated grid connected PV system is again classified in to single-stage and multistage power conditioning systems. In single-stage, only one power processing stage is available to convert the PV power to AC supply. Nowadays, single stage power converters are most widely used in PV applications. The single- stage inverter can perform the buck, boost, and both buck- boost input voltage, inversion and maximum power point. The single-stage inverter has the advantages of improved efficiency, low cost, more reliability, modularity, and compact size than multistage power conversion systems.

Figure 1 shows a block diagram of conventional photovoltaic power conditioning systems. They consist of an inverter, LP-filter and line transformer. The filter eliminates/attenuates the harmonics on produced by the inverter, the filter output is stepped up at the grid level by a low frequency transformer.

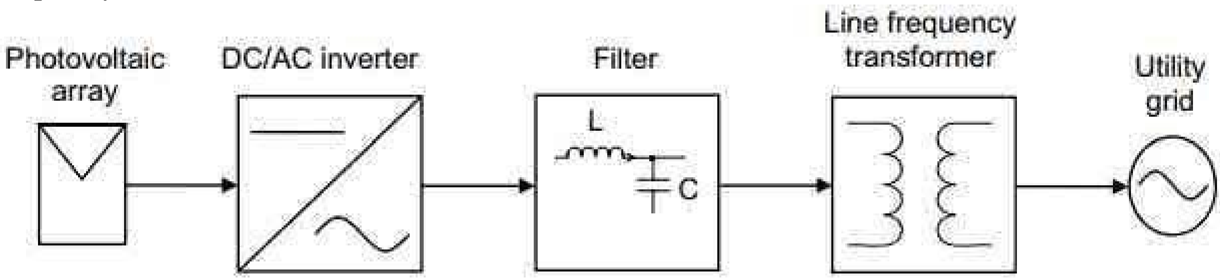


Figure 1: PV PCS with line frequency transformer

Figure 2 shows a block diagram of a conventional isolated type photovoltaic power conditioning system. In this system, a DC/DC converter using a high frequency transformer converts a DC voltage delivered by the PV into a controlled DC voltage suitable for the inverter.

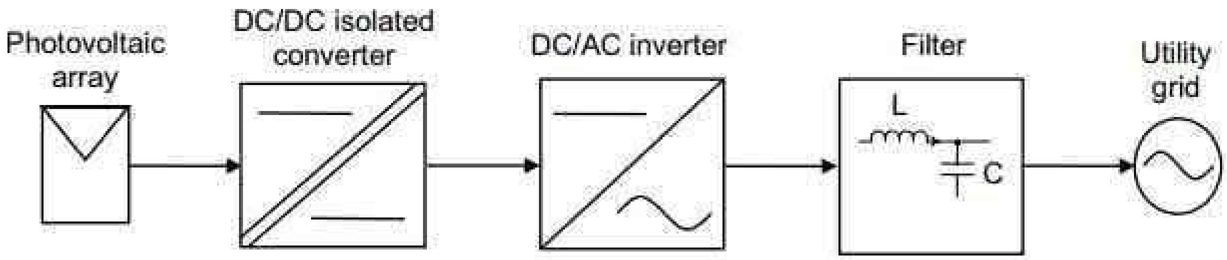


Figure 2: PV PCS with high frequency transformer

Figure 3 shows a block diagram of a conventional non-isolated type photovoltaic power conditioning system. In this system, a DC/DC non-isolated converter receives the fluctuating DC voltage delivered by the PV and converts it into DC voltage suitable for the inverter.

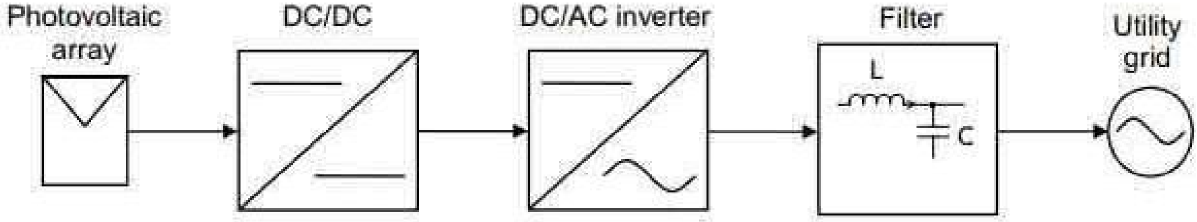
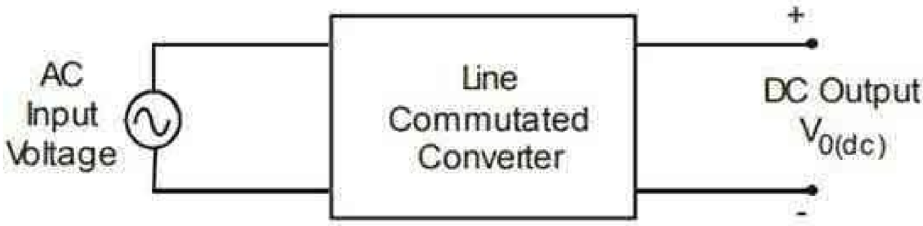


Figure 3: Conventional non-isolated type PV PCS

3.4 LINE COMMUTATED CONVERTERS

3.4.1 Introduction to Controlled Rectifiers

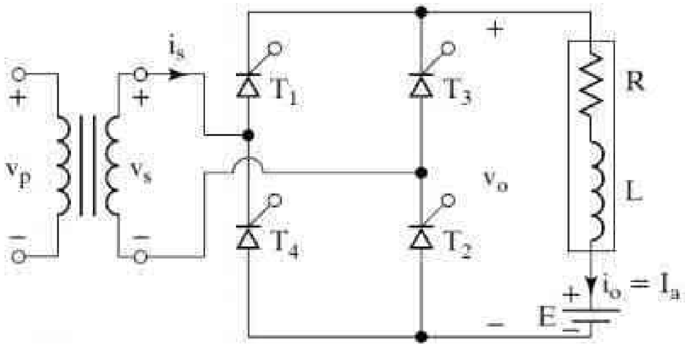


Controlled rectifiers are line commutated ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage. Type of input: Fixed voltage, fixed frequency ac power supply. Type of output: Variable dc output voltage. The input supply fed to a controlled rectifier is ac supply at a fixed RMS voltage and at a fixed frequency. We can obtain variable dc output voltage by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and variable dc (average) output current by varying the trigger angle (phase angle) at which the thyristors are triggered. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

3.4.2 Line commutated converters under inversion mode

Single Phase Full Converter

The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a highly inductive load and a dc source in the load circuit so that the load current is continuous and ripple free (constant load current operation). The fully controlled bridge converter consists of four thyristors T_1, T_2, T_3 and T_4 connected in the form of full wave bridge configuration as shown in the figure. Each thyristor is controlled and turned on by its gating signal and naturally turns off when a reverse voltage appears across it. During the positive half cycle when the upper line of the transformer secondary winding is at a positive potential with respect to the lower end the thyristors T_1 and T_2 are forward biased during the time interval $\omega t = 0$ to π . As soon as the thyristors T_3 and T_4 are triggered a reverse voltage appears across the thyristors T_1 and T_2 and they naturally turn-off and the load current is transferred from T_1 and T_2 to the thyristors T_3 and T_4.



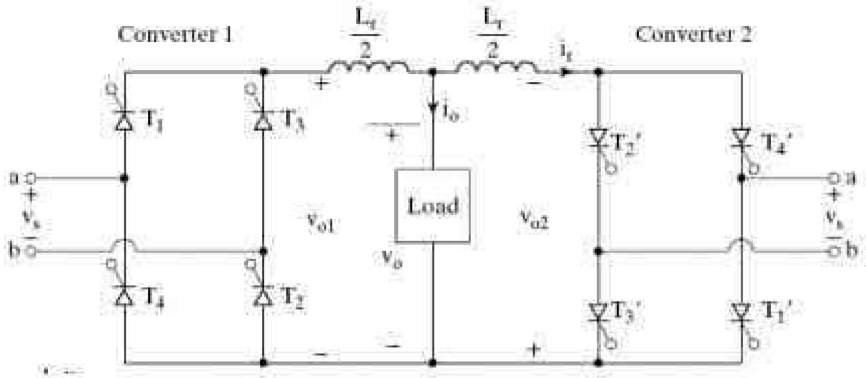
Single Phase Dual Converter

The dual converter system will provide four quadrant operation and is normally used in high power industrial variable speed drives. The converter number 1 provides a positive dc output voltage and a positive dc load current, when operated in the rectification mode. The converter number 2 provides a negative dc output voltage and a negative dc load current when operated in the rectification mode. We can thus have bidirectional load current and bi-directional dc output voltage. The magnitude of output dc load voltage and the dc load current can be controlled by varying the trigger angles of the converters 1 and 2 respectively. There are two modes of operations possible for a dual converter system like non circulating current mode of operation and circulating current mode of operation.

