SWOT Analysis of the Energy Scenario

Strengths

1. **Abundant Renewable Resources**
   Solar, wind, biomass, hydro, and geothermal resources are widely available, providing long-term sustainable energy options.
2. **Technological Advancements**
   Smart grids, energy-efficient appliances, electric vehicles (EVs), and improved power electronics help reduce energy losses and improve reliability.
3. **Government Policies & Incentives**
   Many countries support renewable energy through subsidies, tax benefits, and renewable purchase obligations (RPOs).
4. **Energy Security Improvements**
   Diversification of energy sources reduces dependence on imported fossil fuels.

Weaknesses

1. **High Initial Investment**
   Renewable projects (solar, wind) require high capital cost for installation and grid integration.
2. **Intermittency of Renewable Energy**
   Solar and wind depend on weather conditions; energy storage systems are still expensive.
3. **Old Transmission & Distribution Infrastructure**
   Ageing grids lead to high losses, reliability issues, and poor power quality.
4. **Dependence on Fossil Fuels**
   Many countries still rely heavily on coal and oil, causing high carbon emissions.

Opportunities

1. **Rapid Growth of Renewable Energy Market**
   Falling solar and wind prices make clean energy more attractive for industries and households.
2. **Energy Storage and Smart Grid Development**
   Battery storage, microgrids, and IoT-based monitoring create new opportunities for modernization.
3. **Electric Vehicles (EV) Expansion**
   EV adoption increases electricity demand while reducing oil consumption.
4. **Energy Efficiency Programs**
   Industrial audits, demand-side management (DSM), and green buildings can reduce energy wastage.

Threats

1. **Climate Change and Environmental Issues**
   Rising emissions cause global warming, extreme weather, and environmental degradation.
2. **Energy Price Volatility**
   Fluctuating global oil, gas, and coal prices impact economic stability.
3. **Resource Depletion**
   Fossil fuel reserves are limited and may become economically unviable in the future.

4. **Geopolitical Conflicts**
   International tensions can disrupt fuel supply and cause energy security issues.

World-Transforming Energy by 2050

By 2050, the global energy landscape is expected to undergo a major transformation due to climate goals, technological advancements, and the transition from fossil fuels to clean energy sources. This transformation will influence electricity generation, transportation, industries, and overall economic development.

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1. Shift to Renewable Energy (Majority Share by 2050)

- Renewable energy (solar, wind, hydro, biomass, geothermal) is projected to supply **60–80% of global electricity**.
- Solar PV and wind energy will dominate due to falling costs and large-scale deployment.
- Fossil fuel usage (coal, oil) will drastically decline to meet Net Zero Emission targets.

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2. Electrification of Transport and Industry

- Electric vehicles (EVs) will account for **nearly all new vehicle sales** by 2050.
- Hydrogen-powered heavy transport (trucks, ships, aircraft) will become common.
- Industries such as steel, cement, and chemicals will shift to **green hydrogen** and **electrified heating systems**.

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3. Energy Storage Breakthroughs

- Large-scale battery storage systems will stabilize grids with intermittent solar and wind energy.
- Technologies like **lithium-ion, solid-state batteries, pumped hydro**, and **hydrogen storage** will expand massively.

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4. Smart, Decentralized Energy Systems

- Smart grids using IoT, AI, and blockchain will enable real-time monitoring, demand response, and efficient energy distribution.
- Microgrids and rooftop solar will promote decentralized power systems, especially in rural and remote areas.

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5. Decline of Fossil Fuels & Carbon Neutrality Goals

- Many countries aim for **Net Zero Carbon Emissions by 2050**.
- Coal plants are expected to phase out completely.
- Oil and gas consumption will reduce due to EVs, renewable electricity, and energy efficiency improvements.

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6. Hydrogen Economy Growth

- Green hydrogen (produced using renewable energy) will become a major energy carrier.
- It will replace fossil fuels in:
  - Heavy industries
  - Power generation
  - Energy storage

  - Transport sector

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7. Increase in Enery Efficiency

Buildings will use smart appliances, sensors, and automated HVAC to reduce power consumption.

- Industries will adopt high-efficiency motors, variable speed drives, and waste heat recovery systems.

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8. Global Environmental Benefits

- Reduction in greenhouse gas emissions.
- Decrease in air pollution and improved public health.
- Slower rate of climate change and global warming.

Conclusion

By 2050, the world’s energy system will shift towards **clean, renewable, digital, decentralized, and sustainable** technologies. This transformation will not only reduce carbon emissions but also improve energy security, economic growth, and global environmental conditions.

Prospects of Renewable Energy Sources

Renewable energy sources such as solar, wind, hydro, biomass, and geothermal are expected to play a major role in the future global energy system. Growing environmental concerns, technological progress, and government policies make renewables the most promising long-term solution for energy security and sustainability.

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1. Rising Energy Demand and Need for Clean Power

- Global energy demand is increasing due to population growth and industrialization.
- Renewables can meet this demand without harming the environment.
- Countries aim for *Net Zero emissions* by 2050, increasing renewable installation.

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2. Abundant and Inexhaustible Resources

- Solar radiation, wind flows, water cycles, and biomass are naturally replenished.
- Unlike fossil fuels, renewable energy sources do not deplete over time.
- Most regions have at least one strong renewable resource.

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3. Technological Advancements

- Solar PV, wind turbines, and energy storage systems have become more efficient.
- Falling costs of batteries, smart inverters, and power electronics support large-scale adoption.
- Innovation in hydrogen production (green hydrogen) expands renewable possibilities.

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4. Declining Costs

- Cost of solar and wind energy has fallen significantly in the last decade.
- Levelized Cost of Electricity (LCOE) for renewables is now competitive with coal and gas.
- Large-scale manufacturing makes renewable systems more affordable.

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5. Energy Security and Independence

- Reduces dependence on imported fuels (coal, oil, natural gas).
- Local renewable production strengthens national energy independence.
- Helpful for rural electrification and decentralized systems.

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6. Environmental Benefits

- Zero or very low greenhouse gas emissions.
- Reduces air pollution, water pollution, and ecological damage.
- Helps mitigate climate change and global warming.

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7. Employment and Economic Growth

- Renewable energy sector creates millions of jobs in installation, manufacturing, and maintenance.
- Promotes green industries and sustainable economic development.

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8. Integration with Smart Grids and Storage

- Smart grid technology enables better demand-side management.
- Battery storage, hydrogen storage, and pumped hydro allow continuous power supply.
- Future grids will be more flexible and resilient.

Working Of Solar Drying

The principle of the solar drying technique is to collect solar energy by heating the air volume in solar collectors and to lead the warm air from the collector to the drying chamber. The products to be dried are placed in the drying chamber.

The basic principles employed in a solar dryer are:

1. **Converting light to heat:** Using black surfaces on the inside of a solar dryer is beneficial because black surfaces absorb more sunlight and convert it into heat more efficiently than other colors. When light hits a black character, it is absorbed rather than reflected, and this absorbed energy is then converted into heat. By having black surfaces inside the solar dryer, the absorbed light energy can raise the temperature, promoting more effective drying of the materials placed inside.
2. **Trapping heat:** Using explicit solid materials like plastic bags or glass covers as a covering for the solar dryer is an effective way to trap the heat inside. These materials allow sunlight to pass through and reach the drying chamber, which is converted to heat, but they have a high infrared radiation reflectivity. As a result, once the light energy is converted to heat, it is less likely to escape through the transparent cover, thereby trapping the heat inside the dryer. This is particularly useful on cold and windy days when external heat loss would be significant.
3. **Moving the heat to the food:** The heat generated inside the solar dryer must be efficiently transferred to the dried material. Both natural convection dryers and forced convection dryers use the principle of convection to achieve this. In natural convection dryers, the warm air inside the chamber rises due to its reduced density and carries the heat towards the material being dried. Cooler and moist air from the surroundings replaces the rising warm air, creating a continuous convection cycle.

In forced convection dryers, fans or blowers are used to actively circulate the heated air inside the drying chamber. This forced circulation enhances heat transfer to the materials, ensuring more even and faster drying. The use of forced convection can significantly reduce the drying time compared to natural convection dryers.

By employing these principles of converting light to heat, trapping the heat, and efficiently moving the heat to the material being dried, solar dryers can achieve effective and efficient drying of various products while utilizing renewable energy from the sun.

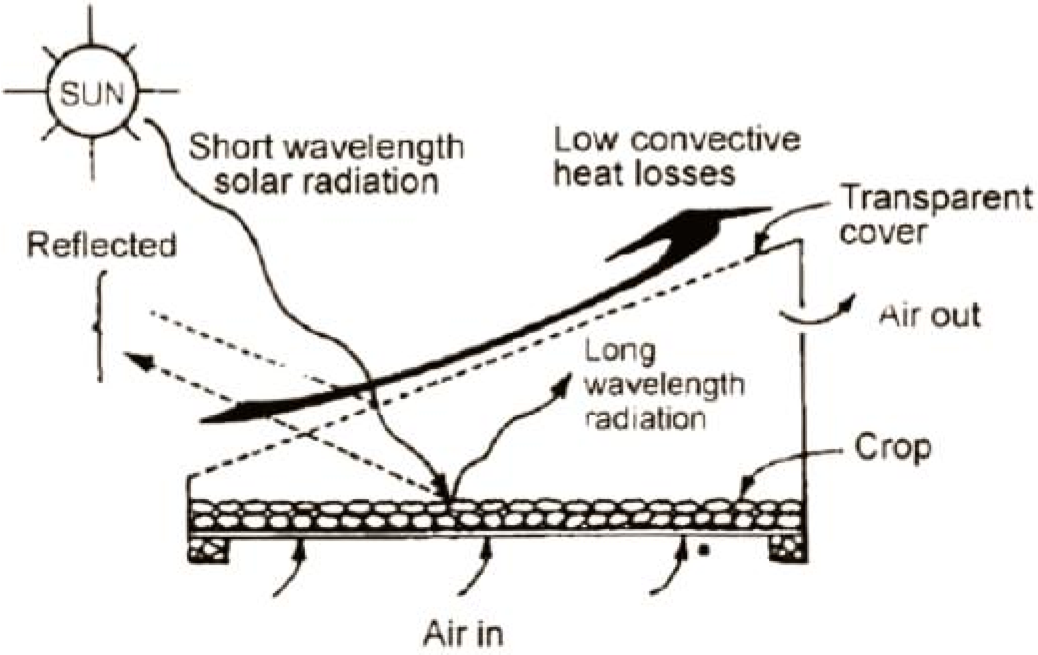
Types OF Solar Drying

Solar Drying is classified into two types:

1. Direct Solar Drying
2. Indirect Solar Drying

1. Direct Solar Drying

Direct solar dryers expose the food or other items directly to the sunlight for drying. In the past, people used simple methods like hanging clothes on lines or laying food on rocks or tents to dry in the sun. Even now, some traditional practices in certain places, like Mongolia, involve using the top of a tent to dry cheese and meat in the sun.

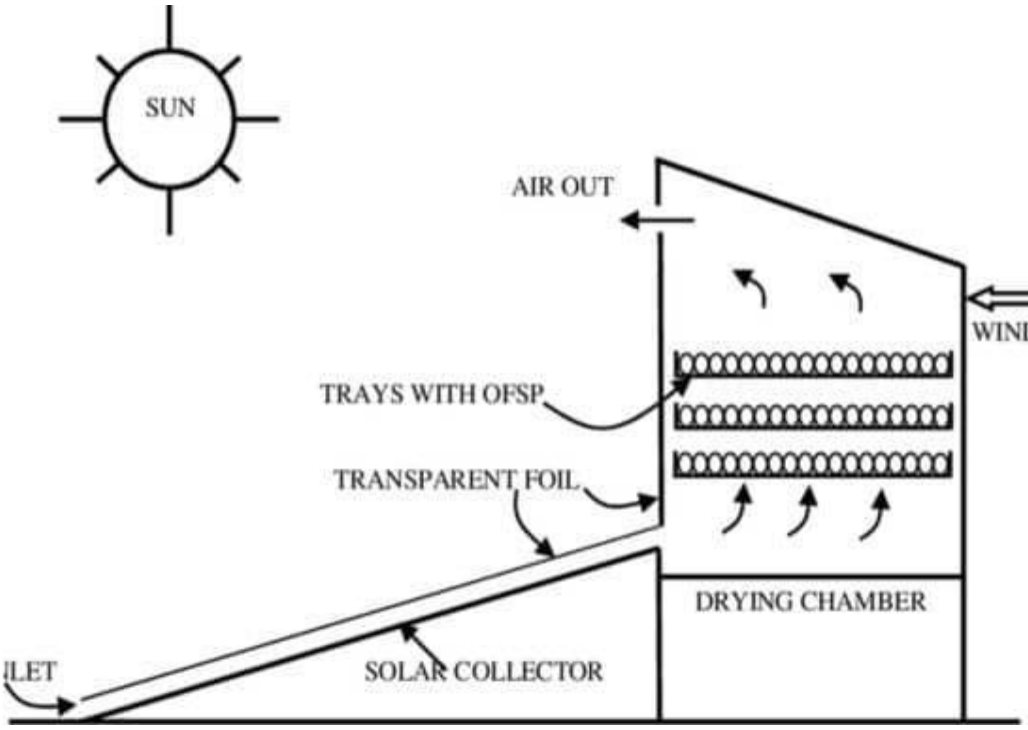


In modern times, we have more sophisticated solar dryers. One type has a black surface that absorbs sunlight and turns it into heat. The substance to be dried is placed directly on this heated surface. These solar dryers might have covers, glass, or vents to make them work even better and more efficiently. The solar energy heats up the surface, which, in turn, helps to dry the food or other items placed on it.

2. Indirect Solar Drying

Indirect solar dryers work differently from direct ones. Instead of directly heating the substance, they heat the incoming air. This heated air is then passed over the substance to be dried, taking away the moisture released from it. The heated air exits through a chimney, carrying the moisture with it.

These dryers can range from simple setups like a tilted frame with black cloth to more complex structures like insulated brick buildings with active ventilation and backup heating systems.



Indirect solar dryers have some advantages. They protect the food or substance from contamination by wind-blown debris or pests like birds, insects, and animals. Additionally, they prevent direct sunlight from chemically altering some foods, which can make them less appetizing.

The temperature inside solar dryers is usually kept between 50-70 degrees Celsius. Modern solar dryers, such as Vyom and others, use materials like polycarbonate sheets or UV preventive glass to protect the food from harmful UV rays that can degrade the dried food. These solar dryers not only speed up the drying process but also keep the food safe from dust, pathogens, bird droppings, and other external elements that could affect its quality.

Drying food using solar dryers allows fruits, vegetables, spices, and other items to be preserved for a longer time. It helps in extending the shelf life of these foods, making them available even when they are out of season or in limited supply.

Advantages of Solar Drying

1. Less product contamination with a transparent cover.
2. Protection from rain, dew, and debris.
3. Higher product quality than open sun drying.
4. Simple and cost-effective construction.

Disadvantages of Solar Drying

1. Crop damage from rodents, birds, and animals.
2. Deterioration from direct sun exposure, rain, storms, and dew.
3. Contamination from dirt, dust, debris, and pollution.
4. Losses from over-drying.
5. Infestation by insects and growth of microorganisms.

Introduction to Solar Ponds:

Solar pond, also called solar ‘salt pond’, is an artificially designed pond, filled with salty water, maintaining a definite concentration gradient. It combines solar energy radiation and sensible heat storage, and as such, it is utilised for collecting and storing solar energy.

A solar pond reduces the convective and evaporative heat losses by reversing the temperature gradient with the help of non-uniform vertical concentration of salts.

Fig. 4.3 illustrates the principle of solar pond.

The vertical configuration of “salt gradient solar pond” normally consists of the following three zones:

1. “Surface (homogeneous) convective zone (SCZ)”- It is adjacent to the surface and serves as a buffer zone between environmental fluctuations at the surface and conductive heat transport from the layer below. It, is about 10 to 20 cm thick with a low uniform concentration at nearly the ambient air temperature.

2. “Lower connective zone (LCG)”- It is at the bottom of the pond, and this is the layer with highest salt concentration, where high temperatures are built up.

3. “Concentration/Intermediate gradient zone (CGZ)”- This zone keeps the two convective zones (SCG and LCG) apart and gives the solar pond its unique thermal performance. It provides excellent insulation for the storage layer, while transmitting the solar radiation. To maintain a solar pond in this non-equilibrium stationary state it is necessary to replace the amount of salt that is transported by molecular diffusion from the LCG to SCZ. This means that salt must be added to the LCG, and fresh water to the SCG whilst brine is removed. The brine can be recycled, divided into water and salt (by solar distillation) and returned to the pond.

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

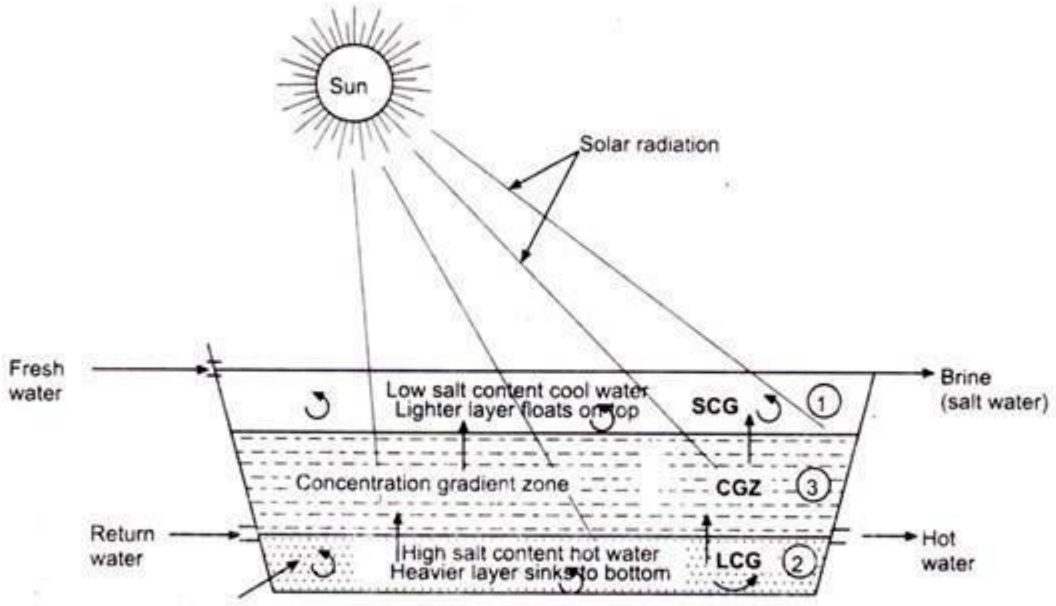


Fig. 4.3. Principle of solar pond.

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

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

(i) Salt concentration.

(ii) The quantity of suspended dust or other particles.

(iii) Surface impurities like leaves or debris, biological material like bacteria and algae.

(iv) The type of salt.

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

The solar pond is an effective collector of diffuse, as well as direct radiation, and will gather useful heat even on cloudy or overcast days. Under ideal conditions, the pond's absorption efficiency can reach 50% of incoming solar radiation, although actual efficiencies average about 20% due to heat losses. Once the lower layer of the pond reaches over 60°C the heat generated can be drawn off through a heat exchanger and used to drive a low temperature organic Rankine cycle (ORC) turbine.

This harnesses the pressure differentials created when a low boiling point organic fluid (or gas) is boiled by heat from the pond via a heat exchanger and cooled by a condenser to drive a turbine to generate electricity. The conversion efficiency of an organic Rankine cycle turbine driving an electric generator is 5—8% (which mean 1—3% from insolation to electricity output).

UNIT-II

WIND AND OTHER ENERGY SYSTEMS

1. Air

- **Air** is a mixture of gases surrounding the Earth.
- Main components:
  - Nitrogen (≈78%)
  - Oxygen (≈21%)
  - Others: Argon, CO_2, water vapour, etc.
- Air has **mass, pressure, and temperature**.

2. Wind

Wind is **air in motion**.

- It flows **from high-pressure areas to low-pressure areas**.
- Caused mainly due to:
  - Unequal heating of Earth's surface by the Sun
  - Differences in air pressure and temperature

□ Wind is named **from the direction it blows from** (e.g., north wind).

3. Global Winds

Global winds are large-scale wind systems that blow **constantly over long distances** across the Earth.

Major Global Wind Belts:

(a) Trade Winds □Blow from **subtropical high pressure** to **equatorial low pressure**

- Direction:
  - Northern Hemisphere: **North-East Trade Winds**
  - Southern Hemisphere: **South-East Trade Winds**
- Important for sailing and climate

(b) Westerlies

- Blow from **subtropics toward mid-latitudes**
- Direction: **West to East**
- Affect weather patterns in many countries

(c) Polar Easterlies

- Blow from **polar high pressure** to **sub-polar low pressure**
- Direction: **East to West**
- Cold and dry winds

4. Local Winds

Local winds blow over **short distances** and **for short durations**, caused by **local temperature differences**.

Common Types of Local Winds:

(a) Sea Breeze □

- Occurs during **daytime**
- Wind blows from **sea to land**
- Reason: Land heats faster than sea

(b) Land Breeze

- Occurs at **night**
- Wind blows from **land to sea**
- Reason: Land cools faster than sea

(c) Mountain Breeze

- Occurs at **night**
- Cold air flows **from mountain to valley**

(d) Valley Breeze

- Occurs during **day**
- Warm air flows **from valley to mountain**

5. Wind Energy Availability in INDIA

Wind power generation capacity in India has significantly increased in recent years. As of 31 March 2025, the total installed wind power capacity was 50.00 gigawatts (GW). India has the fourth largest installed wind power capacity in the world.[2] Wind power capacity is mainly spread across the southern, western, and northwestern states.[3] The onshore wind power potential of India was assessed at 132 GW with minimum 32% CUF at 120 m above the local ground level (agl).[4] Whereas, the estimated potential at minimum 25% CUF is 695 GW at 120 agl.

- India aims to add significant wind capacity, with projections potentially reaching over 100 GW by 2030.

Installed wind power capacity[*citation needed*]

Fiscal year,	cumulative capacity (MW)

2005	6,270
2010	16,084
2014	23,354
2015	26,769
2016	32,280
2017	34,046
2018	35,626
2019	37,669
2020	38,785
2021	40,355
2022	42,633
2023	45,887
2024	48,163

Installed wind capacity by state as of 31 December 2024[33]

State	Total capacity (MW)
Gujarat	12,473.78
Tamil Nadu	11,409.04
Karnataka	6,731.30
Maharashtra	5,216.38
Rajasthan	5,195.82
Andhra Pradesh	4,096.65
Madhya Pradesh	2,844.29
Telangana	128.10
Kerala	63.50
Others	4.30
Total	**48,163.16**

6.Wind Velocity and Power from wind

Wind Velocity (Wind Speed)

Wind velocity (V) is the **speed at which air moves**, usually measured in **m/s**.

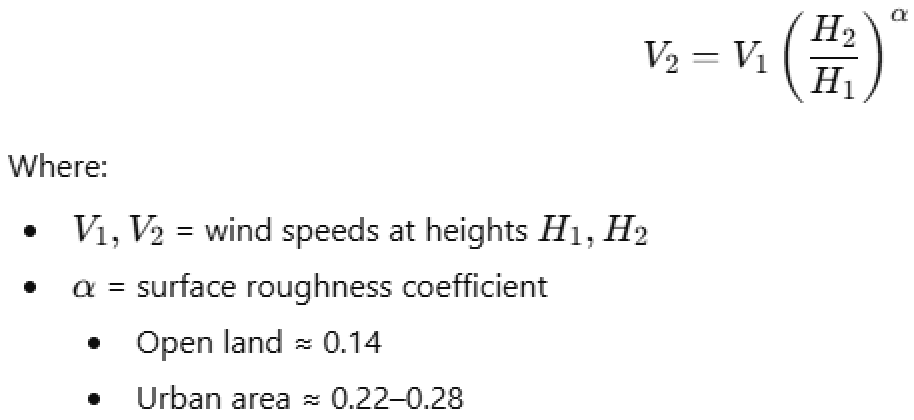
Factors affecting wind velocity:

- Height above ground (higher → faster wind)
- Surface roughness (trees, buildings reduce speed)
- Temperature & pressure difference
- Geography (coastal, plains, hills)

Wind speed variation with height

Wind speed **increases with height** due to reduced friction.