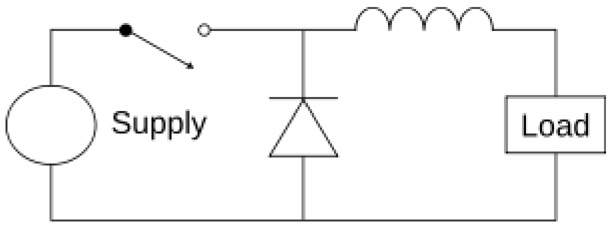
3.4.3 DC-DC Converters

DC-DC Buck Converter

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while stepping up current) from its input (supply) to its output (load). It is a class



of switched-mode power supply (SMPS) typically containing at least two semi conductors 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).

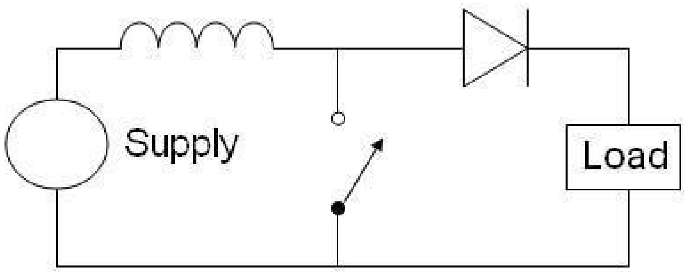


Buck converter circuit diagram.

The basic operation of the buck converter has the current in an inductor controlled by two switches. In the idealized converter, all the components are considered to be perfect. Specifically, the switch and the diode have zero voltage drop when on and zero current flow when off, and the inductor has zero series resistance.

DC-DC Boost Converters

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).

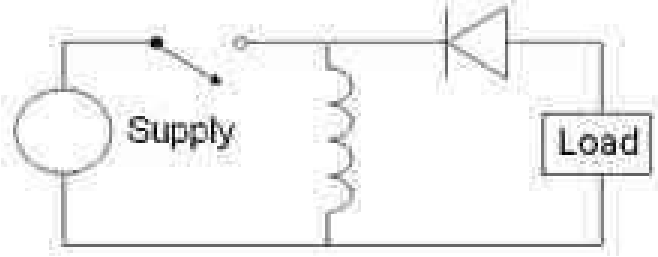


Basic schematic of a boost converter

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. 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. 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.

DC-DC Buck-Boost Converters

A Buck-Boost converter is a type of switched mode power supply that combines the principles of the Buck Converter and the Boost converter in a single circuit. Like other SMPS designs, it provides a regulated DC output voltage from either an AC or a DC input.



Buck-Boost Converters

It is equivalent to a fly-back using a single inductor instead of a transformer. Two different topologies are called buck–boost converter. Both of them can produce a range of output voltages, ranging from much larger (in absolute magnitude) than the input voltage, do wn to almost zero.

Modes of Buck Boost Converters

There are two different types of modes in the buck boost converter. The following are the two different types of buck boost converters.

- Continuous conduction mode.
- Discontinuous conduction mode.

Continuous Conduction Mode

In the continuous conduction mode the current from end to end of inductor never goes to zero. Hence the inductor partially discharges earlier than the switching cycle.

Discontinuous Conduction Mode

In this mode the current through the inductor goes to zero. Hence the inductor will totally discharge at the end of switching cycles.

Applications of Buck boost converter

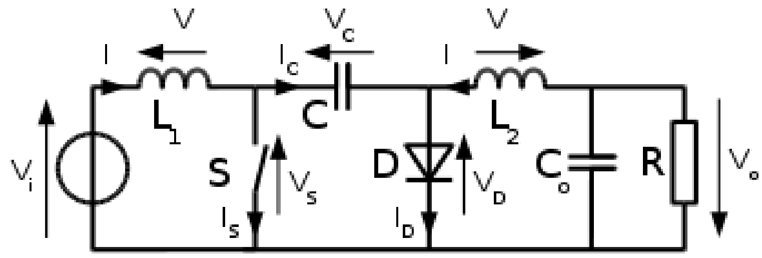
- It is used in the self regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Power amplifier applications.

Advantages of Buck Boost Converter

- It gives higher output voltage.

- Low operating duct cycle.

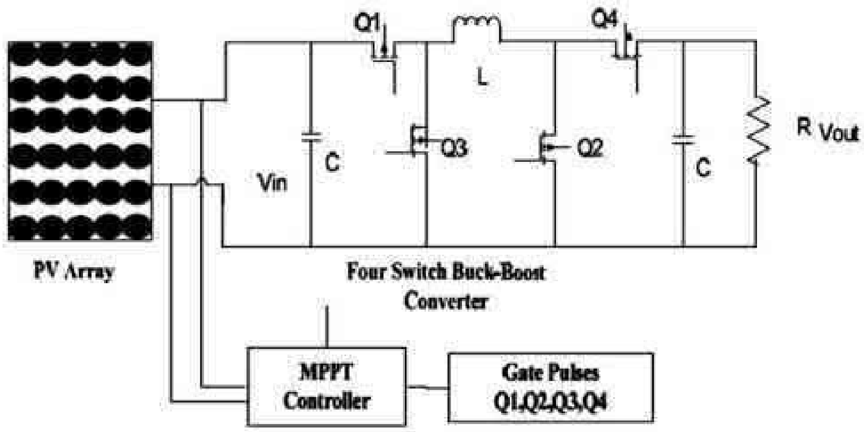
Cuk converter



Schematic of a non-isolated Cuk converter

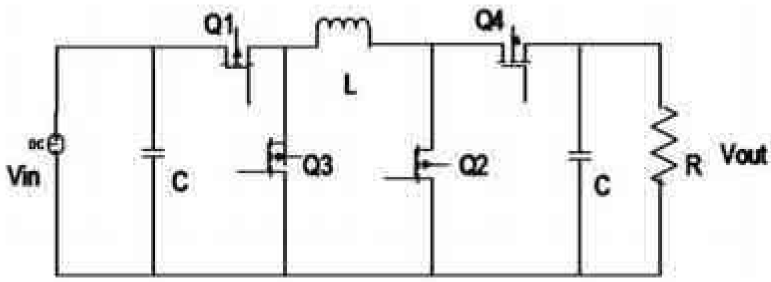
The Cuk converter is a type of DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. Similar to the buck–boost converter with inverting topology, the output voltage of non-isolated Cuk is typically also inverting, and can be lower or higher than the input. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. There are variations on the basic Cuk converter. For example, the coils may share single magnetic core, which drops the output ripple, and adds efficiency. Because the power transfer flows continuously via the capacitor, this type of switcher has minimized EMI radiation. The Cuk converter allows energy to flow bi-directionally by using a diode and a switch.

3.4.4 PV fed Buck Boost Converter (Four switched topology)

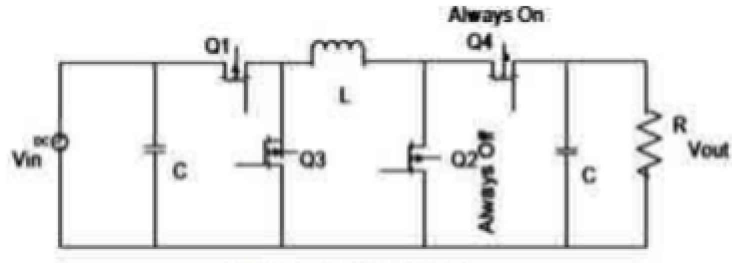


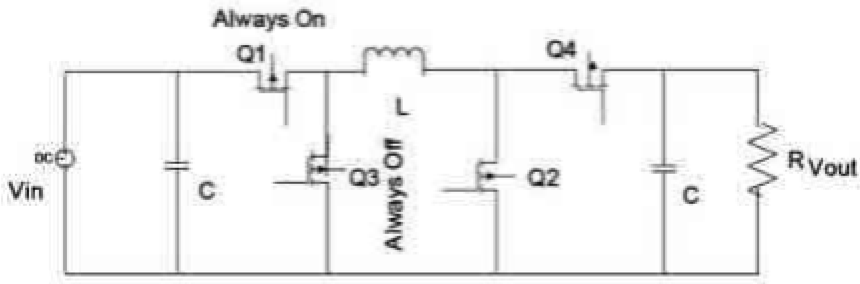
Four-switch power converter is cascaded combination of Buck converter followed by a Boost converter the converter is different from the other DC-DC converters why, because it has four switches to be controlled, that is, two gate pulses we need. This means for the same working point with different values both gate pulses can be used. Furthermore, due to its simple and cascaded combination of Buck-Boost structure, it presents high adaptability and high performance to system voltage changes.

The configuration of the system consists of the Solar PV array fed to FSBB Converter which feeds the Load. It is a combination of Buck converter followed by Boost converter; a four switch buck-boost converter can operate in buck mode or boost mode rather than conventional buck-boost converter. As such, its efficiency can be improved by synchronous rectification the power stage consist of four switches (Q_1, Q_2, Q_3, and Q_4), single inductor (L), and input and output Capacitors.



Four-switch buck-boost converter.





Equivalent circuit in Buck/Boost mode

Here the MOSFETs Q_3,Q_4 share the gate control signal, which is complementary to the gate control signal of MOSFETs Q_1 and Q_2, In the buck-boost mode the MOSFETs Q_1 and Q_2 share gate control signals and turn on and off simultaneously. When the MOSFETs Q_1 and Q_2 are turned on, the input voltage V_{in} is applied, the inductor L stores the energy, output capacitor supplies the load current entirely.

When Q_1 and Q_2 are turned off, MOSFETs Q_3, Q_4 are turned on in this stage the energy is transferred from the inductor to output load and capacitor. Here we are using a synchronous rectification scheme these means we are using MOSFETs instead of diodes to reduce the switching and power losses and to improve efficiency. The Figure shows the equivalent circuit of the converter in buck and boost mode. When Vin is higher than Vout, The MOSFET Q_2 is always OFF, Q_4 is always ON, Q_1 and Q_3 ON and OFF simultaneously thus it works like a buck converter ($V_{in} > V_{out}$) as shown in below figure. When Vin is lower than V_{out}, Q_1 is always ON and Q_3 is always OFF, Q_2 and Q_4 ON and OFF simultaneously it works as a boost converter ($V_{in} < V_{out}$) as shown in below figure.

3.4.5 Current regulated PWM inverters

Current regulation technique plays the most important role in Current Regulated PWM (CR-PWM) inverters which are widely applied in ac motor drives, ac power supply and active filters. The CR-PWM inverters, also known as current mode PWM inverters, implement an on line current feedback (closed loop) type of PWM. In comparison to a conventional feed forward (open loop) voltage controlled PWM inverters they show following advantages: - control of instantaneous peak current, - overload problem is avoided, - pulse drop problem does not occur, - extremely good dynamics, - nearly sinusoidal current waveforms, expect for the harmonics - compensation of the effect of load parameter changes (resistance and reactance). The basic problem involved in the implementation of CR-PWM inverters is the choice of suitable current regulation strategy, which affects both the parameters obtained. The main task of the control system in CR-PWM inverter is to force the current vector in the three phase load according to the reference trajectory.

3.5 SIZING BATTERIES AND INVERTERS FOR A SOLAR PV SYSTEM

3.5.1 Basics of sizing

The most important thing that one needs to know before sizing a PV system is the energy requirements of a setup. A few things that can help are:

1. Wattages and counts of all the appliances that need to be run on solar PV.
2. If you do not have wattages then you can look at the current requirement (in amperes) of the appliances and calculate wattage with this simple formula: Watts = Ampere x 240 (voltage)
3. Electricity bills of the setup. Used to check the monthly electricity units used in a setup. Daily units can be obtained by dividing month units by 28/29/30 or 31 (depending on the number of days in the month for which the bill is generated)

4. Daily usage of each appliance in hours. This is required if you do not have a sample electricity bill. This helps in calculating the number of units of electricity used in a day using the formula below: Units = (Watts x Hours) ÷1000

3.5.2 Sizing a PV panel

To size a PV panel, the most essential thing to know is the Total Units consumed in a day by the appliances in a setup. The size of PV system should not be less than the one that can generate total units consume in a day. Every PV panels has a peak wattage (W_p) mentioned on them. A 1 kW_p (or peak kilo watt) system would generate 5 to 7 units in a day. Thus the right size of PV system (in kW_p) should be estimated by dividing maximum daily usage units divided by 5. If you are going for a grid connected system where extra electricity produced will be sold back to the electricity provider. In such cases you can optimize the size of PV system based on the space that you have for installing PV panels.

3.5.3 Sizing Batteries for PV system

Along with sizing of the PV panel, it is important to size the batteries as well. Because if purchase more batteries then they will not get fully charged, if buy fewer batteries, may not be able to get the maximum benefit out of the solar panel. Most big PV systems use deep cycle (or deep discharge) batteries that are designed to discharge to low energy levels and also to recharge rapidly. These are typically lead acid batteries that may or may not require maintenance. Batteries have energy storage ratings mentioned in Amp-hour (Ah) or milli-Amp-hour (mAh). They also have a nominal voltage that they generate (typically deep discharge batteries are 12 V batteries, cell phone batteries are 5 V batteries, etc). To calculate the total energy a battery can store you can use following formula: Units = (Volt x Ah) ÷1000 or (Volt x mAh) ÷1000000. Batteries should be sized in a way that the units of energy generated by the PV system should be equal to the number we have calculated above. So assuming we have a 1 kWp system and we assume that on an average it generates 6 units a day and if we have to buy 12 V battery for it, the Ah (or storage) of battery required would be: (6 x1000) ÷12 = 500 Ah

3.5.4 Sizing Inverter for a Solar PV system

A power inverter or inverter is a system that converts Direct Current (or DC) to an alternating current (or AC). A solar panel produces DC current, batteries also generate DC current, but most systems we use in our daily lives use AC current. Inverters also have transformers to convert DC output voltage to any AC output voltage. Depending on the type of system (grid or off-grid) various types of inverters are available. Sizing of inverter depends on the wattage of appliances connected to it. The input rating of inverter should never be lower than

the total wattages of the appliances. Also it should have the same nominal input voltage as that of the battery setup. It is always better to have inverter wattage about 20-25% more than that of the appliances connected. This is specifically essential if the appliances connected have compressors or motors (like AC, refrigerator, pumps, etc), which draw high starting current. Most inverters available in market are rated on KVA /VA or Kilo Volt Ampere/Volt Ampere. In ideal situations (power factor of 1) 1 VA = 1 Watt. But in real power factor varies from 0.85 to
0.99 (more about power factor on: What is Power Factor correction and how MDI (Maximum Demand Indicator) penalty can be avoided). So one can assume 1.18 VA = 1 Watt. So if you have a setup where the total wattage of the system is 1000 Watts, it means your inverter size required is more than 1180 VA or 1.18 KVA (add some extra to be on a safer side).

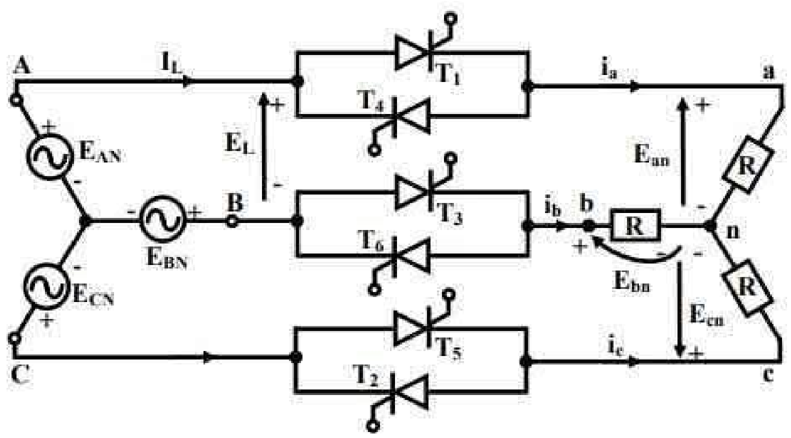
3.6 THREE-PHASE AC VOLTAGE REGULATORS

There are many types of circuits used for the three-phase ac regulators (ac to ac voltage converters), unlike single-phase ones. The three-phase loads (balanced) are connected in star or delta. Two thyristors connected back to back, or a triac, is used for each phase in most of the circuits as described. Two circuits are first taken up, both with balanced resistive (R) load

3.6.1 Three-phase, star connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, three-wire AC regulator (termed as ac to ac voltage converter) with balanced resistive (star-connected) load is shown in Figure. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. The current flow is bidirectional, with the current in one direction in the positive half, and then, in other (opposite) direction in the negative half. So, two thyristors connected back to back are needed in each phase. The turning off of a thyristor occurs, if its current falls to zero. To turn the thyristor on, the anode voltage must be higher that the cathode voltage, and also, a triggering signal must be applied at its gate.

Three-phase, three-wire star connected AC voltage regulator



The expression of the RMS value of output voltage is obtained by per phase for balanced star-connected resistive load which depends on range of firing angle. If is the RMS value of the input voltage per phase, and assuming the voltage, as the reference, the instantaneous input voltages per phase are,

$$e_{AN} = \sqrt{2}E_s sin\omega t$$

$$e_{BN} = \sqrt{2}E_s \sin\,(\omega t - 120^0)$$

$$e_{CN} = \sqrt{2}E_s sin\,(\omega t + 120^0)$$

Then, the instantaneous input line voltages are,

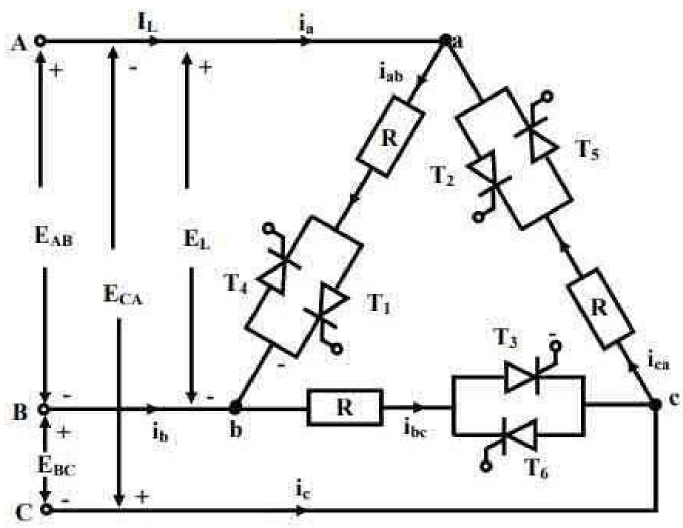
$$e_{AB} = \sqrt{6}E_s sin(\omega t + 30^0)$$

$$e_{BC} = \sqrt{6}E_s \sin\,(\omega t - 90^0)$$

$$e_{CA} = \sqrt{6}E_s sin\,(\omega t + 150^0)$$

3.6.2 Three-phase Delta-connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, delta-connected ac regulator (termed as ac to ac voltage converter) with balanced resistive load is shown in Figure. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. As stated earlier, the numbering scheme may be noted. It may be observed that one phase of the balanced circuit is similar to that used for single phase ac regulator. Since the phase current in a balanced three-phase system is only (1/√3) of the line current, the current rating of the thyristors would be lower than that if the thyristors are placed in the line.