Power law equation:



$$V_2 = V_1 \left(\frac{H_2}{H_1} \right)^{\alpha}$$

Where:

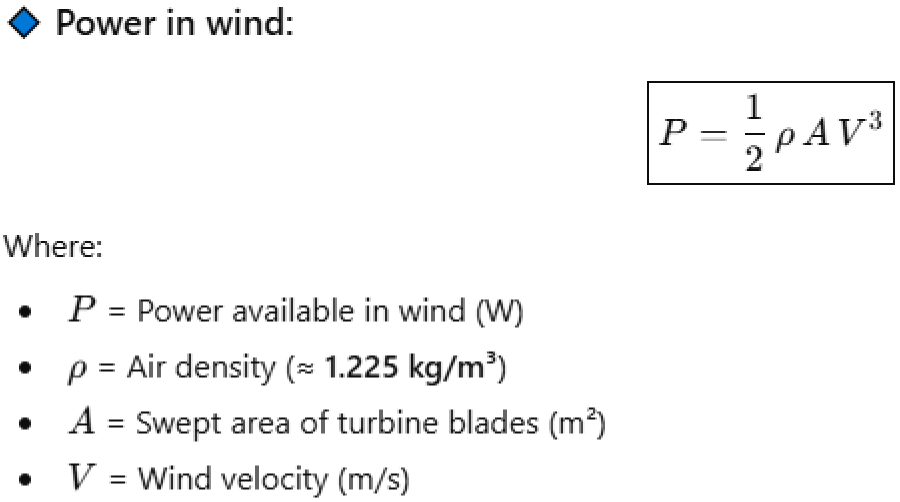
- V_1, V_2 = wind speeds at heights H_1, H_2
- α = surface roughness coefficient
  - Open land ≈ 0.14
  - Urban area ≈ 0.22–0.28

Power Available in Wind

Wind contains **kinetic energy**.
The power comes from **moving air mass**.

Step-by-step idea:

- Moving air → kinetic energy
- Kinetic energy per second → power



◆ Power in wind:

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

Where:

- P = Power available in wind (W)
- ρ = Air density (≈ **1.225 kg/m^3**)
- A = Swept area of turbine blades (m^2)
- V = Wind velocity (m/s)

7.Major Problems associated with Wind Power

1. **Intermittency and Unpredictability**
   Wind speed varies with time and season. This leads to fluctuating power output, making wind power unreliable without energy storage or backup systems.
2. **Site Specific Nature**
   Efficient wind power generation requires locations with high average wind speeds. Suitable sites are limited and often far from load centers.
3. **Low Power Density**
   The energy available in wind is low compared to conventional power sources. Large numbers of turbines and vast land areas are required.
4. **High Capital Cost**
   Initial investment for turbines, foundations, towers, and transmission infrastructure is high, even though operating costs are low.
5. **Grid Integration and Stability Issues**
   Sudden variations in wind speed can cause voltage fluctuations, frequency deviations, and power quality problems in the grid.
6. **Energy Storage Requirement**
   To ensure continuous power supply, wind systems require batteries or hybrid systems, which increase overall cost and complexity.
7. **Environmental and Aesthetic Issues**
   Wind turbines can cause noise pollution, visual impact, and bird/bat mortality.
8. **Maintenance and Mechanical Stress**
   Turbines operate under varying wind loads, leading to mechanical fatigue and increased maintenance requirements.
9. **Transmission Problems**
   Wind farms are often located in remote areas, requiring long transmission lines and additional infrastructure.
10. **Low Capacity Factor**
    Wind turbines do not operate at rated power all the time, resulting in lower capacity utilization compared to thermal plants.

Horizontal Axis Wind Turbine?

At present, the most commonly used wind turbine is HAWT or Horizontal Axis Wind Turbine. These turbines use airfoils (aerodynamic blades) which are connected to a rotor by positioning in upwind or downwind. These are available either in two-bladed or three-bladed and operate at high speed.

Current horizontal axis wind turbines utilize the aerodynamic lift force to rotate every rotor blade similar to an airplane flies. Generally, the aerodynamic lift force works once they exposed to winds around both the higher and lower segments of a blade. The pressure difference which is formed between the top & bottom faces of the blade generates a force in the top direction of the blade. The horizontal axis wind turbine line diagram is shown below.

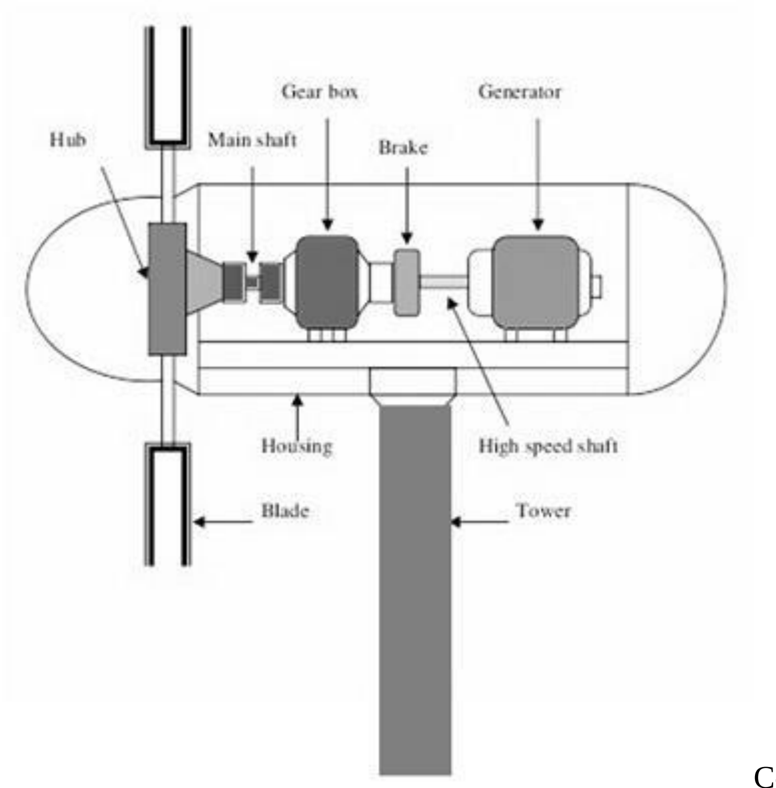
Horizontal Axis Wind Turbine

HAWTs can be used in any direction of wind through the furling system. This system rotates the face of the rotor to come perpendicular to the wind's direction. Therefore, the face of the rotor can be moved to that direction where it can face wind at the highest speed.

Horizontal Axis Wind Turbine Construction and Working

The construction of a horizontal axis wind turbine can be done with different components. So the **horizontal axis wind turbine components** mainly include foundation, nacelle, generator, tower, and rotor blades.

Horizontal axis wind turbines include the rotor shaft & electric generator which are arranged at the top of the tower. Small wind turbines use a simple wind vane, whereas larger wind turbines use wind sensors that are connected through an auxiliary motor. Most wind turbines contain a gearbox, which is used to change the blade rotation from slow to fast, so used to operate an electric generator.



Construction of HAWT

Foundation

For any wind turbine, the foundation gives support to the tower because the wind turbine includes different parts which weigh in tonnes.

Tower

A tower is used to give support to the rotor hub and nacelle on the top of the window turbine. The materials used to make this are concrete, tubular steel, or steel lattice. While designing this turbine, the height of the tower is very important because wind speed enhances with height. So taller towers allow these turbines to capture a huge amount of energy & produce more electricity.

Generally, the output power of a wind turbine enhances by increasing its height & also decreasing the turbulence within the wind. There are different wind turbine towers available like tubular, lattice, guyed wind, tilt upwind & free standing.

Wind Turbine Blades

These blades are mainly used to remove the kinetic energy (KE) of wind & change it to mechanical energy. These types of blades are designed with wood-epoxy or fiberglass-reinforced polyester. These turbines include a minimum of one and maximum multiple blades depending on the design.

Most of the horizontal axis wind turbines include three blades that are connected to the rotor hub. In earlier days, multiple blades based turbines are used as a single blade, two-blade and three blades for grinding & pumping water, etc.

Nacelle

The nacelle includes different components which are used to operate the wind turbine efficiently like the gearbox, brakes, controller, low & high-speed shafts & generator. It is arranged at the top of a tower & a wind vane is arranged on the nacelle.

Hub

A rotor hub is used to connect a shaft and rotor blade of the wind turbine. The hub includes blade bearings, bolts, internals & a pitch system. These are designed with cast iron, welded sheet steel & forged steel. These are available in two types like Hinge-less hub & Teetering hub.

Gear Box

In wind turbines, a gearbox is used to change high toque power with low-speed which is received from a rotor blade to low torque power with high speed. This power is used for the generator. The gearbox is connected in between the generator and main shaft for enhancing rotational speeds from 30 – 60 rpm to 1000 – 1800 rpm.

Gearboxes are made with different materials like superior quality alloys, aluminum cast iron, stainless steel, etc. In wind turbines, there are three types of gearboxes are used like Planetary, Helical, and Worm.

Generator

The rotating mechanical energy of the gearbox is given to the generator through the shaft. It works on ‘Faraday’s law of electromagnetic induction principle. So it changes the energy from mechanical to electrical.

Horizontal Axis Wind Turbine Working

Once the wind blows, a wind turbine changes the kinetic energy from the motion of the wind into mechanical through the revolution of the rotor. After that, this converted energy can be transmitted through the shaft & the gear train toward the generator. Further, this generator converts the energy from mechanical to electrical to generate electricity.

The wind flows on both faces of the airfoil-shaped blade although flows faster on the upper face of the airfoil to create a low-pressure region on the airfoil. The pressure difference between both the top & bottom surfaces results within the aerodynamic lift.

As the blades of a wind turbine are constrained to move in a plane with the hub as the center, the lift force causes rotation about the hub. In addition to the lift force, a drag force perpendicular to the lift force prevents rotor rotation.

The horizontal axis wind turbine design mainly includes a high lift to drag ratio, especially for the blades. So this ratio can change through the blade's length to optimize the output energy for the wind turbine at different speeds of wind. The generator & rotor shaft are arranged within the box at the top of the array.

Advantages and Disadvantages

The **advantages of a horizontal axis wind turbine** include the following.

- It includes high output power as compared to the vertical wind turbine.
- A tall tower gets stronger winds once the wind shear alters.
- High efficiency.
- It is not expensive as compared to vertical type turbine.
- It has high reliability.
- It has a high rate of capacity.
- Its rotational speed is high.
- It is more consistent.
- These turbines are self-starting.
- In this turbine, the vanes are located one face of the turbine center of gravity, which improves stability.
- It can bend the blades so that the turbine blades have the best attack angle.
- The blade can also tilt the rotor during a storm to reduce damage

The **disadvantages of horizontal axis wind turbine** include the following.

- These are available in large size.
- Weight is high.
- We cannot move easily.
- Installation is difficult.
- High noise.
- To design this wind turbine, large machinery is needed.
- Its maintenance is difficult as compared to other wind turbines.

Single-Blade System

Single-blade turbines are rarely used today due to inherent stability issues, but they offer the lowest material costs for the blade itself.

- **Advantages**:
    - **Lowest material and manufacturing cost** for the single blade.
    - **Lighter weight**, which allows for a smaller and lighter tower and easier installation.
- **Disadvantages**:
    - Requires complex **counterweights** and extensive setup to balance the rotor and minimize vibrations.

  - Must rotate at **much higher speeds** to capture the same energy as multi-blade designs, leading to more noise and increased wear/fatigue on components.
  - Experiences significant cyclic loads and **instability** due to the "tower shadow" effect when the blade passes behind the tower.

Double-Blade System

Double-blade turbines offer a compromise between single and three-blade designs but still face dynamic stability issues.

- **Advantages**:
  - **Lower weight and cost** compared to three-bladed designs.
  - Can be installed more easily as the entire assembly can be lifted in a horizontal position.
  - Can achieve higher rotational speeds and tip speed ratios, which can simplify the gearbox design.
- **Disadvantages**:
  - Experiences significant **vibrations and pulsating loads** due to the tower shadow effect and gyroscopic forces, often requiring complex teetering hubs or flexible blades to mitigate stress.
  - Slightly **less aerodynamically efficient** than the three-blade system.
  - Generally **noisier** than three-blade turbines due to the higher rotational speeds.

Multi-Blade System (Typically Three Blades)

The three-bladed configuration is the industry standard for large-scale power generation due to its optimal balance of efficiency, stability, and reliability.

- **Advantages**:
  - **Superior aerodynamic efficiency** and stable performance across a wide range of wind speeds, consistently providing a high power output.
  - **Inherently balanced** design minimizes vibrations, cyclic loads, and noise, extending the lifespan of mechanical components like the gearbox and bearings.
  - Mature and reliable technology with established manufacturing and maintenance processes.
- **Disadvantages**:
  - **Higher material and capital costs** compared to single or double-bladed designs.

- **More difficult to transport and install** due to the large size and weight of the blades and nacelle, requiring specialized equipment and large cranes.
- Requires a more robust and heavy tower structure to support the weight and withstand the higher forces.

Summary Comparison

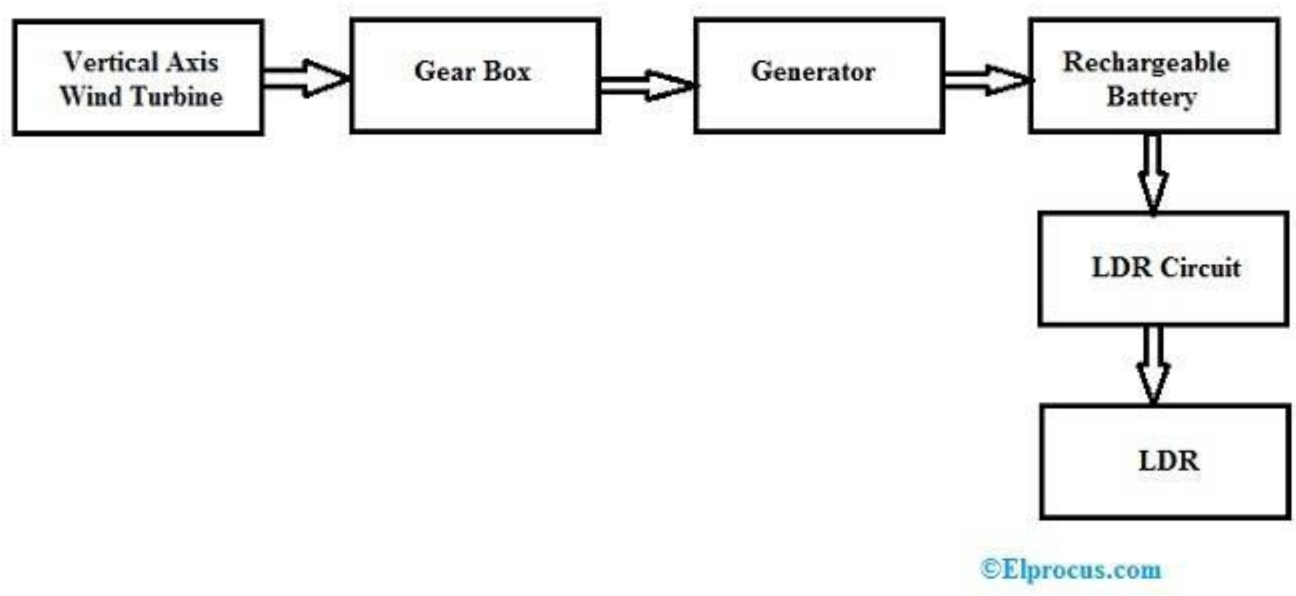
Design Type	**Aerodynamic Efficiency**	**Stability & Vibration**	**Noise Level**	**Cost & Weight**	**Primary Application**
Single-Blade	Lower	Poor, high cyclic loads	High	Lowest cost, lightest	Very limited, niche applications
Double-Blade	Medium, lower than 3-blade	Medium, requires load mitigation	Medium	Lower cost/weight than 3-blade	Limited use, some niche offshore/residential
Multi-Blade (3-blade)	Highest, optimal balance	Excellent, low vibration	Lowest	Highest cost, heaviest	**Dominant for large-scale wind farms**

Vertical Axis Wind Turbine or VAWT?

The Vertical Axis Wind Turbine is a type of wind turbine and it is most frequently used for residential purposes to provide a renewable energy source to the home. This turbine includes the rotor shaft and two or three blades where the rotor shaft moves vertically. So, this turbine movement is related to the spinning of coins on the edge. In this turbine, the generator is placed at the bottom of the tower whereas the blades are covered around the shaft.
The **vertical axis wind turbine working principle** is that, the rotors in the turbine revolve around a vertical shaft by using vertically oriented blades. So they generate electricity by using wind power. The wind operates the rotor which is connected to the generator, so the generator converts the energy from mechanical to electrical. **Vertical axis wind turbine components** are blade, shaft, bearing, frame & blade support.

Vertical Axis Wind Turbine Block Diagram

The block diagram of a vertical axis wind turbine is shown below. The output energy generated from this can be used by any type of load. Here, the automatic lighting system is used as a load. This block diagram includes a Vertical Axis Wind Turbine (VAWT), gearbox, generator, battery, LDR circuit and LED.



Vertical Axis Wind Turbine Block Diagram

Vertical Axis Wind Turbine

The type of Vertical Axis Wind Turbine used in this system is savories VAWT.

Gear Box

A gearbox in a wind turbine is mainly used to enhance the rotating speed from a low sped shaft to a high-speed shaft connecting through an electrical generator. Gears within the gearbox of a wind turbine are subjected to severe cyclic loading because of uneven wind loads that are stochastic within the environment.

Generator

The generator in the wind turbine converts the energy from mechanical to electrical. These generators are a bit strange as compared to generators used in electrical grids.

Rechargeable Battery

The output electric energy generated by the generator will be stored in the rechargeable battery of the wind turbine.

LDR Circuit

The LDR circuit is used to turn ON/OFF the light.

Vertical Axis Wind Turbine Working

This turbine works once the wind turns the turbine. Here, the savory VAWT is used in this lighting system. Once this turbine rotates, then the generator will get it as mechanical input & generate the output as electrical energy.

This turbine is arranged on the dividers of the highway roads. The shape of turbine wings is curved to get the wind for revolution from the 2-way road where the vehicle speed will make this turbine turn. Here, wind speed is used in different ways based on our requirements.

A vertical axis wind turbine is connected to the Gearbox which includes gears. This gearbox is directly connected to the electric generator shaft. This turbine will revolve once the wind blows & the gearbox in this system will enhance the turbine rotations internally & send these rotations to the generator like a mechanical input. So the generator will generate the output as the electrical energy by using this input so that this output will be stored within the rechargeable battery.

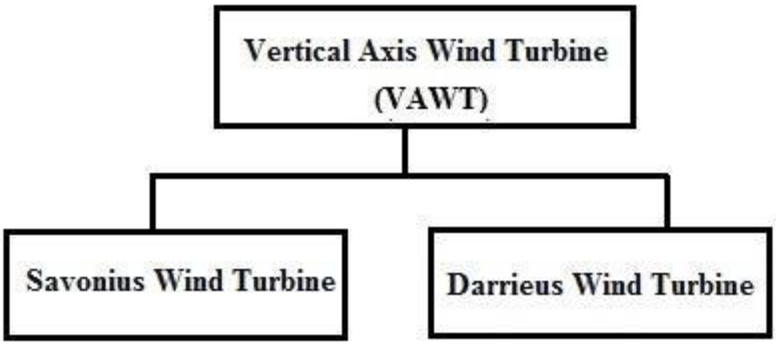
In this way, electricity is generated and stored in the battery using the vehicle's speed with the help of a turbine. The stored energy is used for the automatic lighting system. The LDR circuit uses a resistor, LDR (Light Dependent Resistor), transistor, battery, and LED (Light Emitting Diode).

The transistor collector terminal is connected to the LED's negative terminal whereas the emitter is connected to the GND. Here, the resistor terminals are connected directly to the voltage source whereas the negative is connected to the LDR.

When the LDR circuit is connected directly to the battery, then the LDR will start detecting the light. So when the intensity of light is decreased then LED will be activated automatically. So this LDR circuit is applicable in automatic ON or OFF light systems. When the light intensity of the Sun is decreased in the dusk then LDR will detect the light & supply the LED.

Vertical Axis Wind Turbine Types

The vertical axis wind turbines are available in two types like Savonius Wind Turbine & Darrieus Wind Turbine.



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Types of Vertical Axis Wind Turbine

Savonius Wind Turbine

Savonius wind turbine includes the blades which are arranged around the vertical shaft within a helix form. One of the most significant features of this turbine is the solid wind-receiving area. These turbines mainly rely on the mechanism of flow resistance to make the rotors active which means, the dynamic force of the wind against the turbine blades thrust the rotor into revolution.

Simultaneously, the reverse side of the blades meets an aerodynamic resistance force. This is like when running or cycling, we experience the airflow coming opposite to us. Because of this, these turbines can simply turn fast like the wind speed. Please refer to this link to know more about Savonius Wind Turbine.

What is Savonius Wind Turbine?

The savonius wind turbine definition is that it is employed for the conversion of wind force into torque based on the rotational shift. The turbine is included with multiple aerofoils, but these are not every time placed on the rotational shaft, but also ground positioned or even these are airborne systems.

Savonius Wind Turbine Design

The design of the turbine can be done in two ways one is classic barrel type and the other is Icewind type.

Classic Barrel Design

The construction of a classic barrel savonius wind turbine is so streamlined as because the blades are in half-cylindrical shape and so the name is the barrel. These barrels will not have a meeting point at the axis, but they are away from each other. There are many parameters that define the shape of the barrel. Here, we will be following the below approach:

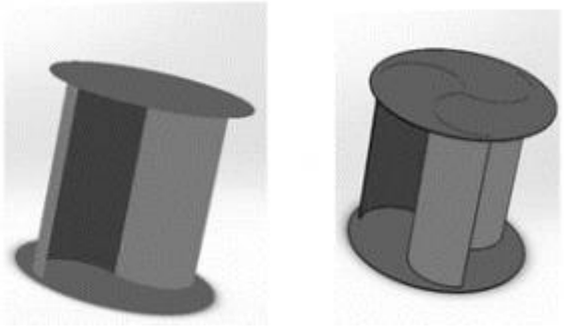
‘D0’ – external diameter of the rotor’s base
‘D’ – blade radius which is the distance that is in between the two blades

‘h’ – rotor height

In order to design the square-shaped turbine, a ratio of D:h is followed. The other proportion that is used in D0: D where defines how much away that the base is ahead of the blade.

The turbine’s base is required for structural reliability as this offers extensive support for the blades in opposing the dragging pressure of the wind thus pushing the rotor blades.

The design of the wind turbine is shown below:



Classic Barrel Savonius Wind Turbine

Icewind Design

Mostly savonius wind turbines that are designed using Icewind type are used for household purposes like farms, houses and in cabins, and telecom towers. The designs are completely high-end, simple, reliable, and less cost and they also need less maintenance for the generation of energy.
They can provide nearly 1000 watts of energy when operated at 10 m/s and a smaller turbine can produce 300 watts at 10 meters/second. These both designs can deliver speeds in the range of 2 – 60 m/sec showing no mechanical issues or overheating. Few of the turbines those are designed using Icewind type are shown as below:

Working

The device in a similar way to a cup anemometer. The **savonius wind turbine working principle** can be easily explained because this is considered as the most streamlined turbine when compared with other turbines. This is a dragging kind of instrument where it consists of some 2 – 3 cups. From the above portion, when the rotor is seen, it appears in the shape of “S” in the form of a cross-section.
Due to this curvature shape, the cups will have minimal dragging when they move in the opposite direction of the wind, whereas they experience maximum drag while moving in the same direction of the wind. This variation in the dragging creates the spinning movement of the savonius turbine.

As these instruments are drag type, they grab minimal wind power when compared with that of other same sized lift kinds of turbines. Most of the brushed section of savonius rotor is close to the ground level when the device has minimal mount having no stretched post thus delivering low energy extraction because of the fewer wind speeds observed at lesser heights.

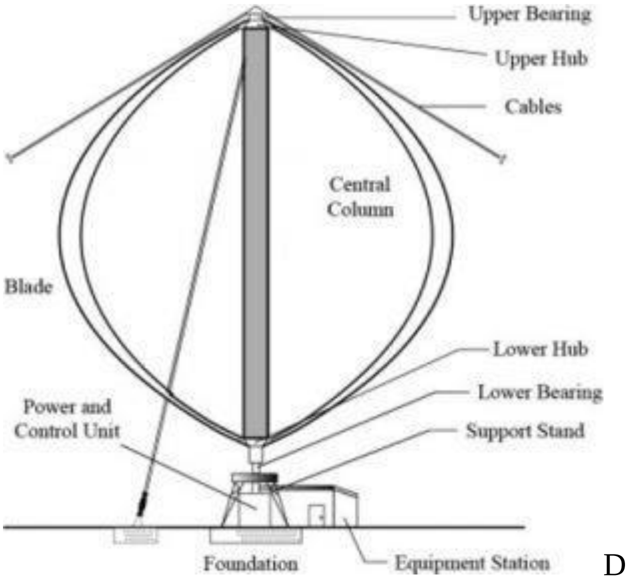
The cups in the savonius wind turbine will not have faster rotational speeds when compared with the wind speed and this creates a tip speed proportion of either one or less than one. This states that the device has minimal rotational speed but produces a higher amount of torque.

So, these instruments are not exactly suitable for the production of electricity as they require higher RPMs for the generation of higher current and voltage values. For this, a gearbox can be inserted to minimize the torque and enhance the generator RPM level, and this corresponds that the turbine does not hold the ability to start by itself.