Assuming the line voltage as the reference, the instantaneous input line voltages are,

$$e_{AB} = \sqrt{2}E_s sin\omega t$$

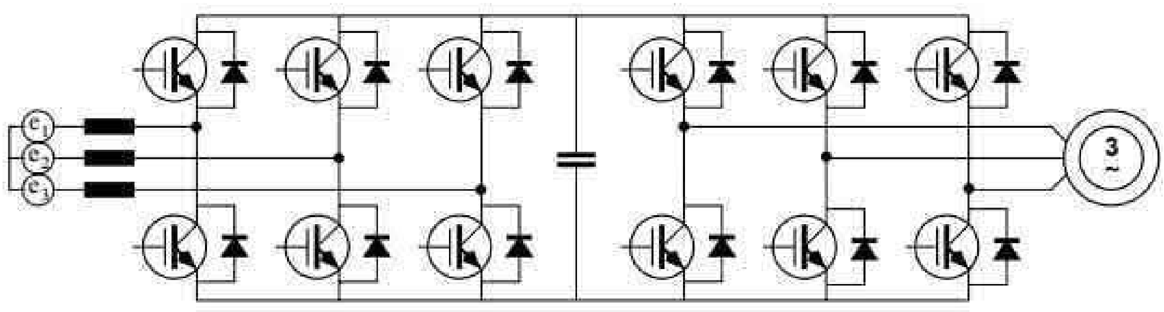
$$e_{BC} = \sqrt{2}E_s \sin\,(\omega t - 120^0)$$

$$e_{CA} = \sqrt{2}E_s sin\,(\omega t + 120^0)$$

3.7 THREE PHASE AC-DC-AC CONVERTERS (THE BACK-TO-BACK CONVERTER)

The back-to-back converter is consists simply of a force-commutated rectifier and a force-commutated inverter connected with a common dc-link shown in figure. The properties of this combination are well known; the line-side converter may be operated to give sinusoidal line currents, for sinusoidal currents, the dc-link voltage must be higher than the peak main voltage, the dc-link voltage is regulated by controlling the power flow to the ac grid and, finally, the inverter operates on the boosted dc-link, making it possible to increase the output power of a connected machine over its rated power. Another advantage in certain applications is that braking energy can be fed back to the power grid instead of just wasting it in a braking resistor.

An important property of the back-to-back converter is the possibility of fast control of the power flow. By controlling the power flow to the grid, the dc-link voltage can be held constant. The presence of a fast control loop for the dc-link voltage makes it possible to reduce the size of the dc-link capacitor, without affecting inverter performance. In fact, the capacitor can be made small enough to be implemented with plastic film capacitors.



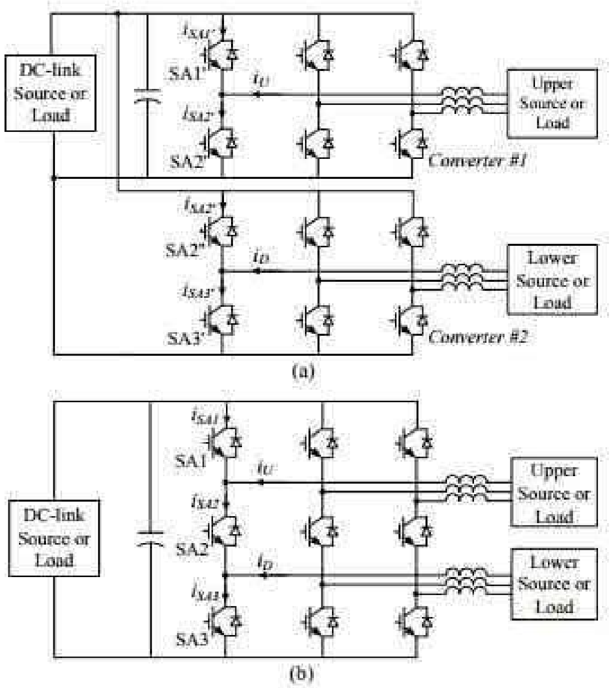
Back-to-back converter

3.7.1 Issues associated with a small DC-link capacitor

Smallest size of the dc-link capacitor is governed by the need to keep the switch-frequent ripple at acceptable (i.e. small) levels. Fluctuations in the load cannot be smoothed in the converter, but must be accommodated by other means. One alternative is to simply transfer such fluctuations to the power grid, but this may re-introduce the line-current harmonics the back to back converter is supposed to eliminate. However, load fluctuations will be random and thus relatively harmless compared to the in-phase harmonics generated by diode rectifiers. Another alternative is to use the load itself. In a typical drive, the mechanical energy stored in the drive is several orders of magnitude larger than the electrical energy stored in the DC-link capacitor in a back-to-back converter. If the application does not need servo-class performance, there is no reason why the rotational speed cannot be allowed to fluctuate slightly.

3.7.2 Application criteria for three-phase nine-switch converters

The nine-switch topology is derived from two converters connected back-to-back (BTB) shown in figure. Two phase legs from converter 1 and 2, respectively, are merged together to compose one phase leg of the nine switch converter, and meanwhile one switch is dismissed. Thus nine-switch converters have only three phase legs and each of them has only three switches.

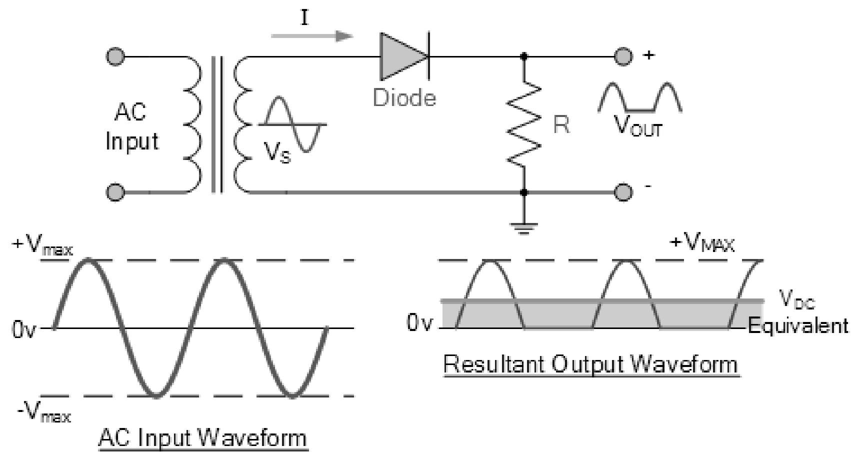


Nine-switch power converters

With such a topology, nine-switch converters retain the DC-link and can achieve all the functions of twelve-switch BTB even with three switches less.

3.8 UNCONTROLLED RECTIFIERS

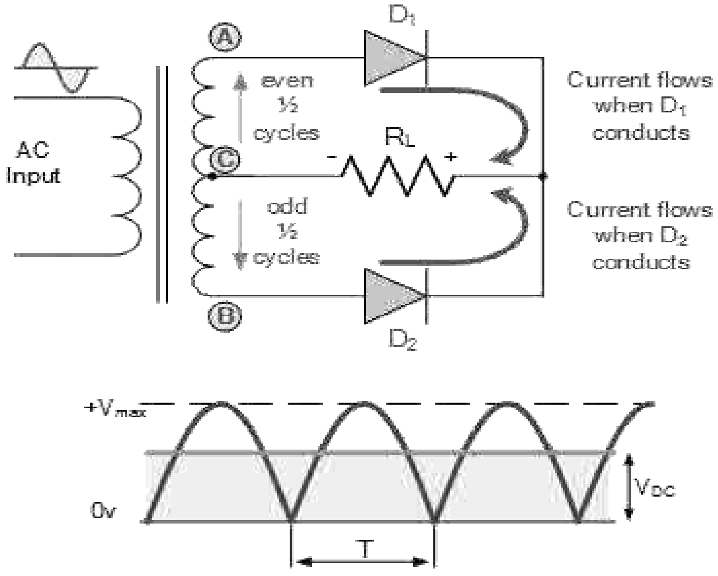
3.8.1 Half Wave Rectifier Circuit



A rectifier is a circuit which converts the *Alternating Current* (AC) input power into a *Direct Current* (DC) output power. The input power supply may be either a single-phase or a multi-phase supply with the simplest of all the rectifier circuits being that of the **Half Wave Rectifier.** The power diode in a half wave rectifier circuit passes just one half of each complete sine wave of the AC supply in order to convert it into a DC supply. Then this type of circuit is called a ―half-wave‖ rectifier because it passes only half of the incoming AC power supply as shown below. During each ―positive‖ half cycle of the AC sine wave, the diode is *forward biased* as the anode is positive with respect to the cathode resulting in current flowing through the diode. During each ―negative‖ half cycle of the AC sinusoidal input waveform, the diode is *reverse biased* as the anode is negative with respect to the cathode.

3.8.2 Full Wave Rectifier Circuit

Like the half wave circuit, a full wave rectifier circuit produces an output voltage or current which is purely DC or has some specified DC component. Full wave rectifiers have some fundamental advantages over their half wave rectifier counterparts. The average (DC) output voltage is higher than for half wave, the output of the full wave rectifier has much less ripple than that of the half wave rectifier producing a smoother output waveform. In a **Full Wave Rectifier** circuit two diodes are now used, one for each half of the cycle. A multiple winding transformer is used whose secondary winding is split equally into two halves with a common centre tapped connection.

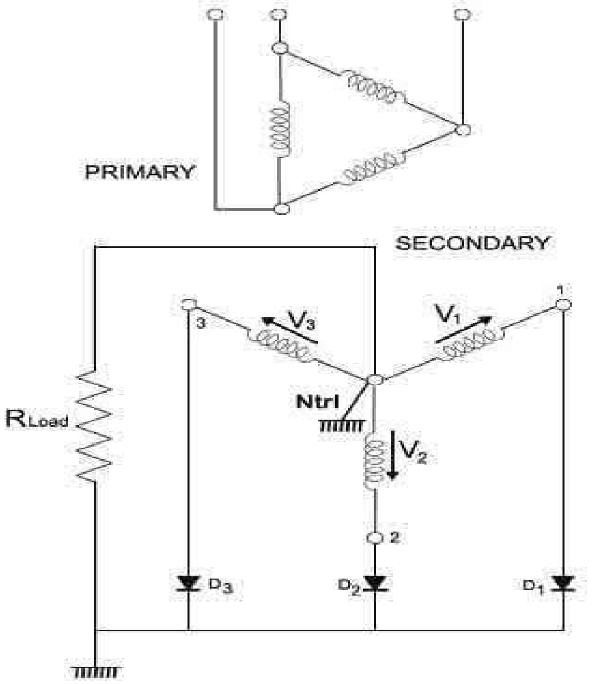


Resultant Output Waveform

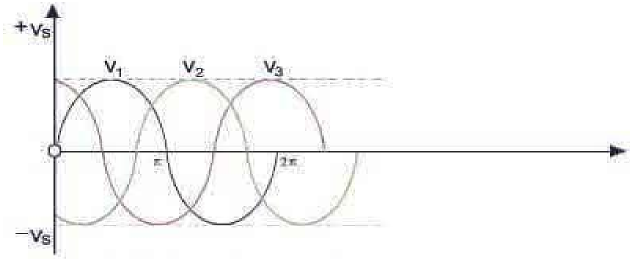
This configuration results in each diode conducting in turn when its anode terminal is positive with respect to the transformer centre point C producing an output during both half-cycles, twice that for the half wave rectifier so it is 100% efficient as shown below. The full wave rectifier circuit consists of two *power diodes* connected to a single load resistance (R_L) with each diode taking it in turn to supply current to the load. When point A of the transformer is positive with respect to point C, diode D_1 conducts in the forward direction as indicated by the arrows. When point B is positive (in the negative half of the cycle) with respect to point C, diode D_2 conducts in the forward direction and the current flowing through resistor R is in the same direction for both half-cycles. As the output voltage across the resistor R is the phasor sum of the two waveforms combined, this type of full wave rectifier circuit is also known as a ―bi- phase‖ circuit.

3.8.3 Three phase Half Wave Rectifier

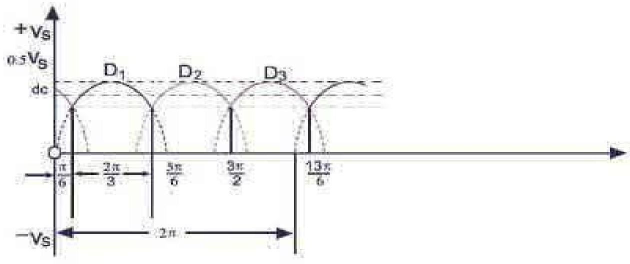
A three phase half wave rectifier, as the name implies, consists of a three phase transformer. Given below is a star connected secondary three phase transformer with three diodes connected to the three phases as shown in the figure. The neutral point _NTRL' of the secondary is considered as the earth for the circuit and is given as the negative terminal for the load.



The input and the output wave forms for the circuit above is shown below. For each one-third of the cycle, each diode conducts. At the instant when one diode out of three is conducting, the other two are left inactive, at that instant their cathodes becomes positive with respect to the anodes. This process repeats for each of the three diodes.



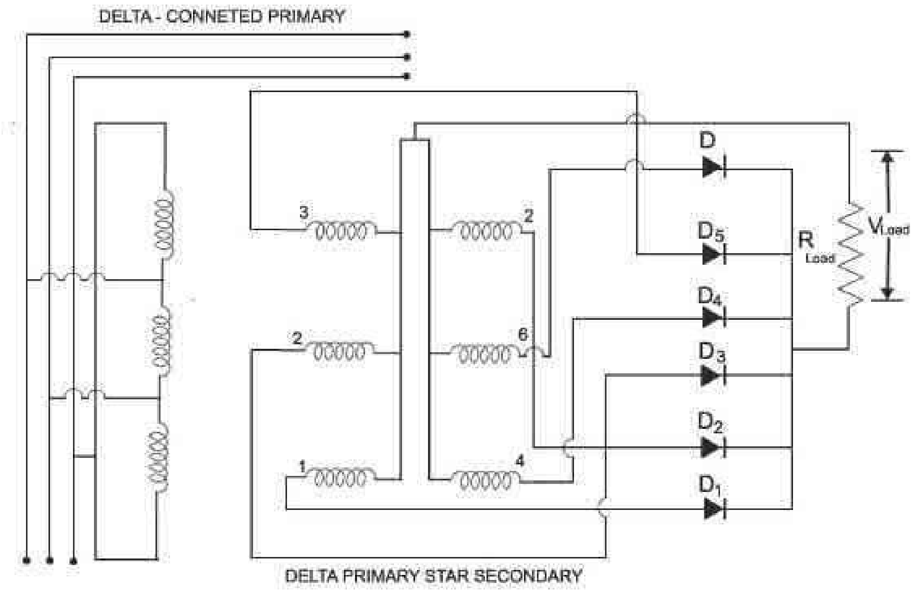
INPUT VOLTAGE WAVEFORM

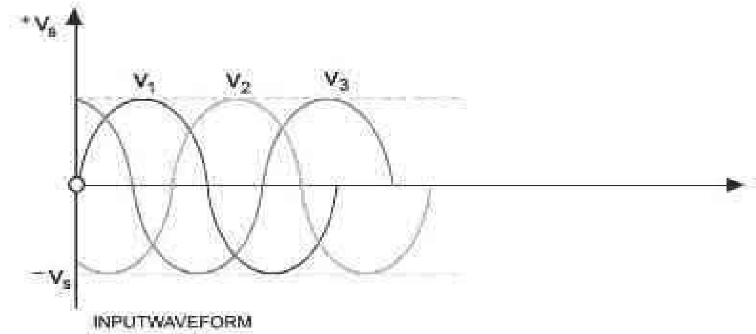


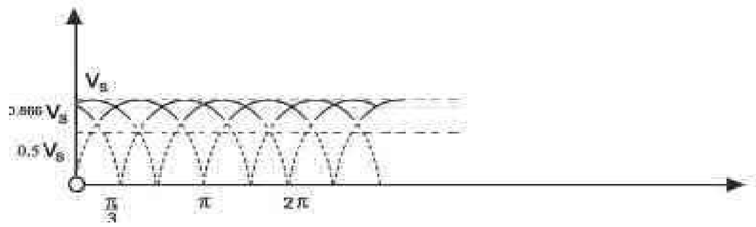
OUTPUT VOLTAGE WAVEFORM

3.8.4 Three Phase Full Wave Rectifier

A three phase full wave rectifier can also be called a six wave half wave rectifier as shown in the figure. The diodes D_1 to D_6 will conduct only for $1/6^{th}$ of the period, with a period of $\pi/3$. As shown in the output wave form, the fluctuation of dc voltage is less in a three phase circuit. The variation lies between the maximum alternation voltage and 86.6% of this, with the average value being 0.955 times the maximum value.