Darrieus Wind Turbine

Darrieus Wind Turbine Design

The design of the Darrieus wind turbine can be done using a number of curved aerofoil blades which are arranged on a rotary framework or shaft. The Darrieus wind turbine is a type of vertical axis wind turbine, used to produce electricity using wind energy. The blade curve of this turbine allows being stressed only in anxiety at high rotary speeds.

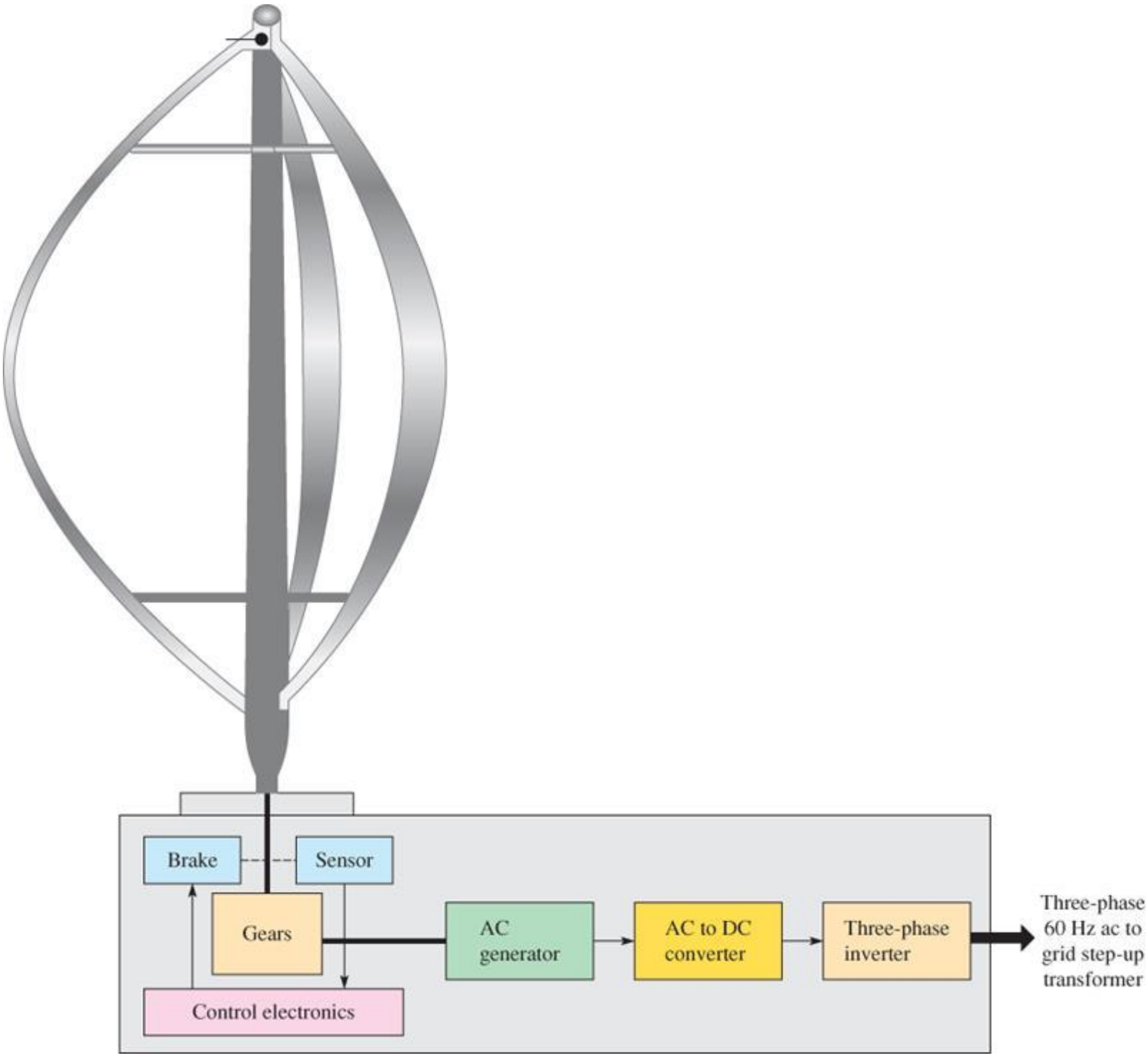


Darrieus Wind Turbine Design

There are numerous closely related wind turbines that utilize straight blades. The Darrieus Wind Turbine Design was patented by a French aeronautical engineer namely Georges Jean Marie Darrieus and filing for the copyright was done on 1st Oct in 1926. There are many troubles while protecting this turbine from severe wind situations and also in designing it as self-starting.

Darrieus Wind Turbine Working Principle

These turbines are not self-starting but it requires a motor which is small powered to begin the revolution. Once it has sufficient speed then the wind flows across the aerofoils starts to produce torque & the rotor can be driven in the region of the wind. In the Darrieus turbine, two mini Savonius rotors are placed on the shaft to start a revolution. These reduce the Darrieus turbine once it gets going but they make the complete device very simpler as well as easier to keep.



Advantages

The **advantages of a vertical axis wind turbin**e include the following.

- Safety for manpower.
- Scalability.
- They can generate electricity in any direction of the wind.
- It doesn’t require a strong supporting tower because the gearbox, generator & other components are arranged on the ground.
- As compared to horizontal axis turbines, these are cheaper to design.
- Installation is easy as compared to other types.
- These are portable so we can simply move from one location to another.
- These are designed with fewer speed blades to reduce the risk to birds & people.
- They work in all weather conditions like variable winds & mountain conditions.
- These are allowable where taller structures are not allowed.
- Its operation is simple so they don’t bother people in residential areas.
- These turbines can be arranged close to the earth so that maintenance, the cost for construction can be reduced.
- To operate these turbines, we don’t require any mechanisms.
- You can use the wind turbine where tall structures are not allowed.

- These are economical, quiet, efficient & ideal for residential energy sources, particularly in urban areas.

Disadvantages

The **disadvantages of a vertical axis wind turbine** include the following.

- As compared to HAWT, the efficiency level will be decreased because of the drag that happens in the blades when they rotate.
- These are very hard to arrange on towers because they are connected on bases like buildings or ground.
- The efficiency of rotation is low.
- Lower accessible wind speed.
- Component Wear-down.
- Low efficiency.
- Self-Starting mechanism.
- Some animals or birds may interrupt its rotation because it is arranged in an open area.
- They have high vibration due to the flow of air close to the ground makes the turbulent flow
- They produce noise pollution

Bio Mass energy Introduction

Biomass energy is renewable energy made from organic matter like plants, animals, and waste; it can be burned or converted into fuels to produce heat, electricity, or biofuels.Renewable organic material derived from plants and animals is called biomass. Through a variety of processes, biomass can be transformed into liquid and gaseous fuels or burned directly for heat. Renewable biomass energy comes from resources that regenerate naturally, making it a clean alternative to fossil fuels. A renewable energy source, biomass energy is produced from organic materials like waste, plants, and animals. It can be used to produce heat, electricity, or biofuels through processes like fermentation, combustion, or decomposition. Biomass lessens reliance on fossil fuels and greenhouse gas emissions. As a sustainable energy option, it makes a substantial contribution to the development of cleaner and more efficient energy systems.

Types of Biomass Energy

Biomass energy may produce wood and agricultural residues, solid waste, landfill gas, alcohol fuels, and animal or plant-based oils. Examples of biomass energy are animal dung, sugarcane bagasse, landfill gas, and alcohol fuels (ethanol and methanol). Different kinds of organic materials with their specific features and applications can utilize biomass energy production. Recognizing the different forms of biomass energy helps identify the most appropriate source for a given set of energy requirements.

- **Wood and Agricultural Products**: Wood biomass includes logs, chips, and sawdust. Agricultural products include grass and crop residues, both significant sources of biomass. These materials are usually directly burned or converted into pellets and briquettes for heating and power generation.
- **Solid Waste**: Biomass energy from municipal solid waste, including both industrial and residential trash, can be generated. This type of biomass will generate heat, or electricity through gasification or combustion while helping to reduce landfill

volumes. Solid waste provides energy for environment-friendly waste management as well as energy generation.

  - **Landfill Gas**: Landfill gas is generated from anaerobic decay of organic waste in the landfill. Carbon dioxide and methane are the gas's principal components, which can then be collected for further use as fuel in the generation of heat or electricity. Because of this process, greenhouse gas emissions would also be reduced by preventing methane released into the atmosphere.
  - **Alcohol Fuel**s: Such kinds of biofuels are derived from fermentation. Biomass materials such as wood, corn and sugarcane can be converted into ethanol and methanol, usually referred to as alcohol fuels. The fuels are mostly used in transportation by part usage or as alternative fuels to gasoline consumption. In so doing, dependency on fossil fuels is reduced while minimizing carbon emissions.
  - **Animal and Plant Material**s: Anaerobic digestion and the creation of biodiesel are techniques that may convert manure from animals and oils from plants to biomass energy. These waste materials will be recycled, and they will also be a source of valuable bioenergy. They encouraged energy diversification and sustainable agriculture.

Photosynthesis Process

Photosynthesis is how plants, algae, and some bacteria use sunlight, water, and carbon dioxide to create their own food (glucose/sugar) and release oxygen, with the process occurring in chloroplasts in two main stages: light-dependent reactions (capturing energy in ATP/NADPH) and the light-independent Calvin cycle (using that energy to build sugar). This fundamental process powers life on Earth, providing energy and the oxygen we breathe.
Overall Equation

- **$6CO_2$ (Carbon Dioxide) + $6H_2O$ (Water) + Light Energy → $C_6H_{12}O_6$ (Glucose) + $6O_2$ (Oxygen)**

Where it Happens

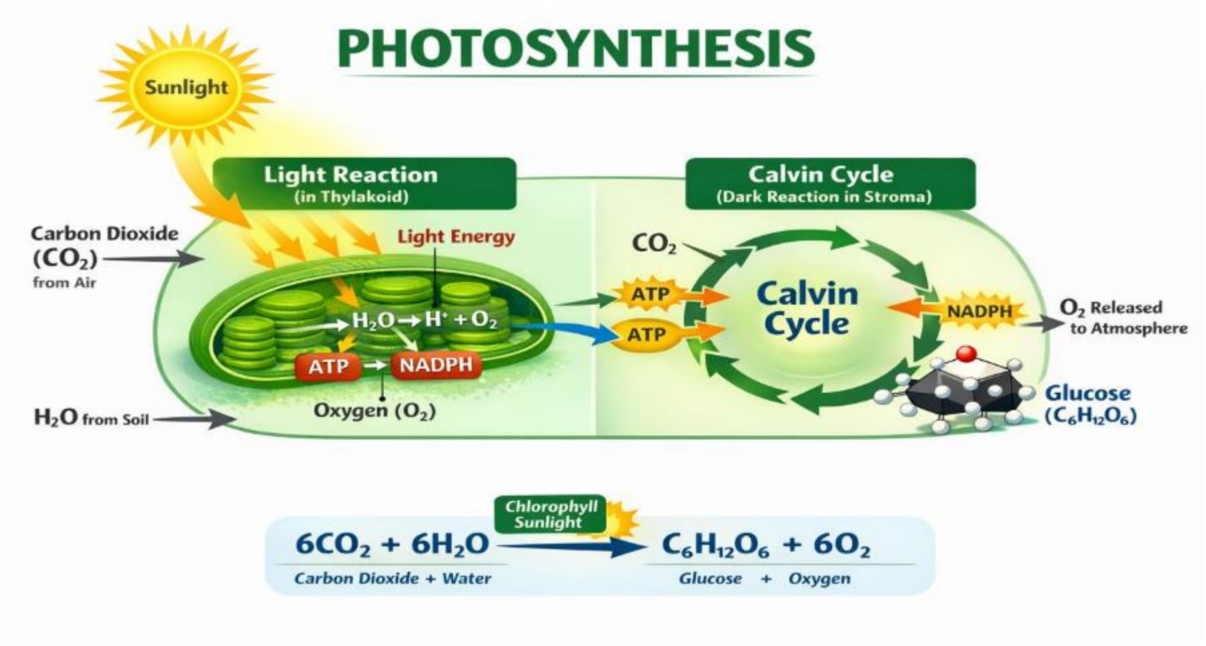
- In plants, within chloroplasts, primarily in leaf cells.

The Two Stages of Photosynthesis

- **Light-Dependent Reactions:** (Occurs in thylakoid membranes)
  - Chlorophyll absorbs light energy.
  - This energy splits water molecules (H_20) into hydrogen, oxygen (released as waste), and electrons.
  - Energy is stored in temporary carriers: ATP and NADPH.

Light-Independent Reactions (Calvin Cycle): (Occurs in the stroma)

- Uses the ATP and NADPH from the first stage.
- Carbon dioxide (Co_2) from the air is combined with hydrogen to form glucose($C_6H_{12}O_6$).
- This glucose provides energy for the plant's growth, or is stored for later use.



Biofuel

Biofuel is a renewable energy source made from organic matter (biomass) like plants, algae, and animal waste, used as an alternative to fossil fuels for transportation, heating, or electricity, with common types being ethanol and biodiesel, offering reduced greenhouse gas (GHG) emissions by recycling atmospheric carbon. Produced through biological or thermochemical processes, biofuels are considered sustainable because their feedstocks can be replenished, supporting energy security and environmental goals.

Types of Biofuels

- **Bioethanol:** Made from plant starches and sugars (like corn, sugarcane) and blended with gasoline (e.g., E10).
- **Biodiesel:** Produced from vegetable oils, animal fats, or recycled cooking grease, used as a replacement for petroleum diesel.
- **Biogas:** Generated from decomposing organic waste (sewage, food scraps) via anaerobic digestion, primarily methane and carbon dioxide.

Production Methods

- **Fermentation:** Sugars are fermented by yeast into ethanol.
- **Transesterification:** Vegetable oils/fats react with alcohol to create biodiesel.
- **Anaerobic Digestion:** Microorganisms break down organic matter without oxygen to produce biogas.

Benefits

- **Renewable:** Derived from constantly replenished biomass.
- **Reduces Emissions:** Considered carbon-neutral as plants absorb CO2 during growth, and combustion releases that same CO2.
- **Energy Security:** Reduces dependence on imported fossil fuels.

Applications

- **Transportation:** Blended with gasoline (ethanol) or diesel (biodiesel).
- **Heating & Electricity:** Biogas can power generators or be used for heating.

Comparison Table: Biofuel vs Biomass

Aspect	Biomass	Biofuel
Definition	Organic raw material from plants, animals, and waste	Processed fuel made from biomass (like ethanol, biodiesel)
Form	Solid (wood, crop residue, dung)	Liquid or gaseous (ethanol, biodiesel, biogas)
Usage	Used for cooking, heating, electricity generation	Used as transport fuel, industrial energy
Processing	Often used directly or with minimal processing	Requires chemical or biological conversion
Examples	Wood, paddy straw, sugarcane bagasse, manure	Ethanol, biodiesel, biogas, methanol
Renewability	Renewable, available in raw form	Renewable, but needs energy and tech for production
Environmental Impact	Can emit smoke if burned directly	Burns cleaner with fewer emissions

BIOMASS RESOURCES

Biomass resources are organic materials from plants, animals, and waste, like crop residues, wood, algae, animal manure, and municipal solid waste, that store solar energy and can be converted into heat, electricity, or biofuels (ethanol, biogas) for heating, power, and transportation, offering a renewable energy alternative to fossil fuels. Key types include agricultural (corn stalks, rice straw), forestry (wood chips, forest debris), animal (manure), and urban (MSW, sewage sludge) sources, used for energy, fertilizer, and bioproducts.

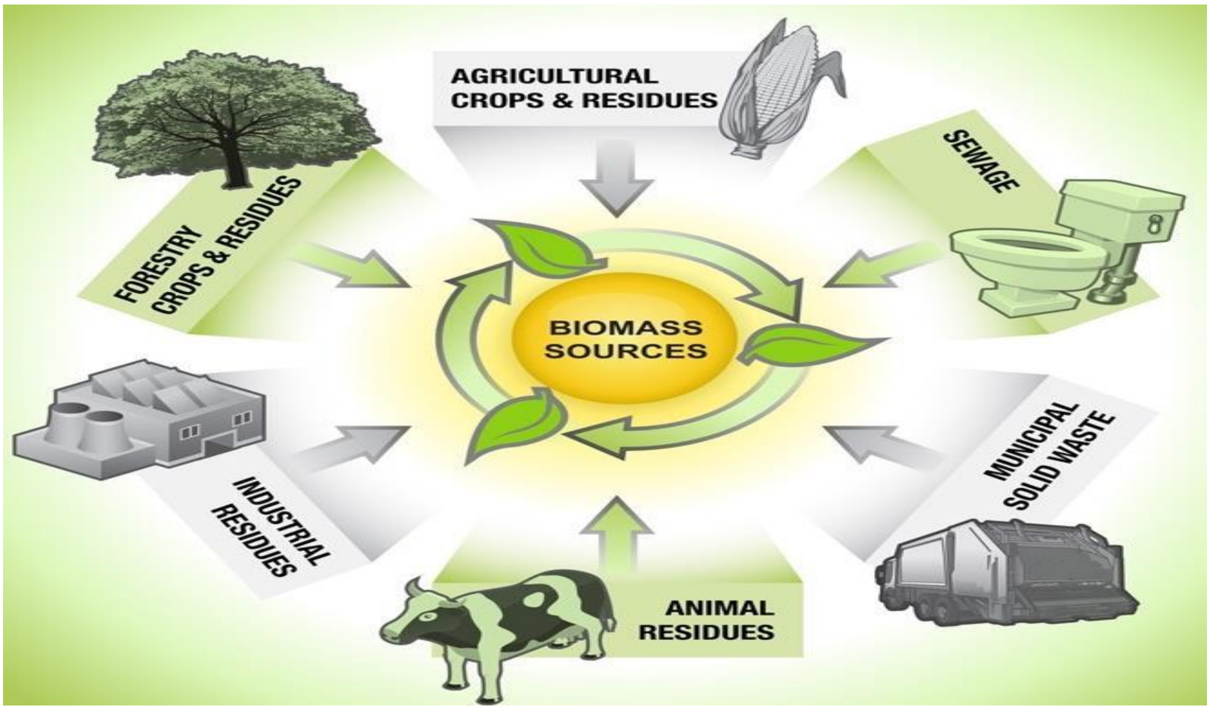
Types of Biomass Resources

- **Agricultural:** Crop residues (straw, stalks), dedicated energy crops (switchgrass), food processing wastes (sugarcane bagasse).

- **Forestry:** Logging residues (limbs, tops), wood processing waste (sawdust), forest thinnings, and dedicated timber crops.
- **Animal:** Manure, poultry litter, and sewage sludge from livestock and urban areas.
- **Municipal & Industrial Waste:** Household garbage (paper, food scraps), industrial byproducts, and landfill gases.
- **Aquatic:** Algae and aquatic plants (water hyacinth).

How They're Used

- **Direct Combustion:** Burning wood, crops, or waste for heat/electricity.
- **Biofuels:** Conversion into liquid fuels like ethanol (from corn/sugarcane) or biodiesel (from oils/fats).
- **Biogas/Methane:** Anaerobic digestion of manure or sewage produces methane for heating or power.
- **Bioproducts:** Creation of bioplastics, biochemicals, biochar, and fertilizers.



Dome and Drum Type Biogas Plants

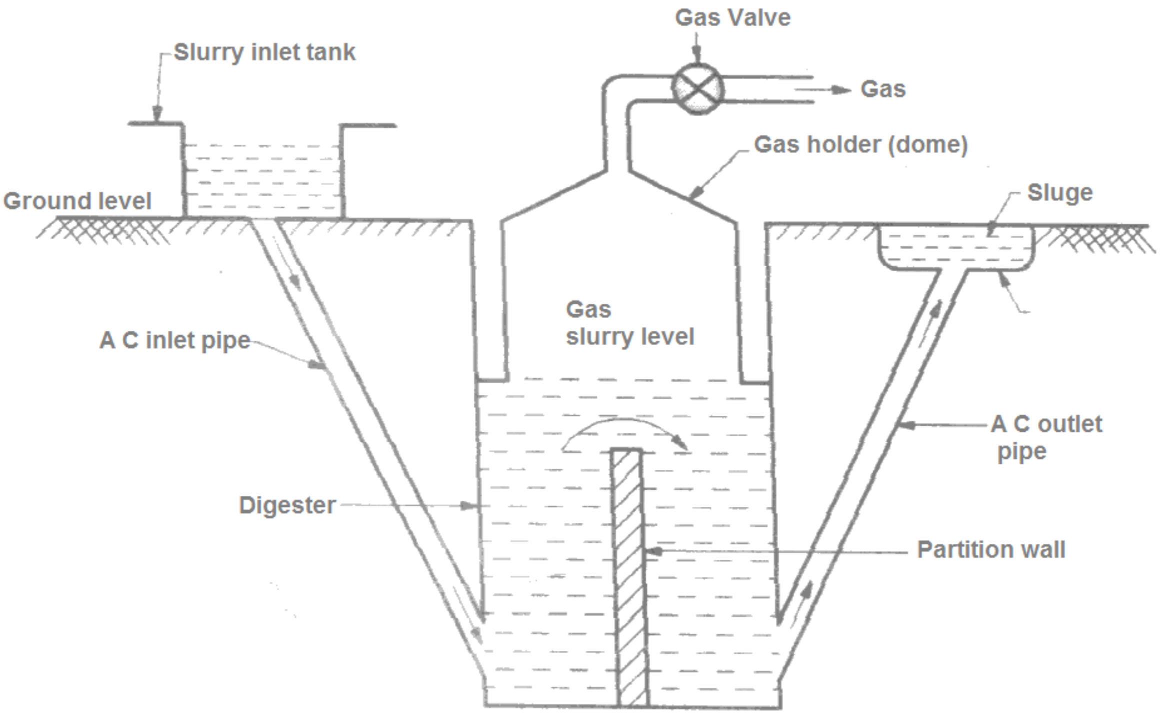
Various models of dome and drum type of biogas plants have been developed by the various agencies. These are mainly of two types:

- Floating drum type biogas plants
- Fixed dome type biogas plants

Floating Drum Type Biogas Plants (Constant Pressure Type)

Many models of floating drum type biogas plants have been developed in various countries. One of the model is discussed here.

Floating drum type KVIC model: A common gobar gas plant suggested by Khadi and Village Industries Commission (KVIC) India, is described below. These are suitable for small scale gas production.



KVIC Gobar Gas Plant

The plant consists of a digester made of masonary construction in the form of a well below the ground level and the floating gas holder, also called as dome, made of mild steel.

In the inlet tank animal waste slurry is prepared containing cow dung and water in the ratio as 1:1 to 1:1.25. The feeding of animal waste slurry is usually done once in a day.

The sludge comes out with the built up of gas pressure in the dome above the partition wall and flows out to the outlet tank through **A C** outlet pipe. This sludge is an excellent fertilizer which can be again fed to the soil.
At the top of the gas holder, the accumulated gas is drawn from the pipe through gas valve. The bifurcation of digestion chamber through a partition wall provides optimum conditions for growth of acid formers and methane formers as the pH value requirement for these bacteria are different.

Therefore, this gives a good yield of biogas. It operates naturally under constant pressure. The diameter of the digester of a gas plant ranges from 1.2 to 6 m and its height varies from 3 m to 6 m. The mild steel gas holders are prone to corrosion, thus needs painting at regular intervals.

This problem can be overcome by using fiber glass reinforced plastic (FRP) material for construction of gas holders, however it is costly.

Advantages of KVIC Plant

1. High gas yield
2. No problem of gas leakage.
3. Works under constant pressure naturally.
4. No problem of mixing of biogas with external air, thus no danger of explosion.