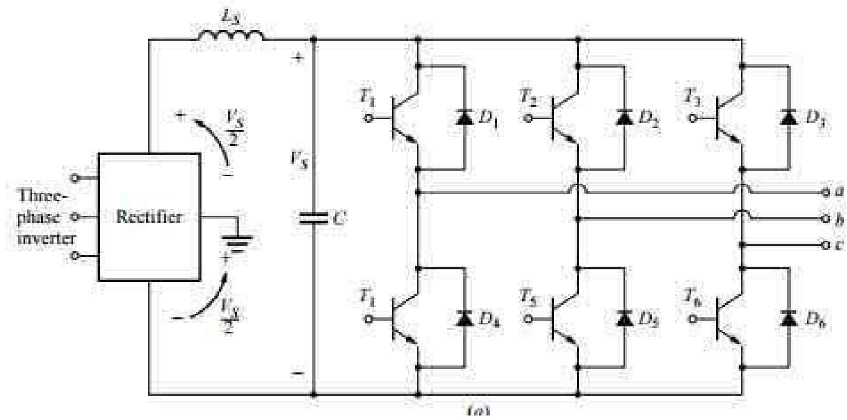
3.9 THREE PHASE PULSE WIDTH MODULATED (PWM) INVERTER

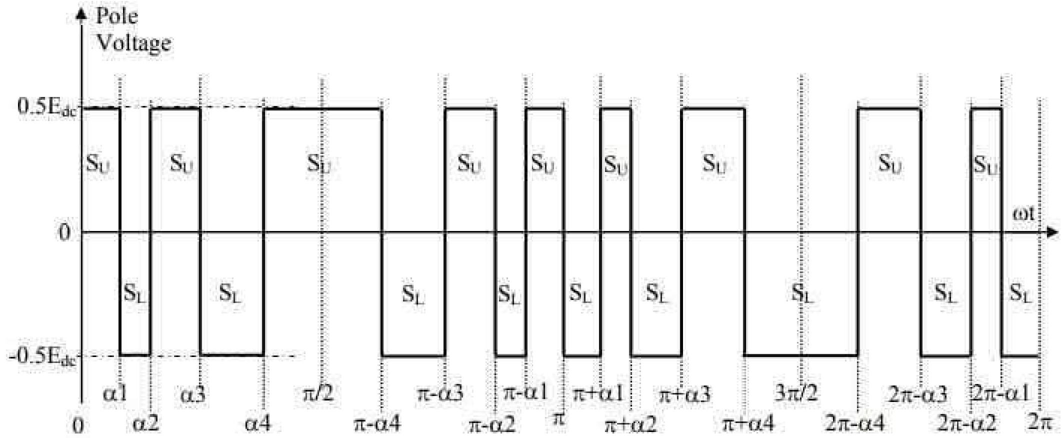
Pulse width modulated (PWM) inverters are among the most used power-electronic circuits in practical applications. These inverters are capable of producing ac voltages of variable magnitude as well as variable frequency. The PWM inverters are very commonly used in adjustable speed ac motor drive loads where one needs to feed the motor with variable voltage, variable frequency supply. For wide variation in drive speed, the frequency of the applied ac voltage needs to be varied over a wide range. The applied voltage also needs to vary almost linearly with the frequency. PWM inverters can be of single phase as well as three phase types. There are several different PWM techniques, differing in their methods of implementation. However in all these techniques the aim is to generate an output voltage, which after some filtering, would result in a good quality sinusoidal voltage waveform of desired fundamental frequency and magnitude. Nature of Pole Voltage Waveforms Output by PWM

Inverters Unlike in square wave inverters the switches of PWM inverters are turned on and off at significantly higher frequencies than the fundamental frequency of the output voltage waveform.

The time instances at which the voltage polarities reverse have been referred here as notch angles. It may be noted that the instantaneous magnitude of pole voltage waveform remains fixed at half the input dc voltage (E_{dc}). When upper switch (SU), connected to the positive dc bus is on, the pole voltage is + 0.5 E_{dc} and when the lower switch, connected to the negative dc bus, is on the instantaneous pole voltage is - 0.5 E^{dc}.

3 phase VSI using power transistors





A typical pole-voltage waveform of a PWM inverter

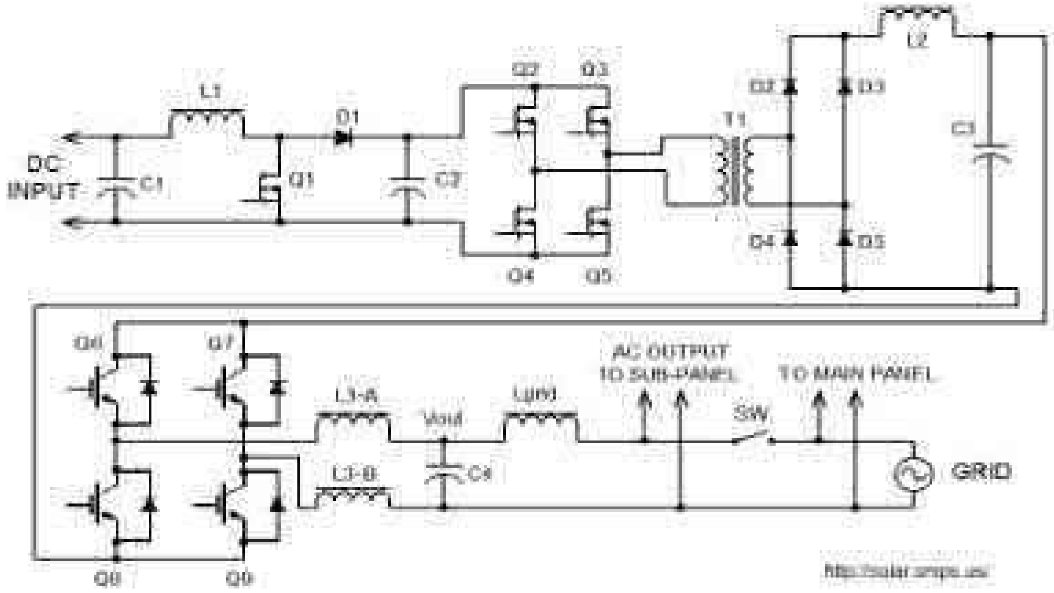
The switching transition time has been neglected in accordance with the assumption of ideal switches. It is to be remembered that in voltage source inverters, meant to feed an inductive type load, the upper and lower switches of the inverter pole conduct in a complementary manner. That is, when upper switch is on the lower is off and vice-versa. Both upper and lower switches should not remain on simultaneously as this will cause short circuit across the dc bus. On the other hand one of these two switches in each pole (leg) must always conduct to provide continuity of current through inductive loads. A sudden disruption in inductive load current will cause a large voltage spike that may damage the inverter circuit and the load.

3.10 GRID INTERACTIVE (GRID-TIE) INVERTERS

3.10.1 Introduction

A grid-tie inverter converts direct current (DC) into an alternating current (AC) suitable for injecting into an electrical power grid, normally 120V RMS at 60Hz or 240V RMS at 50 Hz. Grid-tie inverters are used between local electrical power generators: solar panel, wind turbine, hydro-electric, and the grid. In order to inject electrical power efficiently and safely into the grid, grid-tie inverters must accurately match the voltage and phase of the grid sine wave AC waveform. Some electricity companies will pay for electrical power that is injected into the grid. Payment is arranged in several ways. With net metering the electricity company pays for the net power injected into the grid, as recorded by a meter in the customer's premises. For example, a customer may consume 400 kilowatt-hours over a month and may return 500 kilowatt-hours to the grid in the same month. In this case the electricity company would pay for the 100 kilowatt hours balance of power fed back into the grid. Feed-in tariff, based on a contract with a distribution company or other power authority, is where the customer is paid for electrical power injected into the grid.

3.10.2 Operation



Grid-tie inverters convert DC electrical power into AC power suitable for injecting into the electric utility company grid. The grid tie inverter (GTI) must match the phase of the grid and maintain the output voltage slightly higher than the grid voltage at any instant. A high- quality modern grid-tie inverter has a fixed unity power factor, which means its output voltage and current are perfectly lined up, and its phase angle is within 1 degree of the AC power grid. The inverter has an on-board computer which senses the current AC grid waveform, and outputs a voltage to correspond with the grid. However, supplying reactive power to the grid might be necessary to keep the voltage in the local grid inside allowed limitations. Otherwise, in a grid

segment with considerable power from renewable sources, voltage levels might rise too much at times of high production, i.e. around noon with solar panels.
Grid-tie inverters are also designed to quickly disconnect from the grid if the utility grid goes down. It ensures that in the event of a blackout, the grid tie inverter will shut down to prevent the energy it transfers from harming any line workers who are sent to fix the power grid.
Properly configured, a grid tie inverter enables a home owner to use an alternative power generation system like solar or wind power without extensive rewiring and without batteries. If the alternative power being produced is insufficient, the deficit will be sourced from the electricity grid.

3.10.3 Types

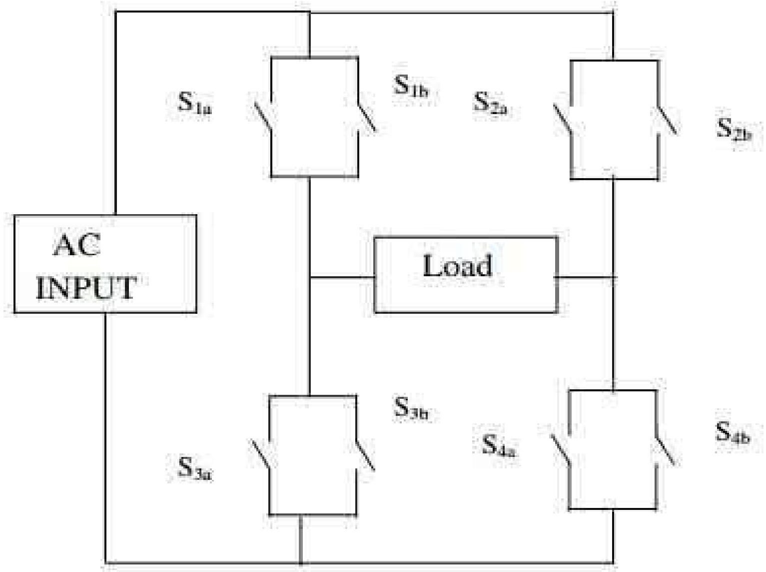
Grid-tie inverters include conventional low-frequency types with transformer coupling, newer high-frequency types, also with transformer coupling, and transformer-less types. Instead of converting direct current directly into AC suitable for the grid, high-frequency transformers types use a computer process to convert the power to a high-frequency and then back to DC and then to the final AC output voltage suitable for the grid. Transformer-less inverter are lighter, smaller, and more efficient than inverters with transformers. But transformer-less inverter have been slow to enter the market because of concerns that transformer-less inverters, which do not have galvanic isolation between the DC side and grid, could inject dangerous DC voltages and currents into the grid under fault conditions.

3.11 MATRIX CONVERTERS

3.11.1 Introduction

The main advantage of matrix converter is elimination of dc link filter. Zero switching loss devices can transfer input power to output power without any power loss. But practically it does not exist. The switching frequency of the device decides the THD of the converter. Maximum power transfer to the load is decided by nature of the control algorithm. Matrix converter has a maximum input output voltage transfer ratio limited to 87 % for sinusoidal input and output waveforms, which can be improved. Further, matrix converter requires more semiconductor devices than a conventional AC-AC indirect power frequency converter. Since monolithic bi-directional switches are available they are used for switching purpose. Matrix converter is particularly sensitive to the disturbances of the input voltage to the system. The instantaneous power flow does not have to equal power output. The difference between the input and output power must be absorbed or delivered by an energy storage element within the converter. The matrix converter replaces the multiple conversion stages and the intermediate energy storage element by a single power conversion stage, and uses a matrix of semiconductor bidirectional switches connecting input and output terminals. With this general arrangement of switches, the power flow through the converter can reverse. Because of the absence of any energy storage element, the instantaneous power input must be equal to the power output, assuming idealized zero-loss switches.

3.11.2 Single Phase Matrix Converter

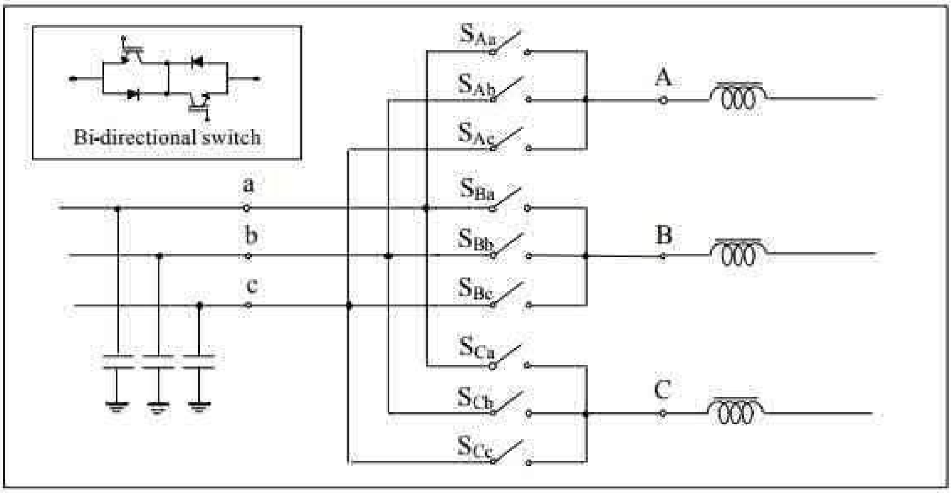


Single Phase Matrix Converter

The AC/AC converter is commonly classified as an indirect converter which utilizes a dc link between the two ac systems and converter that provides direct conversion. This converter consists of two converter stages and energy storage element, which convert input ac to dc and then reconverting dc back to output ac with variable amplitude and frequency. The operation of this converter stages is decoupled on an instantaneous basis by the energy storage elements and controlled independently, so long as the average energy flow is equal. Figure shows the single phase matrix converter switching arrangement.

3.11.3 Three Phase Matrix Converter

Three phase matrix converter consists of nine bidirectional switches. It has been arranged into three groups of three switches. Each group is connected to each phase of the output. These arrangements of switches can connect any input phase. These 3x3 arrangements can have 512 switching states. Among them only 27 switching states are permitted to operate this converter. Here A, B and C are input phase voltage connected to the output phase. Figure shows synchronous operating state vectors of three matrix converter. It shows that the converter switches are switched on rotational basis. In this case no two switches in a leg are switched on simultaneously. These states will not generate gate pulse when one phase of the supply is switched off.



Circuit scheme of a three phase to three phase matrix converter

The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminal are connected to a three phase current-fed system, like an induction motor might be. The capacitive filter on the voltage- fed side and the inductive filter on the current-fed side represented in the scheme are intrinsically necessary. Their size is inversely proportional to the matrix converter switching frequency. It is worth noting that due to its inherent bi-directionality and symmetry a dual connection might be also feasible for the matrix converter: a current-fed system at the input and a voltage-fed system at the output. Taking into account that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short-circuited and the output currents should not be interrupted. From a practical point of view these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant. By this constraint, in a three phase to three phase matrix converter 27 are the permitted switching combinations.

What is a PWM Inverter : Types and Their Applications

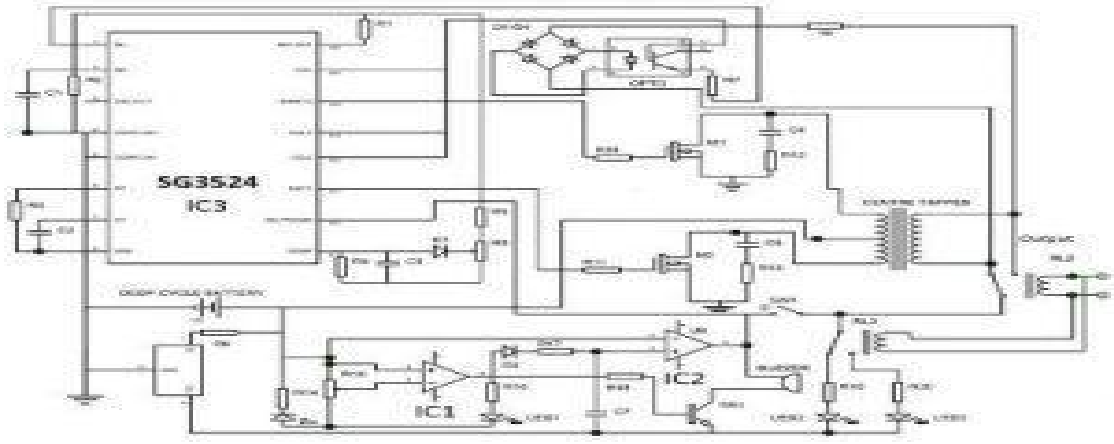
Pulse Width Modulated inverters(PWM inverter) replaced the older versions of inverters and has a wide range of applications. Practically these are used in the power electronics circuits. The inverters based on the PWM technology possess MOSFETs in the switching stage of the output. Most of the inverters available nowadays possess this PWM technology and are capable of producing ac voltage for varying magnitudes and frequencies. There are multiple protection and control circuits in these types of inverters. The implementation of PWM technology in the inverters makes it suitable and ideal for the distinct loads connected.

What is a PWM Inverter?

An inverter whose functionality depends upon the pulse width modulation technology is referred to as PWM inverters. These are capable of maintaining the output voltages as the rated voltages depending on the country irrespective of the type of load connected. This can be achieved by changing the switching frequency width at the oscillator.