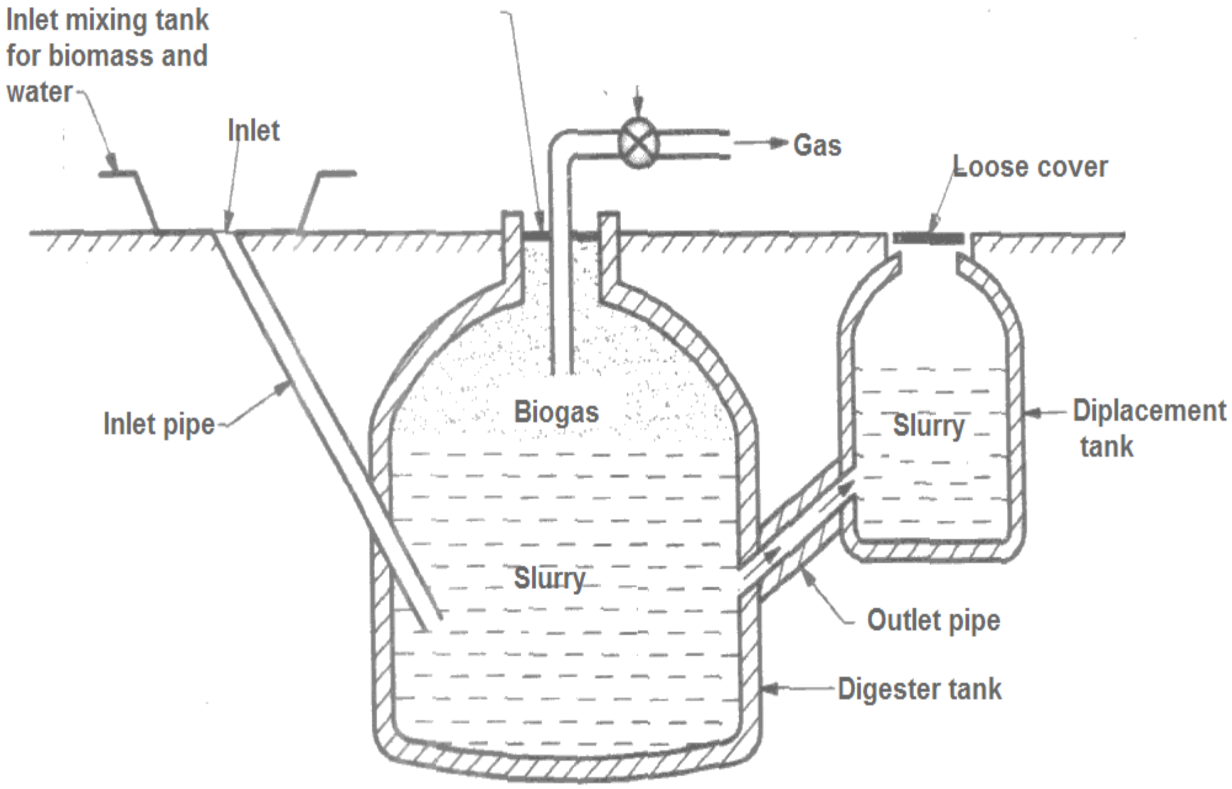
Disadvantages

1. It has higher cost
2. Heat is lost through metal gas holder.
3. Requires painting of drum to avoid corrosion at least twice a year.
4. Requires maintenance of pipes and joints.

Fixed Dome Type Biogas Plants

In fixed dome type biogas plants, the digester and the gas dome (gas collector) are combined and enclosed in the same chamber. These types of plants are best suited for batch type gas plants. These types of plants are more economical compared to floating dome type since only the masonry work is needed for their construction. The digester is usually built below the ground level, particularly for applications in regions having the cold climate.

The gas pressure inside the dome varies depending upon the rate of gas production and its consumption. However, the total volume of gas inside the dome remains constant due to which these are also called as constant volume type biogas plants.



Fixed dome type biogas plant

Many variations of fixed dome type models are developed by various countries keeping in view the availability of local materials, the cost, ease of installation, maintenance and operation etc. Few of the fixed dome type biogas plants are described below.

1. **Fixed dome type domestic biogas plant (Janta model or Chinese model)**: Figure represents the schematic diagram of a fixed dome type biogas plant called as Janta model or Chinese model of biogas plant. It is similar to KVIC model except that both the digester and gas holder are constructed in a fixed dome usually below the ground surface.

The mixture of biomass and water is supplied as feed to the digester through the inlet pipe. The mixture is stirred with a handle (not shown) to form slurry. The biogas generated in the digestion tank by anaerobic digestion is collected in the upper part of the digester.

A stirring arrangement is necessary in the digester if the raw material is a crop residue. The biogas so produced is delivered via the outlet gas pipe. When the gas is produced, the liquid level in the digester drops whereas level in the displacement tank rises.

The height difference between two levels helps in regulating the pressure of gas within the digester. The gas pressures obtained may be as high as 0.1 bar pressure above atmospheric.

Since these plants are constructed underground, their temperature of operation remains unaffected by the environment. Hence, these plants are suitable for winter operation. A manhole cover sealed by clay is provided at the top of digester dome for the purpose of its maintenance.

2. **Flexible bag type biogas plant**: In this the digester is made of flexible plastic material. The biomass with water and biomass slurry is supplied to digester from inlet pipe. After anaerobic digestion the biogas is collected in the upper part of the bag like dome of the digester which gets inflated. The digested slurry is discharged from outlet pipe.

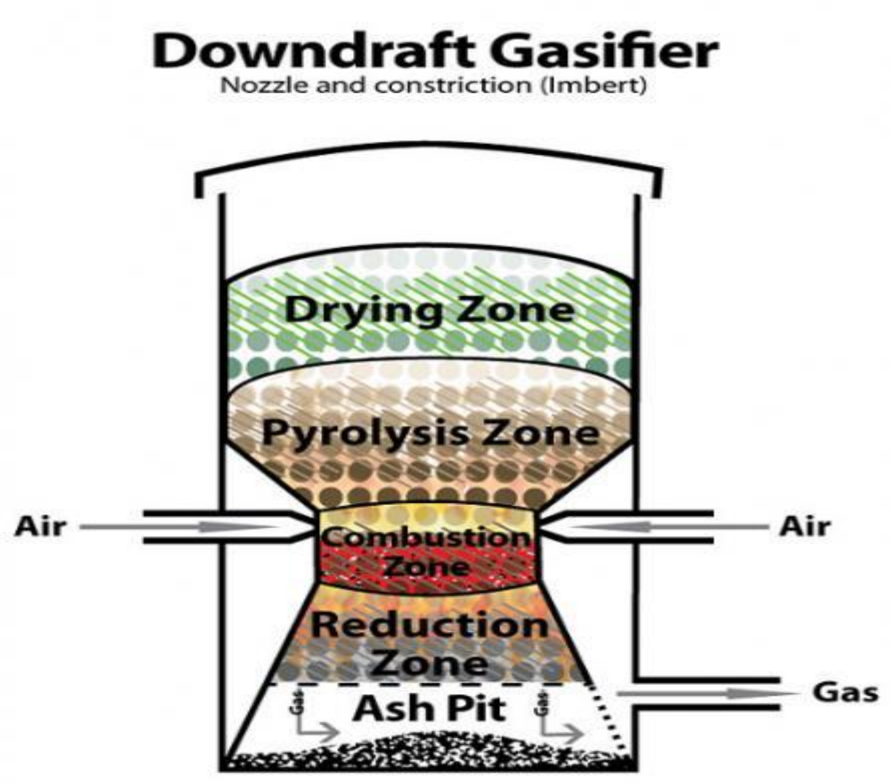
Advantages of Fixed Dome Type Plant

(i) Cost of plant is less compared to floating drum type plant.
(ii) Loss of heat is negligible since these are constructed underground.
(iii) No corrosion problems as in fixed drum type.
(iv) It is maintenance free.

Disadvantages of Fixed Dome Type Plants

(i) Needs skilled labour to operate.
(ii) Gas production/m^3 of digester volume is less.
(iii) Gas is produced at variable pressure.

Bio gasification down draft



In a downdraft gasifier, biomass feedstock is fed from the top, with air entering from the upper sides of the furnace walls. The produced syngas is extracted from the bottom of the furnace. This arrangement, where the material and gas flow in the same direction, is also known as a co-current gasifier. In the oxidation zone, located in the middle of the furnace, air mixes with the feedstock and burns at temperatures of 900–1200°C. The heat generated drives the pyrolysis and reduction reactions above and below the oxidation zone, respectively. The upper pyrolysis zone, with temperatures ranging from 300–700°C, separates volatile components (gas, tar, and water) from the biomass. The top layer is the drying zone, where feedstock is preheated. Below the oxidation zone is the reduction zone, where CO2, carbon, and steam from the oxidation zone undergo reduction reactions. Remaining tars are cracked in this zone, producing syngas rich in CO and H2.

- **Drying Zone**: Biomass (wood, straw) is fed from the top and moisture evaporates due to heat from lower zones.

- **Pyrolysis Zone**: As temperature rises (around 250°C), biomass thermally decomposes, releasing volatile gases (CO, H_2,CH_4, tars) and leaving behind solid charcoal (coke).

- **Oxidation Zone (Throat)**: Air is introduced (often radially) into a constricted throat. Partial combustion of charcoal and volatiles occurs here, creating intense heat (900-1000°C) and driving the reactions.

- **Reduction Zone**: The hot producer gases (CO, H_2,CO_2) from oxidation pass through the remaining hot charcoal bed. Carbon reacts with CO_2 and steam (from drying) to produce more combustible gases (CO, H_2) reducing the gas's CO_2 content.

Fundamental Characteristics of Tidal Power

1. **Predictable and Periodic**
   Tidal power is highly predictable because tides occur due to the gravitational interaction of the **moon, sun, and earth**. Unlike solar and wind energy, tidal cycles can be forecast accurately years in advance.
2. **Renewable and Sustainable**
   Tidal energy is a **renewable resource** and will remain available as long as the moon–earth system exists. It does not get depleted with use.
3. **High Energy Density**
   Seawater has a much **higher density than air**, so tidal currents carry more energy than wind at the same speed, resulting in higher power output per unit area.
4. **Environmentally Clean**
   Tidal power generation produces **no greenhouse gas emissions** or air pollutants during operation, making it an eco-friendly energy source.
5. **Site-Specific Availability**
   Tidal power can be harnessed only at locations with **large tidal ranges or strong tidal currents**, such as estuaries, bays, and narrow channels.
6. **Bi-Directional Nature**
   Power can be generated during both **flood tide (incoming)** and **ebb tide (outgoing)**, depending on the type of tidal plant.
7. **Low Operating Cost**
   After high initial capital investment, tidal power plants have **low operation and maintenance costs** and long service life.
8. **Long Construction Time & High Capital Cost**
   Tidal power plants require massive civil structures (barrages, turbines), making them **capital intensive** with long gestation periods.

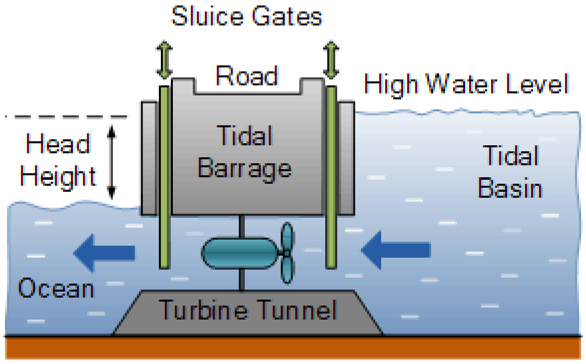
9. **Grid Stability Support**
   Due to predictable output, tidal power helps in **better grid planning and stability** compared to other intermittent renewables.
10. **Limited Global Potential**
    Although reliable, tidal power has **limited global exploitation potential** due to geographical constraints.

Harnessing of Tidal Energy

Introduction

Tidal energy is a form of renewable energy obtained by converting the **potential and kinetic energy of seawater caused by tides** into electrical energy. Tides occur due to the **gravitational attraction of the moon and the sun on the earth**, making tidal energy highly predictable and reliable.

Tidal Barrage Power Generation



Tidal Barrage – A *Tidal Barrage* is a type of tidal power generation that involves the construction of a fairly low dam wall, known as a “barrage” and hence its name, across the entrance of a tidal inlet or basin creating a tidal reservoir.

This dam has a number of underwater tunnels cut into its width allowing sea water to flow through them in a controllable way using “sluice gates”. Fixed within the tunnels are huge water turbine generators that spin as the water rushes past them generating tidal electricity.

A tidal barrage generates electricity using the difference in the vertical height between the incoming high tides and the outgoing low tides. As the tide ebbs and flows, sea water is allowed to flow in or out of the reservoir through a one way underwater tunnel system.

This flow of tidal water back and forth causes the water turbine generators located within the tunnels to rotate producing tidal energy with special generators used to produce electricity on both the incoming and the outgoing tides.

The one disadvantage of **Tidal Barrage Generation**, is that it can only generate electricity when the tide is actually flowing either "in" or "out" as during high and low tide times the tidal water is stationary.

However, because tides are totally predictable, other power stations can compensate for this stationary period when there is no tidal energy being produced. Another disadvantage of a tidal barrage system, is the environmental and ecological effects that a long concrete dam may have on the estuaries they span.

Tidal Stream Generation

Tidal Stream – A *Tidal Stream Generation* system reduces some of the environmental effects of tidal barrages by using turbine generators beneath the surface of the water. Major tidal flows and ocean currents, like the Gulf Stream, can be exploited to extract its tidal energy using underwater rotors and turbines.

Tidal stream generation is very similar in principal to wind power generation, except this time water currents flow across a turbines rotor blades which rotates the turbine, much like how wind currents turn the blades for wind power turbines. In fact, tidal stream generation areas on the sea bed can look just like underwater wind farms.

Unlike off-shore wind power which can suffer from storms or heavy sea damage, tidal stream turbines operate just below the sea surface or are fixed to the sea bed. Tidal streams are formed by the horizontal fast flowing volumes of water caused by the ebb and flow of the tide as the profile of the sea bed causes the water to speed up as it approaches the shoreline.

As water is much more denser than air and has a much slower flow rate, tidal stream turbines have much smaller diameters and higher tip speed rates compared to an equivalent wind turbine. Tidal stream turbines generate a power output on both the ebb and flow of the tide.

One of the disadvantages of **Tidal Stream Generation** is that as the turbines are submerged under the surface of the water they can create hazards to navigation and shipping.

Other forms of tidal energy include tidal fences which use individual vertical-axis turbines that are mounted within a fence structure, known as the caisson, which completely blocks a channel and force water through them. Another alternative way of harnessing tidal power is by using an "oscillating tidal turbine".

3. Tidal Lagoon System

- A **circular or semi-circular enclosure** is built along the coastline.
- Works on the same principle as a tidal barrage.
- Offers **greater flexibility** in location and reduced ecological disturbance.

The Advantages and Disadvantages Of Tidal Energy

Knowing how energy is generated from the ocean’s current and its tidal range. Let’s look at some of the advantages and disadvantages of tidal energy to see if it can be used as an ideal and feasible renewable energy resource.

Advantages of Tidal Energy

- Tidal energy is a renewable energy resource because the energy it produces is free and clean as no fuel is needed and no waste bi-products are produced.
- It has the potential to produce a great deal of free and green energy.
- Generally tidal energy is not expensive to operate and maintain compared to other forms of renewable energies.
- Low visual impact as the tidal turbines are mainly if not totally submerged beneath the water.
- Low noise pollution as any sound generated is transmitted through the water.
- High predictability as high and low tides can be predicted years in advance, unlike wind. Wind Power

- Tidal barrages provide protection against flooding and land damage.
- Large tidal reservoirs have multiple uses and can create recreational lakes and areas where before there were none.

Limitations of Tidal Energy

- High initial capital cost
- Limited suitable locations
- Possible impact on marine ecosystems
- Long construction period

UNIT III

1.Stationary battery storage

Stationary battery storage refers to **rechargeable battery systems installed in a fixed location** to store electrical energy for later use. These systems are crucial for modern energy infrastructure, integrating renewable energy sources, enhancing grid stability, and providing reliable backup power.

Key Components

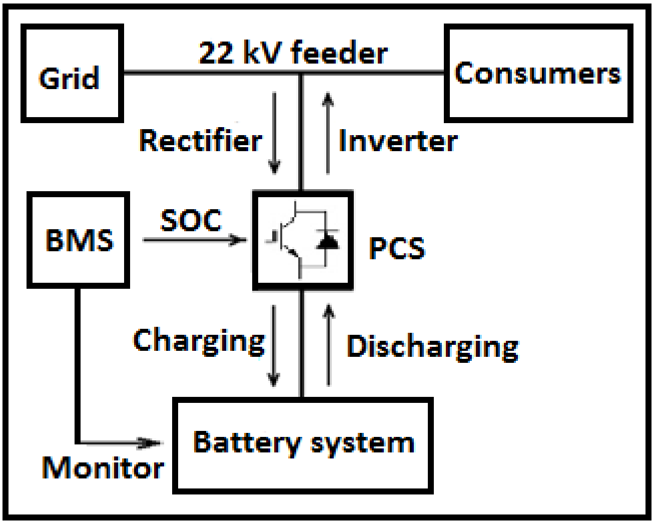
A typical stationary battery energy storage system (BESS) consists of several core components:

- **Battery System/Modules**: These contain individual battery cells (e.g., lithium-ion, lead-acid, flow) where the chemical energy is stored.
- **Power Conversion System (PCS)**: This bidirectional inverter converts direct current (DC) electricity from the batteries into the alternating current (AC) used by homes, businesses, and the grid, and vice-versa during charging.
- **Energy Management System (EMS)**: Often referred to as the "brain" of the system, advanced software and control algorithms optimize charging and discharging cycles based on energy demand, supply, and price signals.
- **Thermal Management System**: This system manages the temperature of the batteries, which is critical for preventing overheating (thermal runaway) or performance degradation due to cold, ensuring safe and efficient operation.
- **Safety and Protection Systems**: These include fire suppression systems, electrical protection devices (fuses, breakers), and environmental sensors to mitigate risks.

Applications

Stationary battery storage systems are used across various market segments due to their flexibility and scalability:

- **Renewable Energy Integration**: They store excess energy generated from intermittent sources like solar and wind power, releasing it when generation is low or demand is high, which ensures a continuous power supply.
- **Grid Services**: Utility-scale BESS enhance grid stability by providing ancillary services like frequency regulation and voltage support. They can also help defer expensive infrastructure upgrades by managing local congestion.
- **Peak Shaving and Load Shifting**: Businesses and homeowners can charge batteries during off-peak hours when electricity is cheap and discharge them during peak demand periods, significantly reducing energy costs.
- **Backup Power/Energy Resilience**: BESS provide an uninterrupted power supply (UPS) for critical infrastructure such as data centers, hospitals, and telecommunication networks during grid outages, ensuring continuous operation.
- **Microgrids**: They are essential components of microgrids, enabling localized energy independence and reliable power, especially in remote areas.



Structure diagram of the Battery Energy Storage System (BESS), as shown in Figure 2, consists of three main systems: the power conversion system (PCS), energy storage system and the battery management system (BMS). The power conversion system consists of a three-phase, full bridgeconverter, which couples the battery system to the electricityutility's network [14].
The BMS (Battery Management System) is used to monitor and measure the power system's performance parameters, such as voltages, currents, and temperatures. A battery energy storage system with an incorrect state of charge may be overcharged or over-discharged. This may damage the storage system, shorten the life time, or even cause fire or an explosion. The BMS will communicate with the PCS (Power Conversion System), the state of charge (SOC) and the state of health (SOH) [14]. When the state of charge (SOC) is 1, the energy storage system is fully charged. The energy storage system should pause charging the storage system, to avoid damaging the batteries. When the SOC is 0, the storage system is discharged fully. The energy storage system should stop discharging the batteries as the battery system is empty

2.Lead Acid Battery

Definition: The battery which uses sponge lead and lead peroxide for the conversion of the chemical energy into electrical power, such type of battery is called a lead acid battery. The lead acid battery is most commonly used in the power stations and substations because it has higher cell voltage and lower cost.

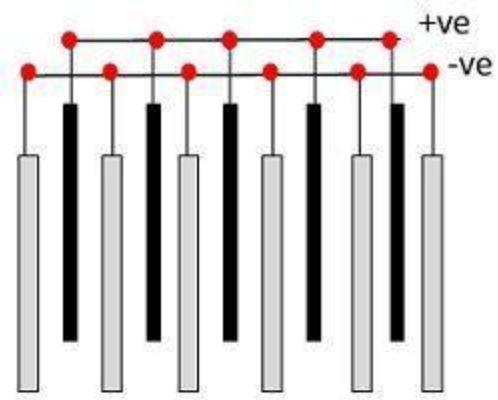
Construction of Lead Acid Battery

The various parts of the lead acid battery are shown below. The container and the plates are the main part of the lead acid battery. The container stores chemical energy which is converted into electrical energy by the help of the plates.

1. Container – The container of the lead acid battery is made of glass, lead lined wood, ebonite, the hard rubber of bituminous compound, ceramic materials or moulded plastics and are seated at the top to avoid the discharge of electrolyte. At the bottom of the container, there are four ribs, on two of them rest the positive plate and the others support the negative plates.

The prism serves as the support for the plates and at the same time protect them from a short-circuit.The material of which the battery containers are made should be resistant to sulfuric acid, should not deform or porous, or contain impurities which damage the electrolyte.

2. Plate – The plate of the lead-acid cell is of diverse design and they all consist some form of a grid which is made up of lead and the active material. The grid is essential for conducting the electric current and for distributing the current equally on the active material. If the current is not uniformly distributed, then the active material will loosen and fall out.



Arrangements of Plates in a Lead-acid-Battery

Circuit GLobe

The grids are made up of an alloy of lead and antimony. These are usually made with the transverse rib that crosses the places at a right angle or diagonally. The grid for the positive and negative plates are of the same design, but the grids for the negative plates are made lighter because they are not as essential for the uniform conduction of the current.

The plates of the battery are of two types. They are the formed plates or plante plates and pasted or faure plates.

Plante’s plates are used largely for stationary batteries as these are heavier in weight and more costly than the pasted plates. But the plates are more durable and less liable to lose active material by rapid charging and discharging. The plantes plate has low capacity weight-ratio.

Faure process is much suitable for manufacturing of negative plates rather than positive plates. The negative active material is quite tough, and it undergoes a comparatively low change from charging and discharging.

3. Active Material – The material in a cell which takes active participation in a chemical reaction (absorption or evolution of electrical energy) during charging or discharging is called the active material of the cell. The active elements of the lead acid are

1. **Lead peroxide (PbO_2)** – It forms the positive active material. The PbO_2 are dark chocolate broom in colour.

2. **Sponge lead** – Its form the negative active material. It is grey in colour.
3. **Dilute Sulfuric Acid (H_2SO_4)** – It is used as an electrolyte. It contains 31% of sulfuric acid.

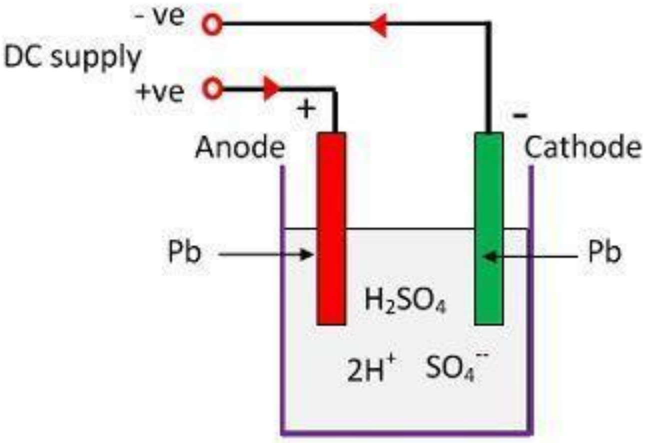
The lead peroxide and sponge lead, which form the negative and positive active materials have the little mechanical strength and therefore can be used alone.

4. Separators – The separators are thin sheets of non-conducting material made up of chemically treated leadwood, porous rubbers, or mats of glass fibre and are placed between the positive and negative to insulate them from each other. Separators are grooved vertically on one side and are smooth on the other side.

5. Battery Terminals – A battery has two terminals the positive and the negative. The positive terminal with a diameter of 17.5 mm at the top is slightly larger than the negative terminal which is 16 mm in diameter.

Working Principle of Lead Acid Battery

When the sulfuric acid dissolves, its molecules break up into positive hydrogen ions ($2H^+$) and sulphate negative ions (SO_4^{--}) and move freely. If the two electrodes are immersed in solutions and connected to DC supply then the hydrogen ions being positively charged and moved towards the electrodes and connected to the negative terminal of the supply. The SO_4^{--} ions being negatively charged moved towards the electrodes connected to the positive terminal of the supply main (i.e., anode).



Charging of Lead Acid Cells

Circuit Globe

Each hydrogen ion takes one electron from the cathode, and each sulphates ions takes the two negative ions from the anodes and react with water and form sulfuric and hydrogen acid.

The oxygen, which produced from the above equation react with lead oxide and form lead peroxide (PbO_2.) Thus, during charging the lead cathode remain as lead, but lead anode gets converted into lead peroxide, chocolate in colour.

If the DC source of supply is disconnected and if the voltmeter connects between the electrodes, it will show the potential difference between them. If wire connects the electrodes, then current will flow from the positive plate to the negative plate through external circuit i.e. the cell is capable of supplying electrical energy.

Chemical Action During Discharging

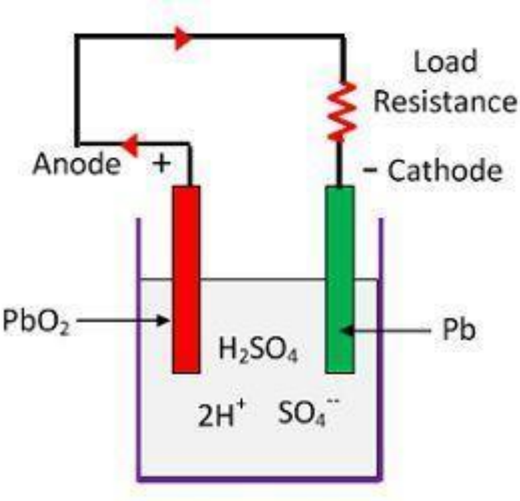
When the cell is full discharge, then the anode is of lead peroxide (PbO_2) and a cathode is of metallic sponge lead (Pb). When the electrodes are connected through a resistance, the cell discharge and electrons flow in a direction opposite to that during charging.