PWM Inverter Circuit Diagram

Circuit diagram of PWM inverter is given in the below diagram



PWM Inverter Circuit Diagram

There are various circuits used in the PWM inverters. Some of them are listed below

Battery Charging Current Sensor Circuit

The purpose of this circuit is to sense the current utilized in charging the battery and maintain it at the rated value. It is important to avoid the fluctuations to protect the batteries' shelf life.

Battery Voltage Sensing Circuit

This circuit is used to sense the voltage required to charge the battery when it is exhausted and begin trickle charging of the battery once it gets fully charged.

AC Mains Sensing Circuit

This circuit is to sense the availability of AC mains**.** If it is available then the inverter will be in a state of charging and in the absence of mains the inverter will be in battery mode.

Soft Start Circuit

It is used to delay the charging for 8 to 10 seconds after resuming the power. It is to protect the MOSFETs from the high currents. This is also referred to as Mains delay.

Change Over Circuit

Based on the mains availability this circuit switches the operation of the inverter between the battery and the charging modes.

Shut Down Circuit

This circuit is to monitor the inverter closely and shut it down whenever any abnormality incurred.

PWM Controller Circuit

To regulate the voltage at the output this controller is used. The circuit needs to perform PWM operations are incorporated in the IC's and these are present in this circuit.

Battery Charging Circuit

The process of charging a battery in the inverter is controlled by this circuit. The output generated by the sensing circuit of the mains and the sensor circuits of the battery is the inputs for this circuit.

Oscillator Circuit

This circuit is incorporated with the IC of PWM. It is used to generate the switching frequencies.

Driver Circuit

The output of the inverter gets driven by this circuit based on the switching signal of frequency generated. It is similar to that of a preamplifier circuit.

Output Section

This output section comprises a step-up transformer and it is used to drive the load.

Working Principle

An inverter designing involves various topologies of power circuits and the methods to control the voltage. The most concentrated part of the inverter is its waveform generated at the output. For the purpose of filtering the waveform inductors and the capacitors are used. In order to reduce the harmonics from the output low pass filters are used.

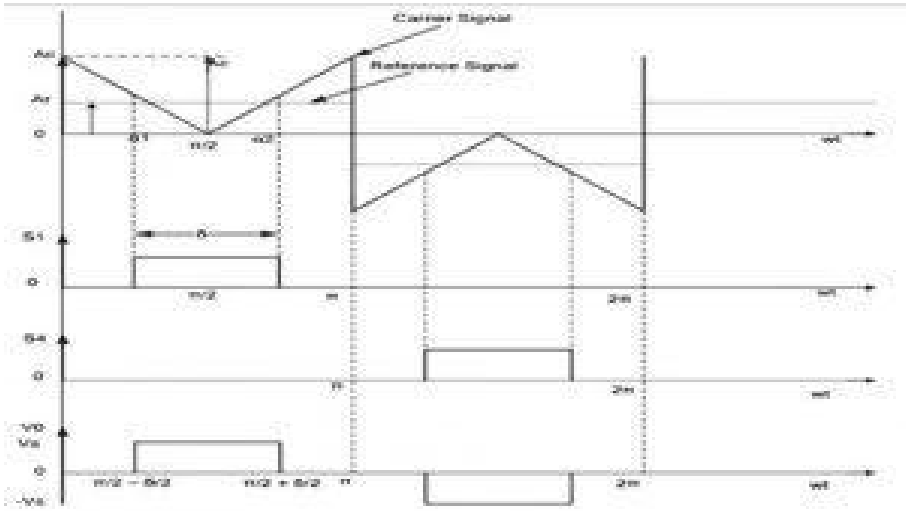
If the inverter possesses a fixed value of output frequencies resonant filters are used. For the adjustable frequencies at the output, filters are tuned above the maximum value of fundamental frequency. PWM technology changes the square wave characteristics. The pulses used for switching are modulated and regulated before it supplied to the connected load. When there is no requirement for voltage control fixed width of the pulse is used.

PWM Inverter Types & Waveforms

The technique of PWM in an inverter comprises of two signals. One signal is for the reference and the other will be the carrier. The pulse required for switching the mode of the inverter can be generated by the comparison among those two signals. There are various PWM techniques.

Single Pulse Width Modulation (SPWM)

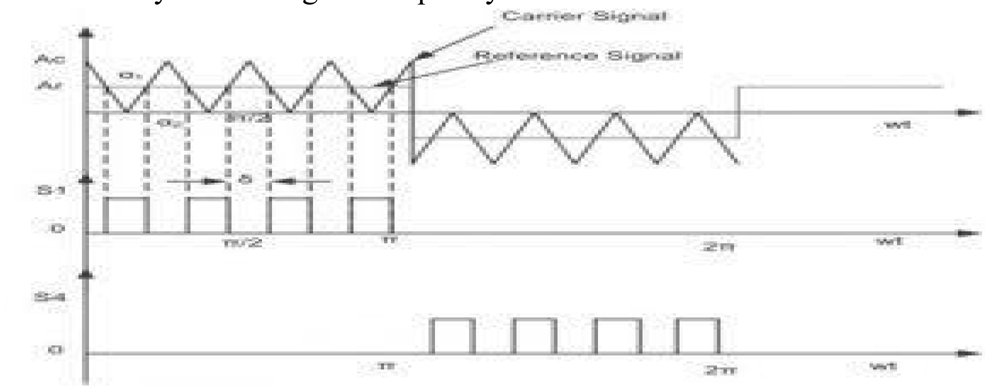
For every half cycle, there is only one pulse available to control the technique. The square wave signal will be for reference and a triangular wave will be the carrier. The gate pulse generated will be the result of the comparison of the carrier and the reference signals. Higher harmonics is the major drawback of this technique.



Single Pulse Width Modulation

Multiple Pulse Width Modulation (MPWM)

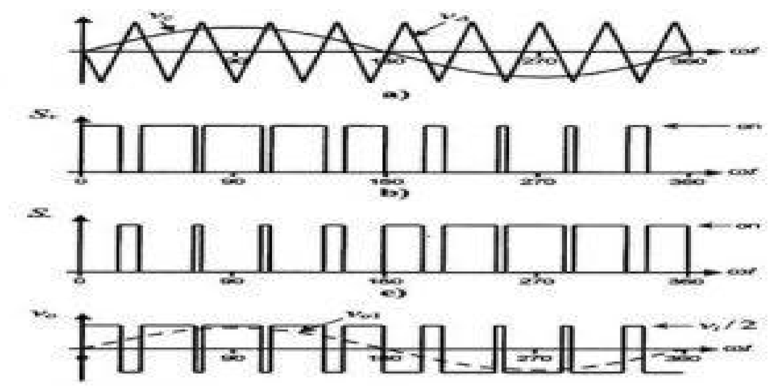
MPWM technique is used to overcome the drawback of SPWM. Instead of a single pulse, multiple pulses are used for every half cycle of the voltage at the output. The frequency at the output is controlled by controlling the frequency of the carrier.



Multiple Pulse Width Modulation

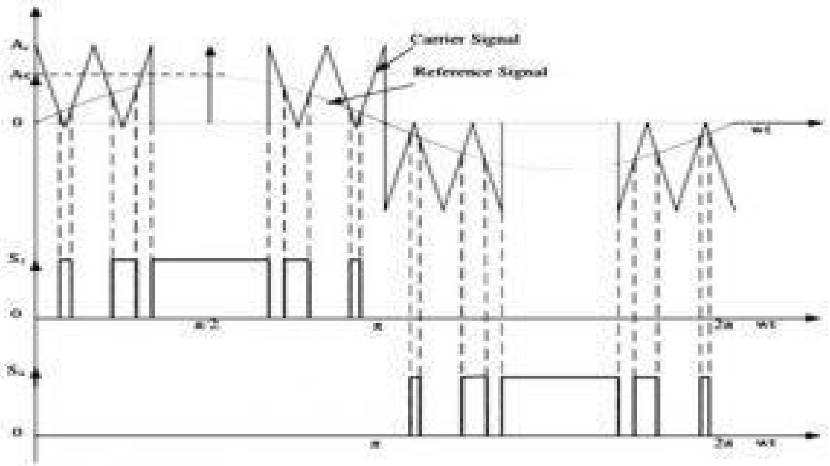
Sinusoidal Pulse Width Modulation

In this type of PWM technique, instead of a square wave, a sine wave is used as a reference and the carrier will be a triangular wave. The sine wave will be the output and its RMS value of voltage is controlled by the modulation index.



Sinusoidal Pulse Width Modulation

Modified Sinusoidal Pulse Width Modulation
The carrier wave is applied for the first and the last sixty-degree interval per every half cycle. This modification is introduced to improve the harmonic characteristics. It decreases the loss due to switching and increases the fundamental component.



Modified Sinusoidal Pulse Width Modulation

Applications

Most commonly PWM inverters are utilized in the speed AC drives where the speed of the drive is dependent on the variation in the frequency of the applied voltage. Majorly the circuits in power electronics can be controlled by using PWM signals. To generate the signals in analog form from digital devices like microcontrollers, the PWM technique is beneficial. Further, there are various applications where PWM technology is used in different circuits.