The hydrogen ions move to the anode and reaching the anodes receive one electron from the anode and become hydrogen atom. The hydrogen atom comes in contacts with a PbO_2, so it attacks and forms lead sulphate ($PbSO_4$), whitish in colour and water according to the chemical equation.

$$PbSO_4 + 2H = PbO + H_2O$$

$$PbO + H_2SO_4 = PbSO_4 + 2H_2O$$

$$\overline{PbO_2 + H_2SO_4 + 2H = PbSO_4 + 2H_2O}$$



Discharging of Lead Acid Cells

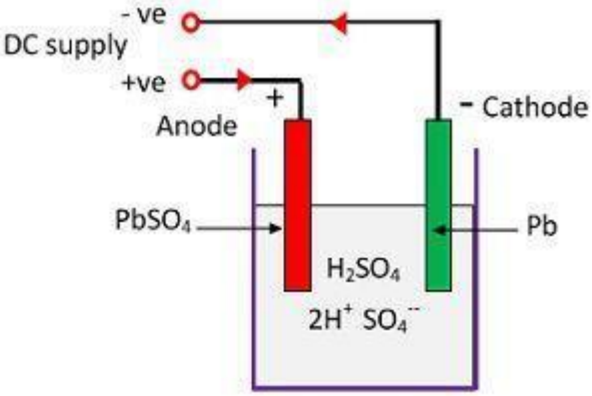
Circuit Globe

The each sulphate ion (SO_4^{--}) moves towards the cathode and reaching there gives up two electrons becomes radical SO_4, attack the metallic lead cathode and form lead sulphate whitish in colour according to the chemical equation.

Chemical Action During Recharging

For recharging, the anode and cathode are connected to the positive and the negative terminal of the DC supply mains. The molecules of the sulfuric acid break up into ions of $2H^+$ and SO_4^{--}. The hydrogen ions being positively charged moved towards the cathodes and receive two electrons from there and form a hydrogen atom. The hydrogen atom reacts with lead sulphate cathode forming lead and sulfuric acid according to the chemical equation.

$$PbSO_4 + 2H_2O + 2H = PbSO_4 + 2H_2SO_4$$



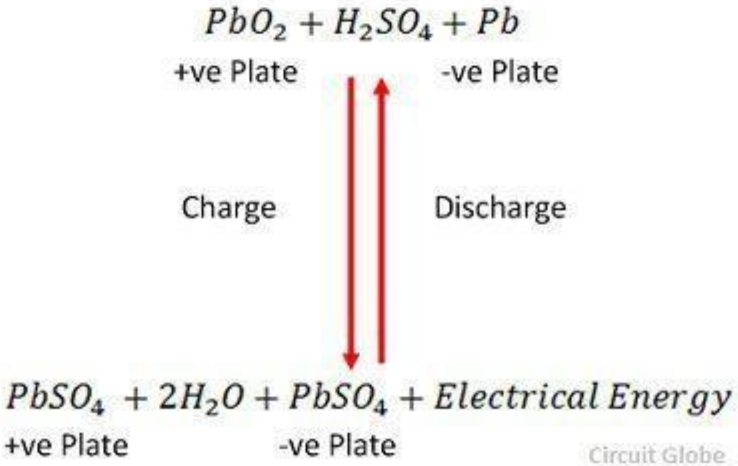
Recharging of Lead Acid Cell

Circuit Globe

SO_4^{--} ion moves to the anode, gives up its two additional electrons becomes radical SO_4, react with the lead sulphate anode and form leads peroxide and lead sulphuric acid according to the chemical equation.

$$PbSO_4 + 2H = H_2SO_4 + Pb$$

The charging and discharging are represented by a single reversible equation given below.



Circuit Globe

The equation should read downward for discharge and upward for recharge.

<u>3. Battery Storage Capacity?</u>

Battery storage capacity refers to the total amount of energy that a battery can store and discharge. It’s usually measured in kilowatt-hours (kWh) for larger systems, like those used in homes or businesses, or amp-hours (Ah) for smaller systems, like those found in electronics or electric vehicles. The higher the storage capacity, the more energy the battery can hold. In practical terms, a battery with a higher storage capacity will last longer between charges and can provide more power when needed.

Think of it like a water tank. The tank’s capacity tells you how much water it can hold. Similarly, a battery’s storage capacity tells you how much energy it can store and supply to power devices, appliances, or even entire homes.

Why Battery Storage Capacity Matters

Understanding battery storage capacity is crucial for making informed decisions, whether you’re choosing a battery for a solar energy system, an electric vehicle, or any other application. The more storage capacity you have, the longer your battery can power things without needing to be recharged. For example, a home solar system paired with a battery storage solution allows you to store energy generated during the day for use at night. If your battery has high storage capacity, you can use more of the solar energy you’ve captured, reducing reliance on the grid.

Battery storage capacity also plays a significant role in reducing energy costs. In places with peak energy pricing, having a larger storage capacity allows you to use stored energy when electricity prices are high, thus saving money on your electricity bill.

Key Factors That Affect Battery Storage Capacity

Several factors influence a battery's storage capacity, and understanding these factors is important for selecting the right battery for your needs. Some of the main elements include:

Battery Chemistry

Different battery chemistries offer varying energy densities, which affect storage capacity. For instance, lithium-ion batteries typically have a higher energy density than lead-acid batteries, meaning they can store more energy in a smaller space. This is why lithium-ion batteries are commonly used in electric vehicles and renewable energy systems.

Size of the Battery

Larger batteries naturally have a higher storage capacity because they have more room for energy. However, size isn’t the only factor—battery design and chemistry also come into play.

Voltage and Current

Voltage refers to the electrical potential, while current is the flow of electricity. The combination of voltage and current determines how much energy a battery can store and how efficiently it can discharge.

State of Charge (SOC)

The SOC indicates how much energy remains in a battery. A fully charged battery has a SOC of 100%, while a completely depleted battery has a SOC of 0%. As the SOC changes, so does the available energy for use.

Efficiency of the Battery

Not all the energy stored in a battery can be used. Battery efficiency accounts for losses that occur during charging and discharging. A highly efficient battery will have less energy loss, allowing it to deliver more usable power.

How to Calculate Battery Storage Capacity

To understand how much energy a battery can hold, it's essential to look at its capacity, which is typically expressed in either kWh or Ah. Here’s a simple breakdown:

Amp-Hours (Ah)

Amp-hours are the most common unit of measurement for small batteries, such as those used in electronics or electric vehicles. If a battery is rated for 10 Ah, this means it can supply 10 amps of current for one hour. To calculate the total capacity, you multiply the voltage by the amp-hour rating:

Capacity (Wh)=Voltage (V)×AmpHours (Ah)

For example, a 12V battery with a 10Ah rating would have a capacity of:

Capacity=12V×10Ah=120Wh

Kilowatt-Hours (kWh)

Larger systems, like those used in homes or businesses, typically use kWh to measure capacity. One kWh is equal to 1,000 watt-hours (Wh). So, for a home energy system that uses a 10 kWh battery, it can supply 10,000 watt-hours of energy. A battery with a 10 kWh capacity can power a 1,000-watt device for 10 hours (if it operates at full efficiency).

Different Uses of Battery Storage Capacity

Battery storage capacity plays a role in various applications, from personal devices to large-scale energy storage. Here’s how battery capacity impacts different industries and use cases:

Home Solar Energy Systems

If you’re using a solar panel system, the battery storage capacity is key to how much of the energy you generate can be used during the night or cloudy days. A larger storage capacity means you can store more energy for later use, reducing your reliance on the grid and saving on electricity bills.

Electric Vehicles (EVs)

The range of an electric vehicle is directly related to its battery capacity. A car with a larger battery storage capacity can travel farther on a single charge, which is a major consideration for potential EV buyers. As battery technology advances, manufacturers are focusing on increasing storage capacity to improve vehicle range and reduce charging frequency.

Off-Grid Living

For those who live off the grid, battery storage capacity is a lifeline. It determines how much energy you can store from sources like solar panels or wind turbines, allowing you to live independently without a connection to the local power grid. In off-grid systems, maximizing storage capacity ensures you have enough energy during periods of low sunlight or wind.

Industrial Applications

Industrial systems, like those used for backup power or in data centers, require high-capacity batteries to ensure reliable power during blackouts or emergencies. The larger the battery capacity, the longer it can provide backup power to critical systems.

4.Coulomb Efficiency (instead of Energy Efficiency)

In battery systems, **Coulomb efficiency** (also called **Charge efficiency** or **Ah efficiency**) is often used instead of energy efficiency because it focuses purely on **charge transfer**, which is more fundamental for electrochemical storage.

1. Definition

Coulomb Efficiency ($\eta_{(c)}$) is the ratio of **charge extracted from the battery during discharge** to the **charge supplied during charging**.

$$\eta_c = \frac{\text{Discharge capacity (Ah)}}{\text{Charge capacity (Ah)}} \times 100\%$$

2. Why Coulomb Efficiency is used instead of Energy Efficiency

(a) Energy efficiency depends on voltage

Energy efficiency considers both current and voltage:

$$\eta_E = \frac{V_d I_d t_d}{V_c I_c t_c}$$

But battery voltage:

- changes with **state of charge**
- changes with **load**
- includes losses due to **internal resistance**

So energy efficiency is affected by external operating conditions.

(b) Coulomb efficiency reflects internal chemistry

Coulomb efficiency depends only on:

- electrochemical reactions
- side reactions (like gassing, self-discharge)

So it directly measures:

How much of the stored charge is actually recoverable.

(c) Easier and more accurate to measure

Only current and time are needed:

$Q=I\times t$

No need to measure varying voltage accurately.

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3. Physical meaning

Coulomb efficiency tells us:

- Whether **all electrons put in during charging come back during discharge**.
- Losses indicate:
  - self-discharge
  - parasitic reactions
  - electrolyte decomposition

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4. Typical values

Battery Type	Coulomb Efficiency
Lead–acid	85–95%
Ni–Cd	70–85%
Ni–MH	65–80%
Li-ion	98–99.9%
Supercapacitor	~100%

5.Battery Sizing Essential?

Battery sizing is crucial in order to ascertain that it can supply power to the connected loads for the time period it is designed. Unsuitable sizing of the battery can pose many serious problems such as permanent battery damage because of over-discharge, low voltages to the load, insufficient backup times.

The **battery sizing** can be initiated once we have the following information:

1. Loads need to be supported by battery
2. Minimal voltage for battery
3. Back up time(s)

IEEE Battery Sizing Calculations

The calculations performed are based on "Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications" and "Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications" IEEE standards. All the calculations in this article are established on conventional lead-acid or nickel-cadmium (NiCd) batteries. The outcomes presented here may not support other types of batteries, so the manufacturer's guidance will require being conferred.

The methodological analysis has the five steps as follows:

Step 1: Collect the total connected loads that the battery requires to supply

Step 2: Develop a load profile and further compute design energy

Step 3: Choose the type of battery and determine the cell characteristics

Step 4: Choose the battery cells required to be linked in series fashion

Step 5: On the basis of design loads, compute the desired Ampere-hour (Ah) battery capacity

Step 1: Collect the Total Connected Loads

The first step is the determination of the total connected loads that the battery needs to supply. This is mostly particular to the battery application like UPS system or solar PV system.

Step 2: Develop the Load Profile

Generally, the "**Autonomy Method**" is utilized to establish a load profile for batteries.

The backup (autonomy) time is frequently provided by the customer. Instead, IEEE standard "Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications" provides certain guidelines for autonomy (backup or discharge) times.

Step 3: Choose the Type of Battery

The following step is the selection of the type of battery (e.g. Lead-acid or nickel-cadmium). While choosing the battery type, the following elements should be considered as per IEEE guidance.

- Ambient temperature threshold
- Charging & discharging characteristics
- Maintenance & Ventilation requisites
- Cell orientation essentials
- Shock and vibration factors
- Anticipated cell life

- Physical properties like dimensions, weight, and battery terminals

Step 4: Choose the Battery Cells Required To Be Linked In Series Fashion

The number of cells required for a particular voltage rating is presented below:

Rated Voltage (V)	Cells (Lead-Acid Battery)
12	6
24	12
48	24
125	60

Nevertheless, the number of cells required can be determined more precisely in order to match with the load tolerance more accurately. The number of battery cells expected to be linked in series fashion must fall between the two limits which are given below:

$$N_{\text{maximum}} = \frac{V_{dc}\left(1 + V_{\text{load,max}}\right)}{V_{\text{charging}}}$$

$$N_{\text{minimum}} = \frac{V_{dc}\left(1 - V_{\text{load,min}}\right)}{V_{\text{eodv}}}$$

Step 5: Compute the Desired Ampere-Hour (Ah) Battery Capacity

The battery capacity desired to accommodate the total designed load over the determined back up (autonomy) time can be computed using the following formula:

$$C_{\text{minimum}} = \frac{E_{de}\left(k_{af} \times k_{tcf} \times k_{crt}\right)}{V_{dc} \times k_{mdod} \times k_{se}}$$

6.Key Battery Storage Technologies & Comparison

- **Lithium-ion Batteries (Li-ion):** High energy density (200–400 Wh/L200 – 400 h/L200–400 Wh/L), efficiency of 85–95%, and 3,000–10,000 cycles. Ideal for electric vehicles (EVs) and residential storage, though they have moderate fire risks.
- **Lead-Acid Batteries:** Mature, low-cost, and robust, often used for uninterruptible power supplies (UPS). However, they have low energy density, shorter life cycles, and poor performance in extreme temperatures.
- **Flow Batteries (e.g., Vanadium Redox):** Excellent for long-duration, grid-scale storage due to non-self-discharge capability and long lifespans. They offer high, fast power response but are less suited for small-scale applications.

- **Sodium-Sulfur Batteries (NaS):** Molten salt batteries with high energy density and high power density, well-suited for grid-level stabilization, though they require high operating temperatures.
- **Supercapacitors:** Offer ultra-fast charge/discharge and an extremely high cycle life (over 1,000,000 cycles). They are best for power quality, frequency regulation, and applications requiring quick bursts of energy.

Performance Comparison Summary

Technology	Efficiency	Cycle Life	Energy Density	Primary Application
Li-ion	85–95%	3,000–10,000	High	EVs, Home Storage
Lead-Acid	70–85%	Short/Low	Low	UPS, Back-up
Flow	65–85%	Very Long	Low-Med	Grid Storage
NaS	75–85%	Long	High	Grid Stability
Supercapacitors	90–95%	>1,000,000	Very Low	Frequency Reg

7.Supercapacitor

A supercapacitor, also known as an ultracapacitor or electric double-layer capacitor (EDLC), is an advanced energy storage solution known for its ultra-fast charging, high power output, and exceptional longevity. Unlike conventional lithium-ion batteries, supercapacitors store energy via electrostatic charge instead of chemical reactions. This enables them to charge and discharge within seconds, with minimal wear over time.Supercapacitors are ideal for applications that demand quick energy delivery or short-term backup power.With the ability to withstand over 1 million charge-discharge cycles and a design that supports eco-friendly, sustainable energy, supercapacitors are rapidly gaining traction as a key component in the future of green energy and high-efficiency power systems.

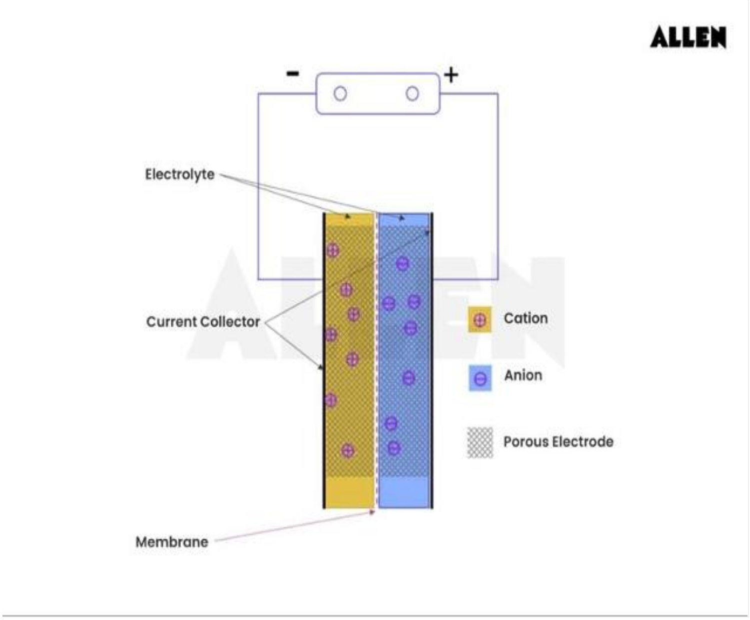
Definition of Supercapacitor

- A supercapacitor (also known as an ultracapacitor or electrochemical capacitor) is an energy storage device that stores electrical energy through the separation of electric charges in an electric double layer or via fast surface redox reactions.

- Supercapacitors are advanced capacitors that store energy electrostatically and/or electrochemically, offering high power density, fast charging, and long cycle life compared to conventional batteries.

- Unlike traditional capacitors, supercapacitors have much higher capacitance values, enabling them to store and deliver energy much more quickly than batteries, though with lower energy density. They are commonly used in applications requiring rapid charge and discharge cycles, high power density, and long cycle life.

Construction And Working of Supercapacitors



Construction of a Supercapacitor

The image shows the basic structure of a supercapacitor, which consists of the following key components:

1. **Electrodes (Porous Electrode):**Two porous electrodes, positioned on the positive and negative sides, feature a large surface area that maximizes charge storage by allowing ions from the electrolyte to penetrate deeply into their structure; this porous design significantly increases the effective contact area between the electrodes and electrolyte, thereby enhancing the overall capacitance of the supercapacitor.

2. **Current Collectors:** Current collectors are conductive materials attached to each electrode that enable the flow of electrons to and from the external circuit, such as a battery or load, effectively connecting the electrodes to the external positive and negative terminals.

3. **Electrolyte:**The electrolyte, which fills the space between the electrodes, contains freely moving ions—cations and anions—that facilitate ion movement; in the image, blue cations (+) represent positive ions, while red anions (−) represent negative ions.

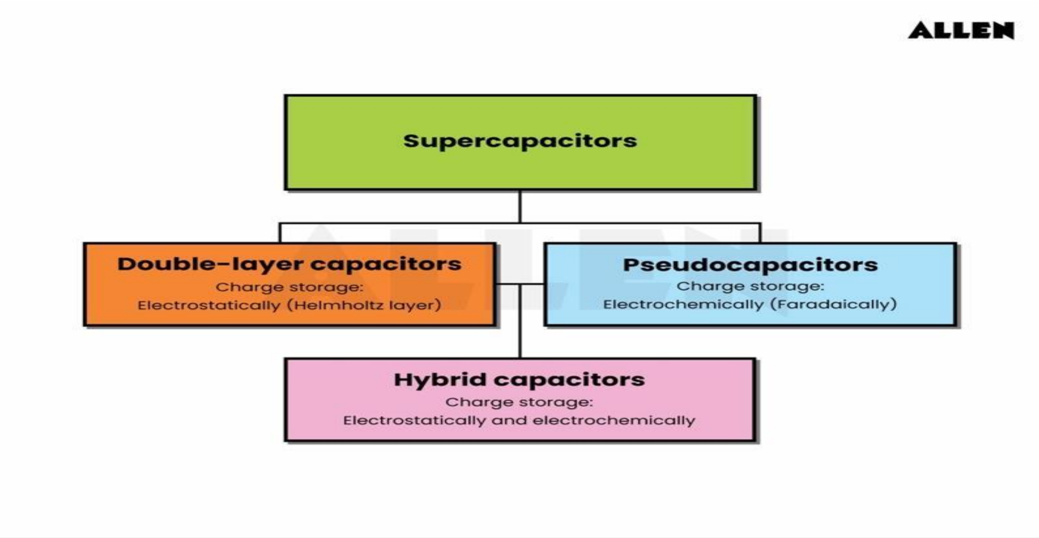
4. **Membrane (Separator):**The membrane physically separates the two electrodes to prevent short circuits while allowing ions to pass between

them, ensuring that only ionic flow occurs through the electrolyte and blocking electron flow.

Working Principle of a Supercapacitor

- When voltage is applied, cations move toward the negative electrode, and anions move toward the positive electrode through the electrolyte.
- Ions accumulate at the electrode-electrolyte interface, forming an electric double layer that stores energy electrostatically.
- The porous electrodes provide a large surface area, boosting capacitance beyond traditional capacitors.
- Current collectors enable electron flow in the external circuit, completing charge and discharge cycles.
- Energy is stored by ion adsorption, allowing rapid charging/discharging and long cycle life without chemical degradation.

Types of Capacitors



8.Historical development of Green Enrgy

Green energy (renewable energy) refers to energy obtained from natural sources that are continuously replenished and cause minimal environmental impact. The development of green energy has evolved over centuries, driven by technological progress, environmental concerns, and the need for sustainable development.

1. Ancient Period (Before 1800)

In early civilizations, humans relied entirely on renewable sources:

- **Solar energy:** Used for drying crops, heating homes, and orientation of buildings.
- **Wind energy:** Sailboats used wind power for transportation.
- **Water energy:** Water wheels were used in ancient Greece, Rome, China, and India for grinding grains ;and irrigation.
- **Biomass:** Wood, animal dung, and agricultural residues were primary fuels for cooking and heating.

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2. Industrial Revolution (1800–1900)

- The discovery of **coal and steam engines** reduced dependence on renewables.
- However, early forms of green energy still existed:
    - Hydropower plants began operating in Europe and the USA.
    - In 1882, the **first hydroelectric power plant** was built in Wisconsin, USA.

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3. Early 20th Century (1900–1950)

- **Hydropower** expanded significantly for electricity generation.
- Early research on **solar cells** began.
- In 1931, the first practical **wind turbine** for electricity was built.
- Fossil fuels dominated due to industrial growth.

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4. Energy Crisis Period (1970–1990)

- The **1973 oil crisis** highlighted the risks of fossil fuel dependency.
- Governments invested in renewable research.
- Development of:
    - Solar photovoltaic (PV) panels.
    - Large wind farms.
    - Biomass and geothermal projects.

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5. Modern Era (1990–2010)

- Climate change concerns increased global interest.
- International agreements like the **Kyoto Protocol (1997)**.

- Rapid technological improvements:
    - Cheaper and efficient solar panels.
    - Grid-connected wind farms.
    - Small-scale biogas plants in rural areas.

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6. Present and Future (2010 onwards)

- Emphasis on **carbon neutrality** and **net-zero emissions**.
- Major developments:
    - Smart grids and energy storage systems.
    - Electric vehicles powered by renewable energy.
    - Floating solar farms and offshore wind power.
- Countries like **India** launched missions such as:
    - National Solar Mission.
    - Wind–solar hybrid projects.

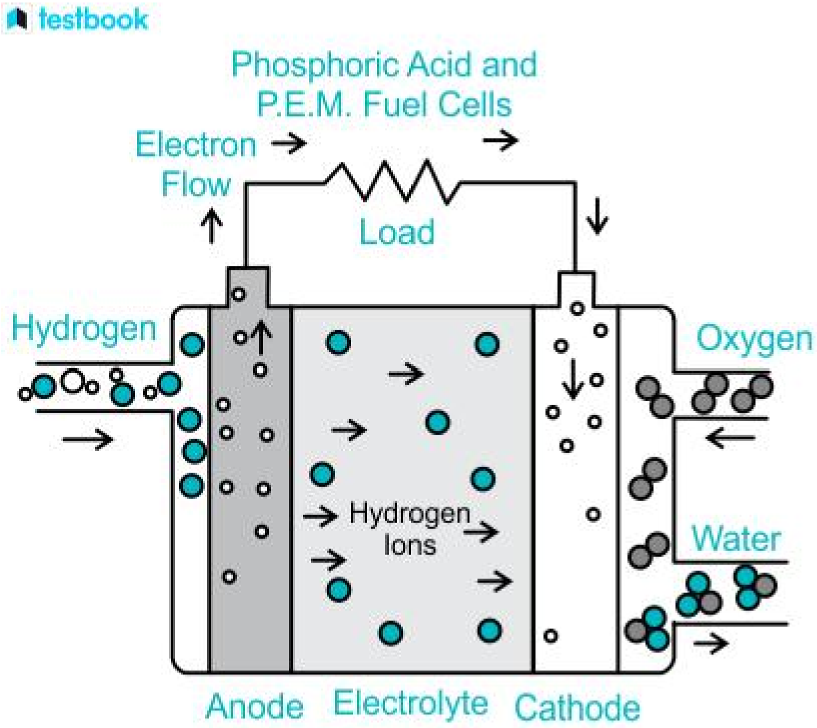
9.Fuel Cell

Fuel Cell is a technology that uses a strong chemical reaction to generate electricity. The fuel cell generates electricity via redox reactions that convert the chemical energy of the fuel with an oxidizing agent into electricity. A fuel cell is a small device with two electrodes: a cathode and an anode. Inside the cell, these electrodes cause an electrochemical reaction.

Fuel cells have a number of advantages over traditional combustion-based technologies that are currently used in many power plants and vehicles. They have higher efficiencies than combustion engines and can directly convert the chemical energy in fuel to electrical energy with efficiencies exceeding 60%.

Fuel Cell Working

To produce a chemical reaction, a fuel cell requires three main components: an anode, a cathode, and an electrolyte.



First, flow fields direct hydrogen fuel to the anode. Hydrogen atoms are ionized (depleted of electrons) and now only have a positive charge.

The oxygen then enters the fuel cell at the cathode and reacts with electrons returning from the electrical circuit as well as ionized hydrogen atoms. After picking up the electrons, the oxygen atom travels through the electrolyte to combine with the hydrogen ion.

The chemical reaction is based on the combination of oxygen and ionized hydrogen.

Cathode Reaction

$O_2+2H_2O+4e^-\rightarrow4OH^-$

Anode Reaction

$2H_2+4OH^-\rightarrow4H_2O+4e^-$

Net Cell Reaction

$2H_2+O_2\rightarrow2H_2O$

Types of Fuel Cell

The following are the various types of fuel cells:

Phosphoric Acid Fuel Cell

As the electrolyte in phosphoric acid fuel cells, liquid phosphoric acid is used. PAFCs generate electricity with an efficiency of more than 40%, and nearly 85% of the steam produced by this fuel cell is used for cogeneration. Aside from the nearly 85% cogeneration efficiency, one of the main benefits of this type of fuel cell is that it can use impure hydrogen as fuel. PAFCs can tolerate a CO concentration of about 1.5%, allowing them to use a broader range of fuels. Sulfur must be removed from gasoline before use.

Polymer Electrolyte Membrane (PEM) Fuel Cell

While conducting protons, these fuel cells, also known as Proton Exchange Membrane Fuel Cells, operate at temperatures ranging from 50 to 100 °C. Electrodes, bipolar plates, a polymer membrane, and a catalyst are used in these cells.

Solid Acid Fuel Cell

A solid oxide fuel cell generates electricity by utilizing the movement of electrons in a few basic steps. Natural gas is steam-reformed. At lower temperatures, the molecular structure of the solid acid material works in a specific order. However, due to the phase transition, conductivity can significantly increase at high temperatures.

Alkaline Fuel Cell

Alkaline Fuel Cells operate on an aqueous alkaline solution. This solution helps to saturate the permeable milieu and separate the electrodes. These cells operate at 90 °C and are very efficient in producing heat and water in addition to electric power.

Solid Oxide Fuel Cell

A solid oxide fuel cell (SOFC) is an electrochemical device that converts hydrogen and carbon monoxide directly from hydrocarbon fuels into electricity. Dense solid oxide is used as the electrolyte material in Solid Oxide Fuel Cells, which conduct negative oxygen ions from the cathode to anode.

Molten Carbonate Fuel Cell

Molten carbonate fuel cells (MCFCs) were created for natural gas, biogas, and coal-fired power plants for use in electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte that is made up of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte.

Advantages of Fuel Cell

Some fuel cell advantages are listed below.

- Renewable and simple to obtain.
- In comparison to fossil fuels, it is more durable and energy efficient.
- Minimal noise pollution.
- When compared to other energy sources, it performs admirably.
- Hydrogen is a dependable and adaptable energy source that can contribute to zero-carbon energy initiatives.
- Reduces carbon residues.

Application of Fuel Cell

Fuel cells are extremely useful and have numerous applications.

- When the primary power supply fails, they serve as a backup power source. Computer systems, manufacturing facilities, and homes are examples of backup applications.
- Fuel cells can obtain over 80% energy efficiency when co-generation is used.
- The quality of power provided by a fuel cell does not decrease over time.
- Some fuel cells’ portability is extremely useful in some military applications.
- Fuel cells are significantly lighter.
- Fuel cells are used as backup energy sources.

9.Thermodynamic and Electrochemical Principles

2.1.1 Electrochemical Aspects

All power generation systems require an energy balance to demonstrate the functioning of the system in detail. In a similar fashion the fuel cell system requires an energy or heat balance analysis (EG&G Services Parsons 2000). The energy balance analysis in the fuel cell should be based on energy conversion processes like power generation, electrochemical reactions, heat loss, *etc*. The energy balance analysis varies for the different types of fuel cells because the various types of electrochemical reactions occur according to the fuel cell type. The enthalpy of the reactants entering the system should match the sum of the enthalpies of the products leaving the cell, the net heat generated within the system, the dc power output from the cell, and the heat loss from the cell to its surroundings. The energy balance analysis is done by determining the fuel cell temperature at the exit by having information of the reactant composition, the temperatures, H_2 and O_2 utilization, the power produced, and the heat loss (Srinivasan 2006).

The fuel cell reaction (inverse of the electrolysis reaction) is a chemical process that can be divided into two electrochemical half-cell reactions. The most simple and common reaction encountered in fuel cells is (Atkins 1986)

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O \qquad (2.1)$$

Analyzing from a thermodynamic point of view, the maximum work output obtained from the above reaction is related to the free-energy change of the reaction. Treating this analysis in terms of the Gibbs free energy is more useful than that in terms of the change in Helmholtz free energy, because it is more practical to carry out chemical reactions at a constant temperature and pressure rather than at constant temperature and volume. The above reaction is spontaneous and thermodynamically favored because the free energy of the products is less than that of the reactants. The standard free energy change of the fuel cell reaction is indicated by the equation

$$\Delta G = -n\mathrm{F}E \tag{2.2}$$

Where ΔG is the free energy change, n is the number of moles of electrons involved, E is the reversible potential, and F is Faraday's constant. If the reactants and the products are in their standard states, the equation can be represented as

$$\Delta G^0 = -n\mathrm{F}E^0 \tag{2.3}$$

The value of ΔG corresponding to (2.1) is −229 kJ/mol, $n = 2$, F = 96500 C/g.mole electron, and hence the calculated value of E is 1.229 V.

The enthalpy change ΔH for a fuel cell reaction indicates the entire heat released by the reaction at constant pressure. The fuel cell potential in accordance with ΔH is defined as the thermo-neutral potential, E_t,

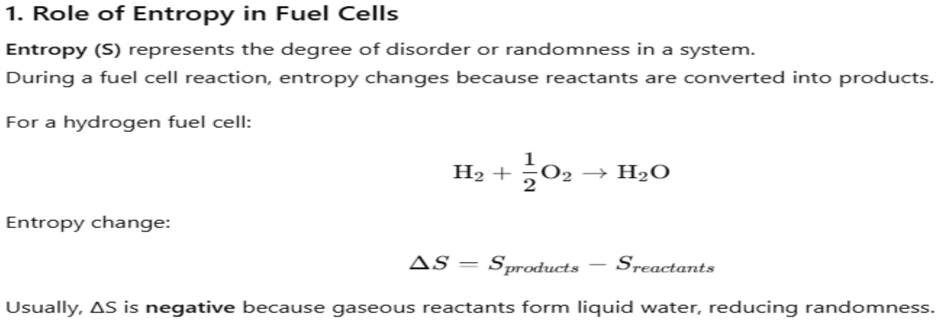
$$\Delta H = -n\mathrm{F}E_t \tag{2.4}$$

where E_t has a value of 1.48 V for the reaction represented by Equation 2.1.

The electrochemical reactions taking place in a fuel cell determine the ideal performance of a fuel cell; these are shown in Table 2.1 for different kinds of fuels depending on the electrochemical reactions that occur with different fuels, where CO is carbon monoxide, e^- is an electron, H_2O is water, CO_2 is carbon dioxide, H^+ is a hydrogen ion, O_2 is oxygen, CO_3^{2-} is a carbonate ion, H_2 is hydrogen, and OH^- is a hydroxyl ion.

11.Entropy and the Theoretical Efficiency of Fuel Cells

Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy. Their theoretical efficiency is fundamentally governed by **entropy (ΔS)** and **Gibbs free energy (ΔG)**, making thermodynamics central to understanding their performance.



1. Role of Entropy in Fuel Cells

Entropy (S) represents the degree of disorder or randomness in a system.
During a fuel cell reaction, entropy changes because reactants are converted into products.

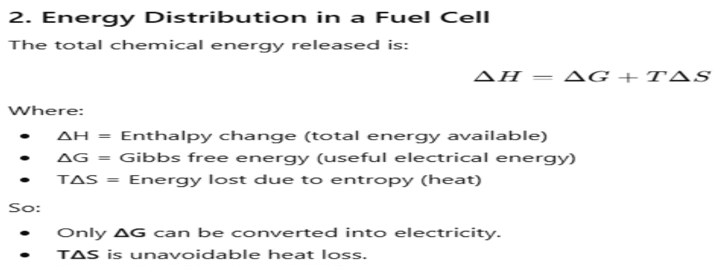
For a hydrogen fuel cell:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Entropy change:

$$\Delta S = S_{products} - S_{reactants}$$

Usually, ΔS is **negative** because gaseous reactants form liquid water, reducing randomness.



2. Energy Distribution in a Fuel Cell

The total chemical energy released is:

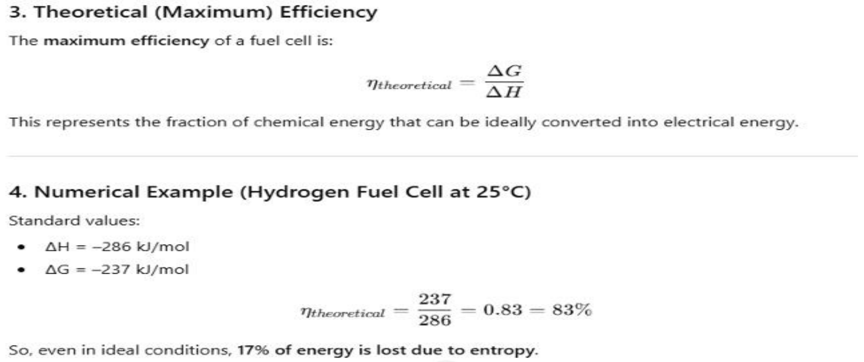
$$\Delta H = \Delta G + T\Delta S$$

Where:

- ΔH = Enthalpy change (total energy available)
- ΔG = Gibbs free energy (useful electrical energy)
- $T\Delta S$ = Energy lost due to entropy (heat)

So:

- Only **ΔG** can be converted into electricity.
- **TΔS** is unavoidable heat loss.



3. Theoretical (Maximum) Efficiency

The **maximum efficiency** of a fuel cell is:

$$\eta_{theoretical} = \frac{\Delta G}{\Delta H}$$

This represents the fraction of chemical energy that can be ideally converted into electrical energy.

---

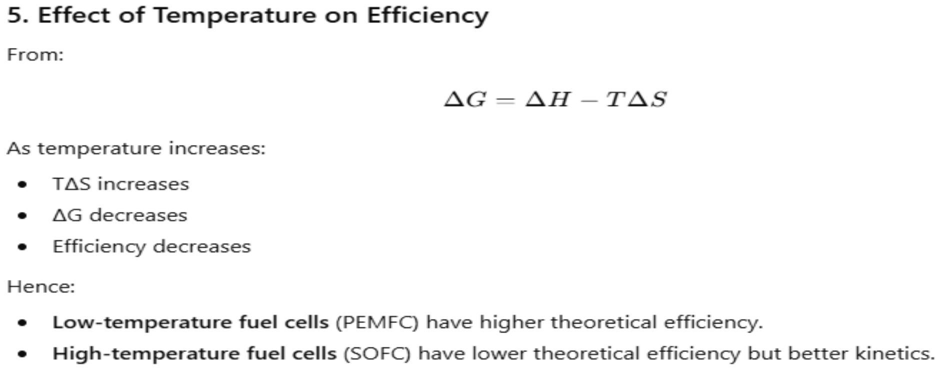
4. Numerical Example (Hydrogen Fuel Cell at 25°C)

Standard values:

- $\Delta H = -286$ kJ/mol
- $\Delta G = -237$ kJ/mol

$$\eta_{theoretical} = \frac{237}{286} = 0.83 = 83\%$$

So, even in ideal conditions, **17% of energy is lost due to entropy.**



5. Effect of Temperature on Efficiency

From:

$$\Delta G = \Delta H - T\Delta S$$

As temperature increases:

- $T\Delta S$ increases
- ΔG decreases
- Efficiency decreases

Hence:

- **Low-temperature fuel cells** (PEMFC) have higher theoretical efficiency.
- **High-temperature fuel cells** (SOFC) have lower theoretical efficiency but better kinetics.

12.Gibbs Free Energy and Fuel Cell Efficiency (Exam-Oriented)

Fuel cells convert chemical energy directly into electrical energy. The **Gibbs free energy change (ΔG)** of the electrochemical reaction determines the **maximum useful electrical energy** that can be obtained. Therefore, fuel cell efficiency is fundamentally governed by Gibbs free energy.

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1. Gibbs Free Energy

Gibbs free energy is defined as:

$G = H - TS$

Change in Gibbs free energy:

$\Delta G = \Delta H - T\Delta S$

Where:

- ΔG = Gibbs free energy change (useful work)
- ΔH = Enthalpy change (total chemical energy)
- T = Absolute temperature
- ΔS = Entropy change

2.1 Fuel Cell Efficiency

The thermal efficiency of an energy conversion device is defined as the amount of useful energy produced relative to the change in stored chemical energy (commonly referred to as thermal energy) that is released when a fuel is reacted with an oxidant. Hence the efficiency may be defined as

$$\eta_e = \frac{\text{useful output energy}}{\Delta H} \tag{2.15}$$

Hydrogen (fuel) and oxygen (oxidant) can exist in each other’s presence at room temperature, but if heated to above 500 °C and at high pressure they explode violently. The combustion reaction for these gases can be forced to occur below 500 °C in the presence of a flame, such as in a heat engine. In the case of a fuel cell, a catalyst can increase the rate of reaction of H_2 and O_2 at temperatures lower than 500 °C in the ambient of an electrolyte. In high temperature fuel cells a non-combustible reaction can occur at temperatures over 500°C because of controlled separation of the fuel and oxidant. The process taking place in a heat engine is thermal, where as the fuel cell process is electrochemical. The difference in these two processes in energy conversion is the fact behind efficiency comparison for these two systems. In the ideal case of an electrochemical energy conversion reaction such as a fuel cell the change in Gibbs free energy of the reaction is available as useful electric energy at the output of the device. The ideal efficiency of a fuel cell operating irreversibly may be stated as

$$\eta = \Delta G^e/\Delta H$$

Fuel Cell: Characteristics Curve & Losses

The properties and control characteristic curve of the fuel cell are examined for designing the overall power conversion system to obtain the required voltage and power output for various applications.

Fuel Cell Losses

Several sources contribute to irreversible losses in a practical fuel cell. The losses, which are often called polarization losses, originate primarily from **three sources**:

(1) Losses due to the rate of reaction,
(2) Ohmic or resistance loss, and
(3) Concentration polarization or gas transport loss.

These losses result in a cell voltage (V) for a fuel cell that is less than its ideal potential, E (V = E − Losses).

13.Fuel Cell Characteristics Curve

A typical voltage-current characteristic of a fuel cell is shown in **Figure 1.** As can be seen, the actual voltage decreases as a function of the current drawn from the fuel cell.

As shown, fuel cell I-V characteristic curve is divided into three regions: R-1, R-2, and R-3. The point at the boundary of regions R-2 and R-3 is known as **maximum power density point or knee/optimum point**.

Loading the fuel cells above the maximum power point (MPP) current will shift the operating point right of the optimum point (region R-3) causing a sudden collapse of the fuel cell voltage to zero. Therefore, no power could be drawn from the cell.

Extended operation in region R-3 may damage the fuel cell. Fuel cells are generally operated in the region R-2 of the characteristics shown in **Figure 1.**

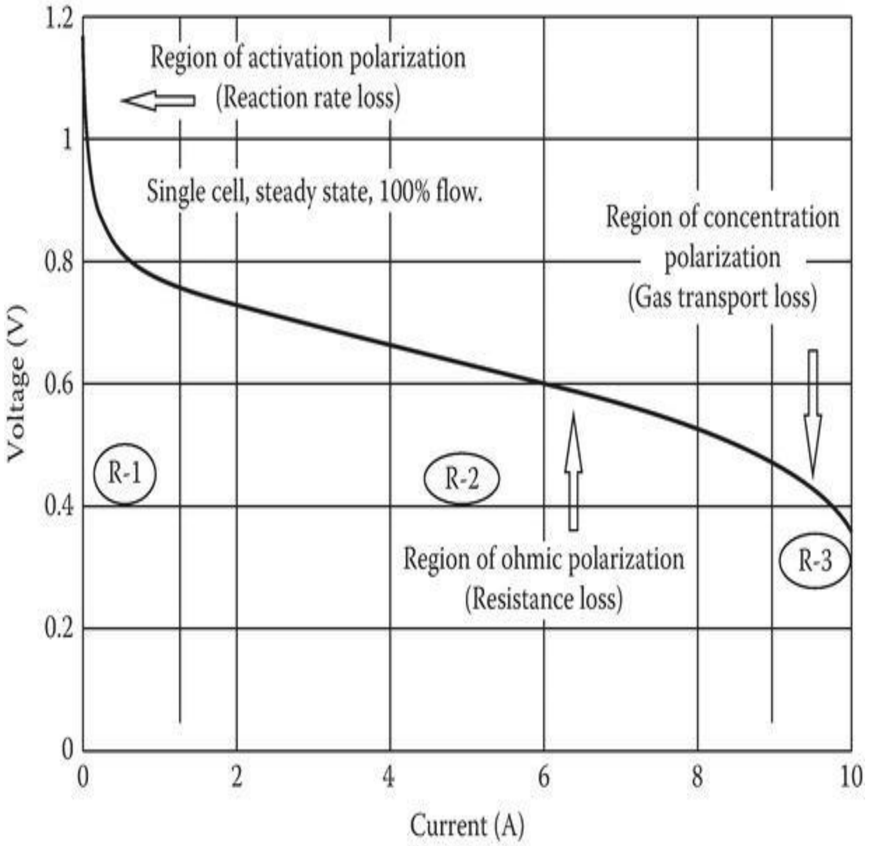


Figure 1 Typical fuel cell V–I characteristic curve.

Various **PEMFC characteristics** as a function of typical values of current density are presented in **Figure 2.** **Figure 2a** is referred to as the performance curve showing the voltage as a function of the current density. The efficiency indicated on the secondary vertical axis is proportional to the cell voltage.

The power density is shown in **Figure 2b** as a function of the current density. The efficiency as a function of power density is shown in **Figure 2c**. The efficiency increases at light load. The dotted line demonstrates above the maximum power regime.

Figure 2d shows a typical efficiency characteristic of a complete fuel cell system in a vehicle, as a function of load power. It also compares with the thermal efficiency with a typical internal combustion engine (ICE) in a vehicle.

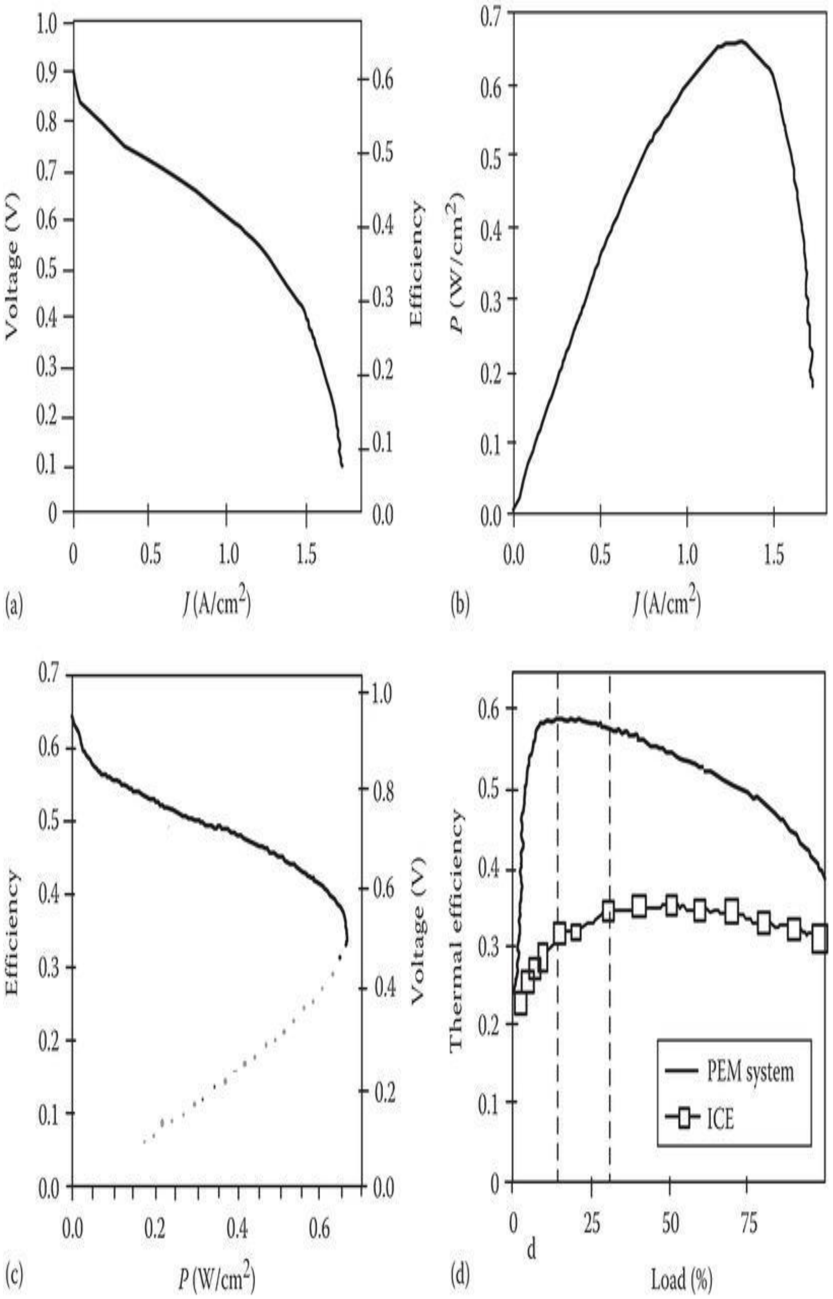


Figure 2 Typical characteristic curves of a PEMFC: (a) performance curve, (b) power density, (c) efficiency, and (d) system efficiency.

Summary of Fuel Cell Technologies

Table 1 compares specific parameters—the electrolyte, operating temperature, and electrical efficiency—for the fuel cells discussed in this section.

Fuel Cell Type	**Electrolyte**	**Operating Temperature**	**Electrical Efficiency**
Proton exchange membrane fuel cell (PEMFC)	Solid organic polymer polyper fluorosulphonic acid	50° C to 100° C	25% to 58%
Direct-methanol fuel cell (DMFC)	Polymer similar to PEMFC	50° C to 120° C	25% to 40%
Phosphoric acid fuel cell (PAFC)	Liquid phosphoric acid	150° C to 200° C	40% to 50%
Alkaline fuel cell (AFC)	Potassium hydroxide	100° C to 250° C	60% to 70%
Solid oxide fuel cell (SOFC)	Yttria-stabilized zirconia	600° C to 1,000° C	35% to 43%
Molten-carbonate fuel cell (MCFC)	Liquid solution of lithium sodium or potassium carbonates	600° C to 700° C	45% to 47%

Types of Fuel Cells

Fuel cells of various types have been developed. They are generally classified based on the electrolyte used, because the electrolyte determines a system's operating temperature and, in part, the type of fuel that can be used.

Hydrogen – Oxygen Fuel Cell

The hydrogen-oxygen fuel cell is one type of fuel cell. The half-reactions take place when hydrogen gas and oxygen gas are bubbled through two porous platinum-coated electrodes. Electrons flow from the negative pole to the positive pole via the external circuit. Their energy is used to power an electric motor or another device as they do so. A typical hydrogen fuel cell, for example, employs graphite electrodes embedded with platinum-based catalysts to accelerate the two half-cell reactions.

$H_2 + 1/2\ O_2 \rightarrow H_2$	$\Delta G_f = 229$ kJ/mol
$H_2 \rightarrow 2\ H^+ + 2\ e^-$	$E^0 = 0.00$ V
$O_2 + 4\ e^- + 4\ H^+ \rightarrow 2\ H_2O$	$E^0 = 1.2$V

The source of hydrogen is a major issue with hydrogen fuel cells. Because the amount of H_2 in the atmosphere is so low, it must be produced.

The majority of hydrogen is currently produced from natural gas and petroleum. It can also be made from coal through the water gas and water gas shift reactions. All of these processes use the energy stored in fossil fuels and thus emit CO_2.

Electrolysis can produce hydrogen from electricity generated by other sources (such as nuclear power, hydropower, or solar energy). However, this is the opposite reaction of the hydrogen fuel cell reaction. H_2 is clearly a medium for energy transfer rather than the fuel.

Alkaline fuel cells

These are devices in which the electrolyte is an aqueous solution of sodium hydroxide or potassium hydroxide. Almost always, the fuel is hydrogen gas, with oxygen (or oxygen in the air) acting as the oxidizer. However, if the by-product oxides were efficiently removed and the metal was fed continuously as a strip or powder, zinc or aluminum could be used as an anode.

- This was the fuel cell that served as the primary source of power for the Apollo space program.
- An aqueous alkaline solution is used in these cells to saturate a porous matrix, which is then used to separate the electrodes.
- Operating temperatures are quite low (approximately 90°C).
- These cells are extremely effective. Along with electricity, they generate heat and water.

Phosphoric acid fuel cells

The electrolyte in these cells is orthophosphoric acid. Phosphoric acid which is used as an electrolyte in these fuel cells channels the H^+. On a small scale, phosphoric acid fuel cells have been proposed and tested for local municipal power stations as well as in remote-site generators.

- The electrodes are made of catalyzed carbon and are arranged in back-to-back pairs to form a series generation circuit.
- These cells operate at temperatures ranging from 150°C to 200°C.
- Because phosphoric acid is non-conductive, electrons must travel to the cathode via an external circuit.
- Because the electrolyte is acidic, the components of these cells corrode or oxidize over time.

Molten carbonate fuel cells

The fuel is made up of a mixture of hydrogen and carbon monoxide produced by water and fo ssil fuel. Molten potassium lithium carbonate serves as the electrolyte. Molten carbonate fuel cells should be useful in both small and large power plants.

- An operating temperature of approximately 650 °C (1,200 °F) is required.
- Because of the high operating temperature and the presence of the carbonate electrolyte, the anode, and cathode of this cell are prone to corrosion.
- These cells can also run on carbon-based fuels like natural gas and biogas.

Solid oxide fuel cells

Solid oxide fuel cells are similar to molten carbonate devices in some ways. However, the majority of the cell materials are special ceramics containing nickel. The electrolyte is a yttria-treated ion-conducting oxide such as zirconia. As with molten carbonate cells, the fuel for these experimental cells is thus expected to be hydrogen combined with carbon monoxide. While the path of the internal reactions would be different, the cell products would be water vapor and carbon dioxide.

- Solid oxide fuel cells would be designed for use in central power plants where temperature variation could be efficiently controlled and fossil fuels were available.
- These fuel cells are extremely efficient and relatively inexpensive (theoretical efficiency can even approach 85%).
- These cells' operating temperatures are extremely high (lower limit of 600°C, standard operating temperatures lie between 800°C and 1000°C).
- Because of their high operating temperatures, solid oxide fuel cells are only suitable for stationary applications.

$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	**(overall reaction)**
$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	**(oxidation reaction)**
$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$	**(reduction reaction)**

Methanol Fuel Cell

Methanol is a liquid fuel that can be produced through fermentation from renewable resources. The electrochemical reactions described below are used in direct methanol fuel cells:

Anode reaction	**$CH_3OH + H_2O \rightarrow CO_2 + 6\ H^+ + 6\ e^-$**
Cathode reaction	**$3/2\ O_2 + 6\ H^+ + 6\ e^- \rightarrow 3\ H_2O$**
Cell reaction	**$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O$**

- Carbon dioxide, a greenhouse gas, is produced during the electrochemical reaction. The anodic reaction necessitates the use of an expensive, precious metal catalyst. A typical alloy is a ruthenium and palladium. However, another disadvantage of this fuel cell is methanol's toxicity.
- Methanol is also compatible with hydrogen fuel cells. Steam reforming methanol at 250 degrees Celsius produces CO_2, H_2, and a trace of CO.

Hydrogen Energy

Hydrogen Energy can be used as alternative to the fossil fuel and many scientists around the world feel that hydrogen as a source of energy could be a permanent solution to the global crisis we are facing in our energy supplies.

As Hydrogen (symbol, H) gas can be produced from water, it is therefore one of the lightest, most efficient, cost effective and cleanest fuel on the planet and as such has the great potential of being one of our primary fuels for powering our vehicles for a cleaner, greener future.

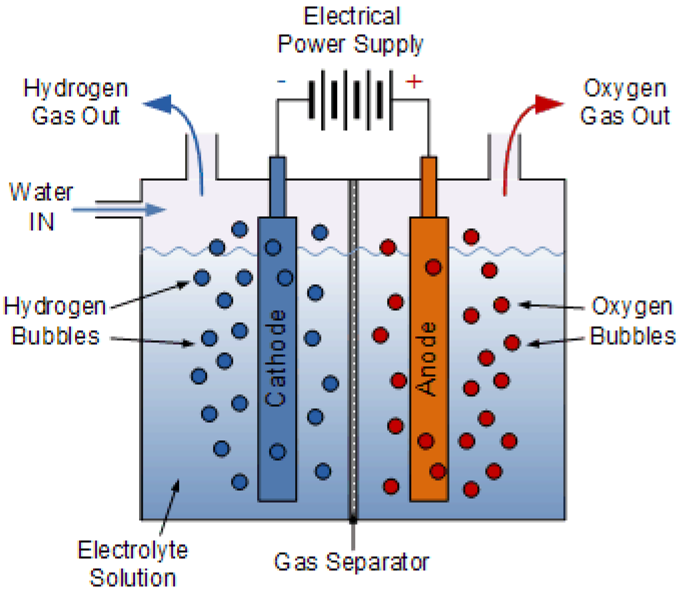
Hydrogen is the simplest and most abundant element on Earth. A hydrogen atom consists of only one proton and one electron making it the first element in the periodic table, having an atomic number of just 1. But despite its simplicity and abundance, hydrogen does not occur naturally as a gas here on the Earth instead it is always combined with other elements.

For example, water as H_2O. This is handy since over 72% of our planet is covered with water making the production of hydrogen as a source of energy highly sustainable, and a good candidate in our attempt to increase energy efficiency.

Producing Hydrogen Energy using Electrolysis

Electrolysis is the process by which an electric current is passed through water and breaks the chemical bonds that exist between the hydrogen and oxygen atoms. The equipment used for doing this is called an "electrolyser". An electrolyser basically consists of a positive element called the Anode (A), a negative element called the Cathode (K), both immersed in a liquid called an electrolyte which can carry a current.

Hydrogen Gas from Electrolysis



When an electrical voltage supply is connected to the two electrodes, an electrical current is passed through the conducting electrolyte causing electrons to flow from the anode (where oxidation occurs) to the cathode (where reduction occurs) breaking down the water into its constituent elements, of hydrogen and oxygen.

A separator type membrane is used to separate the hydrogen's protons and electrons. In most cases water electrolysis is used to produce the hydrogen, but the electrolyte can also be a solution of water and acids or metal salts.

The electrical current also breaks the molecular bonds between the atoms and once broken, the atomic particles (hydrogen and oxygen) become either positively or negatively charged and are free to move through the electrolyte.

As the two electrodes are also positively and negatively charged from the battery supply, this attracts the free atoms towards them with the hydrogen atoms being attracted to the negative electrode forming bubbles of hydrogen gas.

Generally, the positive hydrogen atoms gather at the anode (which is negative), while the negative oxygen ions reside at the cathode (which is positive). When the hydrogen and oxygen gases formed at either terminal and large enough they break free and rise to the surface were the hydrogen gas is collected and the oxygen gas is vented. Then we can see that electrolysis is a method of producing chemical energy (hydrogen and oxygen) by passing an electric current through a chemical substance called a watery electrolyte.

Once the hydrogen has been collected and purified, we can then use the clean hydrogen as a fuel in a number of different ways as it has a wider range of flammability limits and a lower ignition energy than many other fuels. Also being used mainly as an industrial gas, the technologies need for the production, storage, and transmission of hydrogen are well established in the chemical industries.

Benefits of Hydrogen Energy

- **Environmental Sustainability:** When produced from renewable sources (green hydrogen), it produces zero harmful greenhouse gases, helping to combat climate change.
- **Energy Storage & Flexibility:** Acts as a long-duration energy storage medium to balance intermittent renewable sources like wind and solar.
- **High Efficiency:** Fuel cells coupled with electric motors are 2–3 times more efficient than internal combustion engines running on gasoline.
- **Energy Security:** Can be produced domestically from water, biomass, or natural gas, reducing reliance on imported fuels.
- **High Power Density:** Provides faster refueling and longer range for heavy-duty, long-distance transportation compared to batteries.

Primary Applications

- **Transportation (Fuel Cells):** Powers fuel cell electric vehicles (FCEVs), including passenger cars, trucks, buses, trains, and ships.
- **Industrial Processes:** Used in refining petroleum, manufacturing fertilizer (ammonia), producing steel, and in glass/semiconductor manufacturing.
- **Power Generation:** Provides stationary electricity and heat for commercial, residential, and industrial use, including backup power for data centers.
- **Energy Storage & Grid Stability:** Stores excess renewable energy for later use, supporting grid reliability.
- **Heating:** Used for high-temperature industrial heating and potentially in residential heating systems.

problems associated with hydrogen energy

1. High Production Costs and Carbon Intensity

The "cleanliness" of hydrogen depends entirely on its production method, most of which are currently carbon-intensive or expensive.

- **Dominance of Fossil Fuels**: Approximately **99% of global hydrogen** (Gray Hydrogen) is currently produced from natural gas or coal, processes that emit more greenhouse gases than diesel or coal when the full lifecycle is considered.

- **Green Hydrogen Expense**: Producing hydrogen via electrolysis powered by renewables (Green Hydrogen) is currently **two to four times more expensive** than fossil-fuel-based methods ($2.28–$7.39/kg vs. $0.67–$1.31/kg).
- **Energy Efficiency**: The "well-to-wheel" efficiency is low. For instance, in transportation, converting electricity to hydrogen and then back to electricity in a fuel cell results in significant energy loss compared to using a battery-electric vehicle.

2. Storage and Transportation Hurdles

Hydrogen's physical properties make it exceptionally difficult to handle compared to traditional fuels.

- **Low Energy Density**: Hydrogen has a very low volumetric energy density. To store a useful amount, it must be compressed to extremely high pressures (up to 700 bar) or liquefied at cryogenic temperatures (**-253°C**), both of which are energy-intensive processes.
- **Infrastructure Gaps**: Most existing pipelines and refueling stations are not compatible with hydrogen. Building a dedicated network is estimated to cost **over $500 billion** for even a partial transition in the U.S..
- **Hydrogen Embrittlement**: Hydrogen atoms can penetrate and weaken metals like steel, causing them to become brittle and prone to cracking or sudden failure.

3. Significant Safety Risks

Hydrogen presents unique hazards that complicate its use in public or residential settings.

Gexcon +1

- **High Flammability and Leakage**: It has a wide flammability range (4%–75% in air) and requires very low ignition energy—even a tiny static spark can trigger it. Its small molecular size also makes it highly prone to leaking through seals and materials.
- **Invisible Hazards**: Hydrogen burns with a **nearly invisible flame** and is odorless, making leaks and fires difficult to detect without specialized equipment.
- **Explosion Potential**: In confined spaces, leaked hydrogen can accumulate and lead to violent detonations with powerful shockwaves.

4. Environmental and Social Impacts

- **Resource Intensity**: Green hydrogen requires massive amounts of **fresh water** (roughly 9 liters of water per 1 kg of hydrogen), which poses challenges in water-scarce regions.

- **Pollutant Emissions**: While burning hydrogen doesn't produce CO2, it can produce **nitrogen oxides (NOx)**—a respiratory irritant—at rates up to six times higher than natural gas due to its high combustion temperature.
- **Global Warming Potential**: If hydrogen leaks into the atmosphere, it acts as an indirect greenhouse gas with a warming potential estimated to be **11 times greater than CO2**.

UNIT III

Energy Storage and Green Energy:

Stationary Battery Storage

- Stationary battery storage refers to **rechargeable battery systems installed in a fixed location** to store electrical energy for later use. These systems are crucial for modern energy infrastructure, integrating renewable energy sources, enhancing grid stability, and providing reliable backup power.
- A typical stationary battery energy storage system (BESS) consists of several core components:
- **Battery System/Modules**: These contain individual battery cells (e.g., lithium-ion, lead-acid, flow) where the chemical energy is stored.
- **Power Conversion System (PCS)**: This bidirectional inverter converts direct current (DC) electricity from the batteries into the alternating current (AC) used by homes, businesses, and the grid, and vice-versa during charging.
- **Energy Management System (EMS)**: Often referred to as the "brain" of the system, advanced software and control algorithms optimize charging and discharging cycles based on energy demand, supply, and price signals.
- **Thermal Management System**: This system manages the temperature of the batteries, which is critical for preventing overheating (thermal runaway) or performance degradation due to cold, ensuring safe and efficient operation.
- **Safety and Protection Systems**: These include fire suppression systems, electrical protection devices (fuses, breakers), and environmental sensors to mitigate risks.
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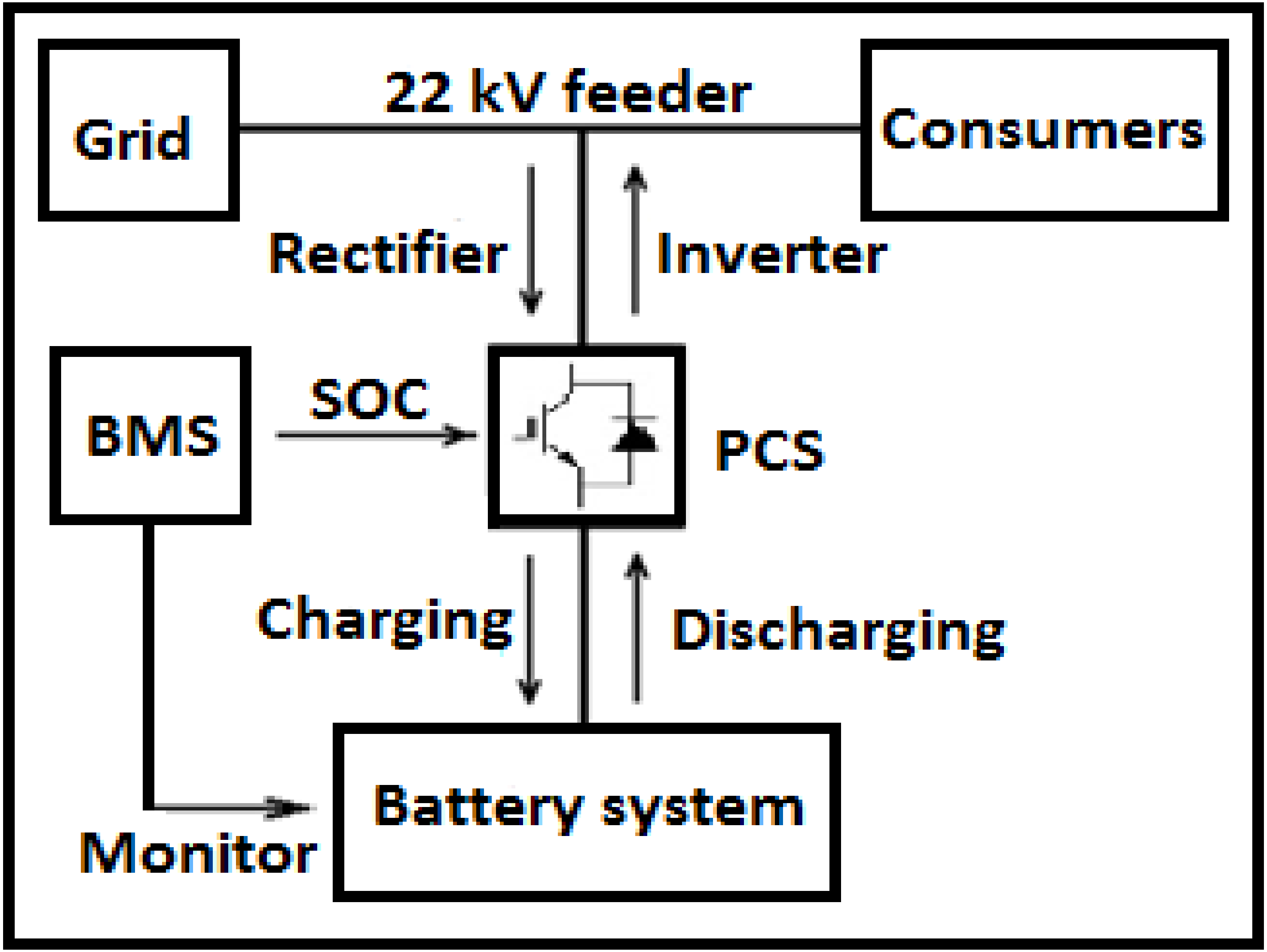

Grid
22 kV feeder
Consumers
Rectifier
Inverter
BMS
SOC
PCS
Charging
Discharging
Monitor
Battery system

- Structure diagram of the Battery Energy Storage System (BESS), as shown in Figure 2, consists of three main systems: the power conversion system (PCS), energy storage system and the battery management system (BMS).
- The power conversion system consists of a three-phase, full bridge converter, which couples the battery system to the electricity utility’s network .
- The BMS (Battery Management System) is used to monitor and measure the power system’s performance parameters, such as voltages, currents, and temperatures.
- A battery energy storage system with an incorrect state of charge may be overcharged or over-discharged. This may damage the storage system, shorten the life time, or even cause fire or an explosion.
- The BMS will communicate with the PCS (Power Conversion System), the state of charge (SOC) and the state of health (SOH) .
- When the state of charge (SOC) is 1, the energy storage system is fully charged. The energy storage system should pause charging the storage system, to avoid damaging the batteries.
- When the SOC is 0, the storage system is discharged fully. The energy storage system should stop discharging the batteries as the battery system is empty.

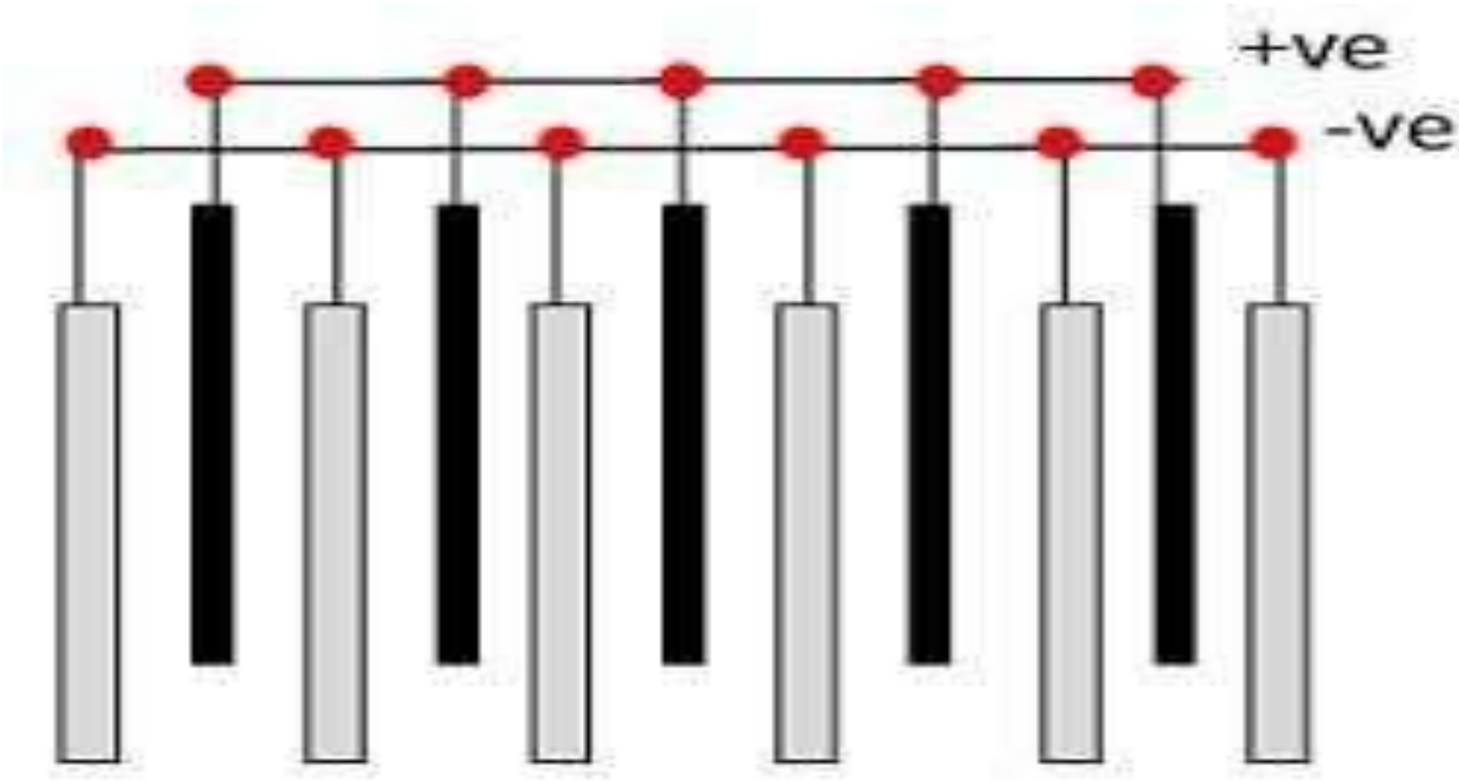
- **Applications**
- Stationary battery storage systems are used across various market segments due to their flexibility and scalability:
- **Renewable Energy Integration**: They store excess energy generated from intermittent sources like solar and wind power, releasing it when generation is low or demand is high, which ensures a continuous power supply.
- **Grid Services**: Utility-scale BESS enhance grid stability by providing ancillary services like frequency regulation and voltage support. They can also help defer expensive infrastructure upgrades by managing local congestion.
- **Peak Shaving and Load Shifting**: Businesses and homeowners can charge batteries during off-peak hours when electricity is cheap and discharge them during peak demand periods, significantly reducing energy costs.
- **Backup Power/Energy Resilience**: BESS provide an uninterrupted power supply (UPS) for critical infrastructure such as data centers, hospitals, and telecommunication networks during grid outages, ensuring continuous operation.
- **Microgrids**: They are essential components of microgrids, enabling localized energy independence and reliable power, especially in remote areas.

Lead Acid Battery

- **Definition:** The battery which uses sponge lead and lead peroxide for the conversion of the chemical energy into electrical power, such type of battery is called a lead acid battery. The lead acid battery is most commonly used in the power stations and substations because it has higher cell voltage and lower cost.

Construction of Lead Acid Battery

- **1. Container –** The container of the lead acid battery is made of glass, lead lined wood, ebonite, the hard rubber of bituminous compound, ceramic materials or moulded plastics and are seated at the top to avoid the discharge of electrolyte. At the bottom of the container, there are four ribs, on two of them rest the positive plate and the others support the negative plates.
- **2. Plate –** The plate of the lead-acid cell is of diverse design and they all consist some form of a grid which is made up of lead and the active material. The grid is essential for conducting the electric current and for distributing the current equally on the active material. If the current is not uniformly distributed, then the active material will loosen and fall out.

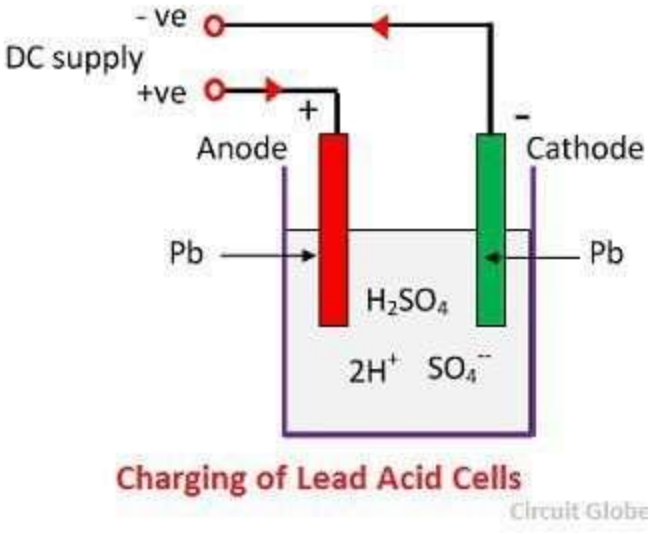


Arrangements of Plates in a Lead-acid-Battery

- **3. Active Material –** The material in a cell which takes active participation in a chemical reaction (absorption or evolution of electrical energy) during charging or discharging is called the active material of the cell. The active elements of the lead acid are
- **Lead peroxide (PbO_2)** – It forms the positive active material. The PbO_2 are dark chocolate broom in colour.
- **Sponge lead** – Its form the negative active material. It is grey in colour.
- **Dilute Sulfuric Acid (H_2SO_4)** – It is used as an electrolyte. It contains 31% of sulfuric acid.
- The lead peroxide and sponge lead, which form the negative and positive active materials have the little mechanical strength and therefore can be used alone.
- **4. Separators –** The separators are thin sheets of non-conducting material made up of chemically treated leadwood, porous rubbers, or mats of glass fibre and are placed between the positive and negative to insulate them from each other. Separators are grooved vertically on one side and are smooth on the other side.
- **5. Battery Terminals –** A battery has two terminals the positive and the negative. The positive terminal with a diameter of 17.5 mm at the top is slightly larger than the negative terminal which is 16 mm in diameter.

Working Principle of Lead Acid Battery

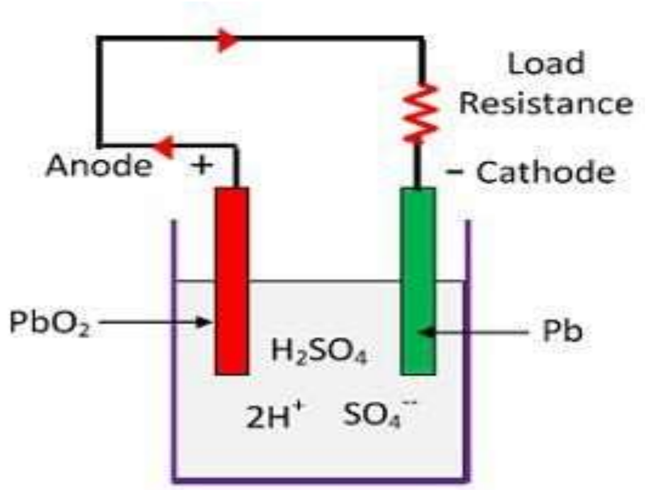
- When the sulfuric acid dissolves, its molecules break up into positive hydrogen ions ($2H^+$) and sulphate negative ions (SO_4^{--}) and move freely.
- If the two electrodes are immersed in solutions and connected to DC supply then the hydrogen ions being positively charged and moved towards the electrodes and connected to the negative terminal of the supply.
- The SO_4^{--} ions being negatively charged moved towards the electrodes connected to the positive terminal of the supply main (i.e., anode).
- Each hydrogen ion takes one electron from the cathode, and each sulphates ions takes the two negative ions from the anodes and react with water and form sulfuric and hydrogen acid.
- The oxygen, which produced from the above equation react with lead oxide and form lead peroxide (PbO_2.) Thus, during charging the lead cathode remain as lead, but lead anode gets converted into lead peroxide, chocolate in colour.



If the DC source of supply is disconnected and if the voltmeter connects between the electrodes, it will show the potential difference between them.

If wire connects the electrodes, then current will flow from the positive plate to the negative plate through external circuit i.e. the cell is capable of supplying electrical energy.

- Chemical Action During Discharging
- When the cell is full discharge, then the anode is of lead peroxide (PbO_2) and a cathode is of metallic sponge lead (Pb).
- When the electrodes are connected through a resistance, the cell discharge and electrons flow in a direction opposite to that during charging.
- The hydrogen ions move to the anode and reaching the anodes receive one electron from the anode and become hydrogen atom.
- The hydrogen atom comes in contacts with a PbO_2, so it attacks and forms lead sulphate ($PbSO_4$), whitish in colour and water according to the chemical equation.



Discharging of Lead Acid Cells

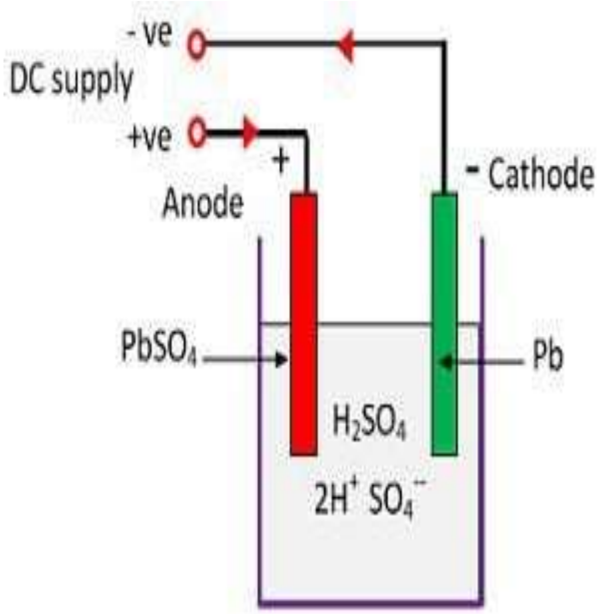
Circuit Globe

$$PbSO_4 + 2H = PbO + H_2O$$

$$PbO + H_2SO_4 = PbSO_4 + 2H_2O$$

$$\overline{PbO_2 + H_2SO_4 + 2H = PbSO_4 + 2H_2O}$$

- **Chemical Action During Recharging**
- For recharging, the anode and cathode are connected to the positive and the negative terminal of the DC supply mains.
- The molecules of the sulfuric acid break up into ions of $2H^+$ and SO_4^{--}.
- The hydrogen ions being positively charged moved towards the cathodes and receive two electrons from there and form a hydrogen atom.
- The hydrogen atom reacts with lead sulphate cathode forming lead and sulfuric acid according to the chemical equation.



Recharging of Lead Acid Cell

Circuit Globe

$$PbSO_4 + 2H_2O + 2H = PbSO_4 + 2H_2SO_4$$

Battery Storage Capacity

- Battery storage capacity refers to the total amount of energy that a battery can store and discharge. It’s usually measured in kilowatt-hours (kWh) for larger systems, like those used in homes or businesses, or amp-hours (Ah) for smaller systems, like those found in electronics or electric vehicles. The higher the storage capacity, the more energy the battery can hold. In practical terms, a battery with a higher storage capacity will last longer between charges and can provide more power when needed.
-
- Think of it like a water tank. The tank’s capacity tells you how much water it can hold. Similarly, a battery’s storage capacity tells you how much energy it can store and supply to power devices, appliances, or even entire homes.

- Understanding battery storage capacity is crucial for making informed decisions, whether you’re choosing a battery for a solar energy system, an electric vehicle, or any other application. The more storage capacity you have, the longer your battery can power things without needing to be recharged. For example, a home solar system paired with a battery storage solution allows you to store energy generated during the day for use at night. If your battery has high storage capacity, you can use more of the solar energy you’ve captured, reducing reliance on the grid.
-
- Battery storage capacity also plays a significant role in reducing energy costs. In places with peak energy pricing, having a larger storage capacity allows you to use stored energy when electricity prices are high, thus saving money on your electricity bill.

- Several factors influence a battery's storage capacity, and understanding these factors is important for selecting the right battery for your needs. Some of the main elements include:
- **Battery Chemistry**
- Different battery chemistries offer varying energy densities, which affect storage capacity. For instance, lithium-ion batteries typically have a higher energy density than lead-acid batteries, meaning they can store more energy in a smaller space. This is why lithium-ion batteries are commonly used in electric vehicles and renewable energy systems.
- **Size of the Battery**
- Larger batteries naturally have a higher storage capacity because they have more room for energy. However, size isn’t the only factor—battery design and chemistry also come into play.

- **Voltage and Current**
- Voltage refers to the electrical potential, while current is the flow of electricity. The combination of voltage and current determines how much energy a battery can store and how efficiently it can discharge.
- **State of Charge (SOC)**
- The SOC indicates how much energy remains in a battery. A fully charged battery has a SOC of 100%, while a completely depleted battery has a SOC of 0%. As the SOC changes, so does the available energy for use.

- **Efficiency of the Battery**
- Not all the energy stored in a battery can be used. Battery efficiency accounts for losses that occur during charging and discharging. A highly efficient battery will have less energy loss, allowing it to deliver more usable power.

- **How to Calculate Battery Storage Capacity**

- To understand how much energy a battery can hold, it's essential to look at its capacity, which is typically expressed in either kWh or Ah. Here’s a simple breakdown:
- **Amp-Hours (Ah)**
- Amp-hours are the most common unit of measurement for small batteries, such as those used in electronics or electric vehicles. If a battery is rated for 10 Ah, this means it can supply 10 amps of current for one hour. To calculate the total capacity, you multiply the voltage by the amp-hour rating:
- **Capacity (Wh)=Voltage (V)×AmpHours (Ah)**
- For example, a 12V battery with a 10Ah rating would have a capacity of:
- Capacity=12V×10Ah=120Wh
-
- **Kilowatt-Hours (kWh)**
- Larger systems, like those used in homes or businesses, typically use kWh to measure capacity. One kWh is equal to 1,000 watt-hours (Wh). So, for a home energy system that uses a 10 kWh battery, it can supply 10,000 watt-hours of energy. A battery with a 10 kWh capacity can power a 1,000-watt device for 10 hours (if it operates at full efficiency).

Coulomb Efficiency (instead of Energy Efficiency)

- **Definition**
- **Coulomb Efficiency ($\eta_{(c)}$)** is the ratio of **charge extracted from the battery during discharge** to the **charge supplied during charging**.

$$\eta_c = \frac{\text{Discharge capacity (Ah)}}{\text{Charge capacity (Ah)}} \times 100\%$$

- **Why Coulomb Efficiency is used instead of Energy Efficiency**
- **(a) Energy efficiency depends on voltage**
- Energy efficiency considers both current and voltage:

$$\eta_E = \frac{V_d I_d t_d}{V_c I_c t_c}$$

- But battery voltage:
- changes with **state of charge**
- changes with **load**
- includes losses due to **internal resistance**
- So energy efficiency is affected by external operating conditions.

- **(b) Coulomb efficiency reflects internal chemistry**
- Coulomb efficiency depends only on:
- electrochemical reactions
- side reactions (like gassing, self-discharge)
- So it directly measures:
- *How much of the stored charge is actually recoverable.*
- **(c) Easier and more accurate to measure**
- Only current and time are needed:
- $Q=I\times t$
- No need to measure varying voltage accurately.

Typical values

Battery Type	Coulomb Efficiency
Lead–acid	85–95%
Ni–Cd	70–85%
Ni–MH	65–80%
Li-ion	98–99.9%
Supercapacitor	~100%

Battery Sizing

- Battery sizing is crucial in order to ascertain that it can supply power to the connected loads for the time period it is designed. Unsuitable sizing of the battery can pose many serious problems such as permanent battery damage because of over-discharge, low voltages to the load, insufficient backup times.
- The **battery sizing** can be initiated once we have the following information:
- Loads need to be supported by battery
- Minimal voltage for battery
- Back up time(s)

- **IEEE Battery Sizing Calculations**
- The calculations performed are based on “Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications” and “Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications” IEEE standards. All the calculations in this article are established on conventional lead-acid or nickel-cadmium (NiCd) batteries. The outcomes presented here may not support other types of batteries, so the manufacturer’s guidance will require being conferred.
- The methodological analysis has the five steps as follows:
- **Step 1:** Collect the total connected loads that the battery requires to supply
- **Step 2:** Develop a load profile and further compute design energy
- **Step 3:** Choose the type of battery and determine the cell characteristics
- **Step 4:** Choose the battery cells required to be linked in series fashion
- **Step 5:** On the basis of design loads, compute the desired Ampere-hour (Ah) battery

Different Battery storage technologies and comparison of their performance

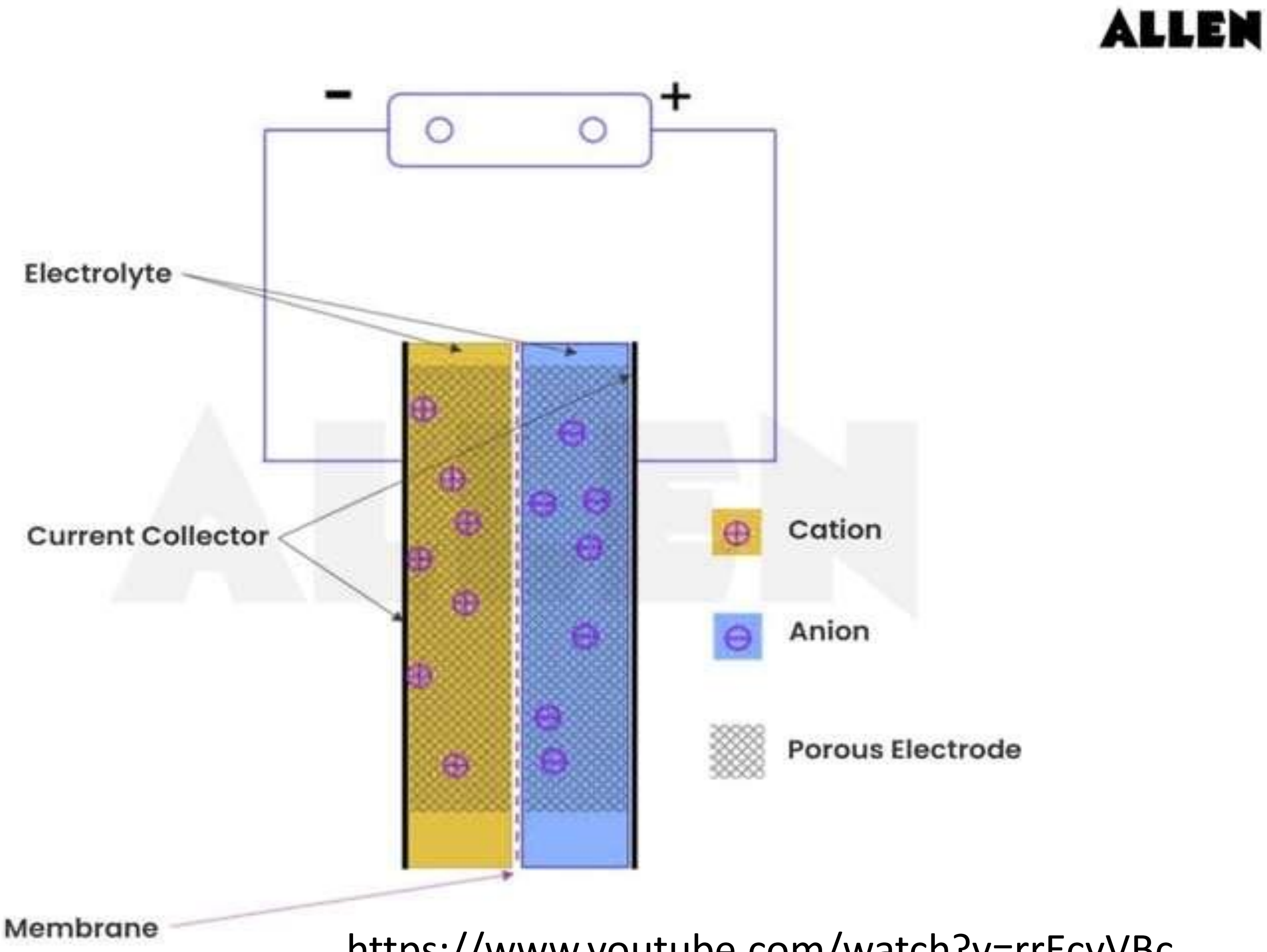
Performance Comparison Summary

Technology	Efficiency	Cycle Life	Energy Density	Primary Application
Li-ion	85–95%	3,000–10,000	High	EVs, Home Storage
Lead-Acid	70–85%	Short/Low	Low	UPS, Back-up
Flow	65–85%	Very Long	Low-Med	Grid Storage
NaS	75–85%	Long	High	Grid Stability
Supercapacitors	90–95%	>1,000,000	Very Low	Frequency Reg

Supercapacitor

- A supercapacitor, also known as an ultracapacitor or electric double-layer capacitor (EDLC), is an advanced energy storage solution known for its ultra-fast charging, high power output, and exceptional longevity.
- Unlike conventional lithium-ion batteries, supercapacitors store energy via electrostatic charge instead of chemical reactions. This enables them to charge and discharge within seconds, with minimal wear over time.
- Supercapacitors are ideal for applications that demand quick energy delivery or short-term backup power.
- With the ability to withstand over 1 million charge-discharge cycles and a design that supports eco-friendly, sustainable energy, supercapacitors are rapidly gaining traction as a key component in the future of green energy and high-efficiency power systems
- **Defination**
- **A supercapacitor (also known as an ultracapacitor or electrochemical capacitor) is an energy storage device that stores electrical energy through the separation of electric charges in an electric double layer or via fast surface redox reactions.**

Construction And Working of Supercapacitors



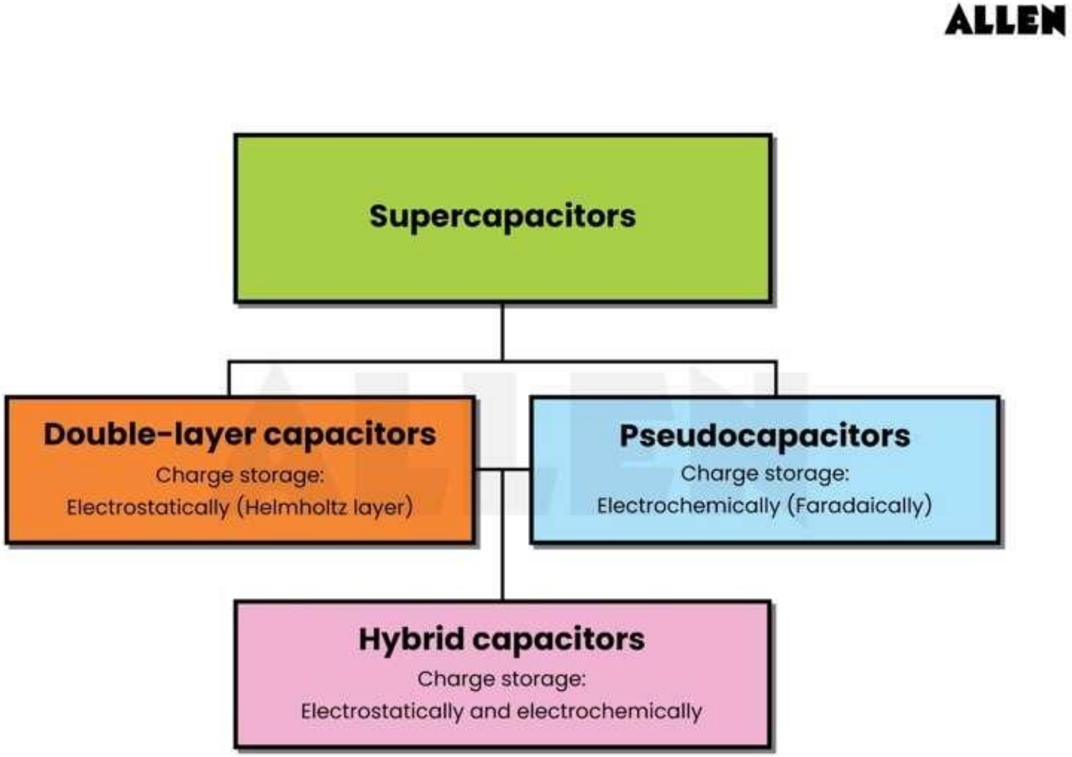
https://www.youtube.com/watch?v=rrEcyVBcV7k

- The image shows the basic structure of a supercapacitor, which consists of the following key components:
- **Electrodes (Porous Electrode):**Two porous electrodes, positioned on the positive and negative sides, feature a large surface area that maximizes charge storage by allowing ions from the electrolyte to penetrate deeply into their structure; this porous design significantly increases the effective contact area between the electrodes and electrolyte, thereby enhancing the overall capacitance of the supercapacitor.
- **Current Collectors:** Current collectors are conductive materials attached to each electrode that enable the flow of electrons to and from the external circuit, such as a battery or load, effectively connecting the electrodes to the external positive and negative terminals.
- **Electrolyte:**The electrolyte, which fills the space between the electrodes, contains freely moving ions—cations and anions—that facilitate ion movement; in the image, blue cations (+) represent positive ions, while red anions (−) represent negative ions.
- **Membrane (Separator):**The membrane physically separates the two electrodes to prevent short circuits while allowing ions to pass between them, ensuring that only ionic flow occurs through the electrolyte and blocking electron flow

Working Principle of a Supercapacitor

- When voltage is applied, cations move toward the negative electrode, and anions move toward the positive electrode through the electrolyte.
- Ions accumulate at the electrode-electrolyte interface, forming an electric double layer that stores energy electrostatically.
- The porous electrodes provide a large surface area, boosting capacitance beyond traditional capacitors.
- Current collectors enable electron flow in the external circuit, completing charge and discharge cycles.
- Energy is stored by ion adsorption, allowing rapid charging/discharging and long cycle life without chemical degradation.

Types of Capacitors



Supercapacitors

Double-layer capacitors
Charge storage:
Electrostatically (Helmholtz layer)

Pseudocapacitors
Charge storage:
Electrochemically (Faradaically)

Hybrid capacitors
Charge storage:
Electrostatically and electrochemically

Historical Development Green Energy:

- **1. Ancient Period (Before 1800)**
- In early civilizations, humans relied entirely on renewable sources:
- **Solar energy:** Used for drying crops, heating homes, and orientation of buildings.
- **Wind energy:** Sailboats used wind power for transportation.
- **Water energy:** Water wheels were used in ancient Greece, Rome, China, and India for grinding grains ;and irrigation.
- **Biomass:** Wood, animal dung, and agricultural residues were primary fuels for cooking and heating.

2. Industrial Revolution (1800–1900)

- The discovery of **coal and steam engines** reduced dependence on renewables.
- However, early forms of green energy still existed:
  - Hydropower plants began operating in Europe and the USA.
  - In 1882, the **first hydroelectric power plant** was built in Wisconsin, USA.

3. Early 20th Century (1900–1950)

- **Hydropower** expanded significantly for electricity generation.
- Early research on **solar cells** began.
- In 1931, the first practical **wind turbine** for electricity was built.
- Fossil fuels dominated due to industrial growth.

4. Energy Crisis Period (1970–1990)

- The **1973 oil crisis** highlighted the risks of fossil fuel dependency.
- Governments invested in renewable research.
- Development of:
  - Solar photovoltaic (PV) panels.
  - Large wind farms.
  - Biomass and geothermal projects.

5. Modern Era (1990–2010)

- Climate change concerns increased global interest.
- International agreements like the **Kyoto Protocol (1997)**.
- Rapid technological improvements:
  - Cheaper and efficient solar panels.
  - Grid-connected wind farms.
  - Small-scale biogas plants in rural areas.

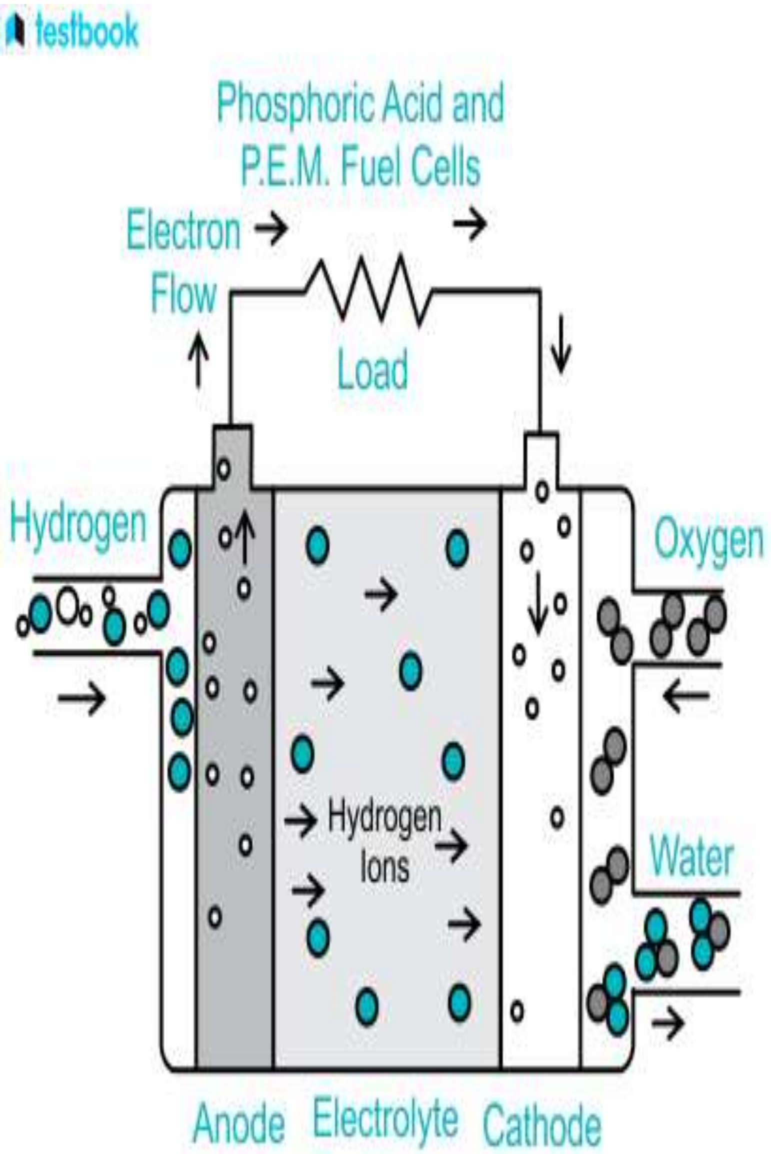
6. Present and Future (2010 onwards)

- Emphasis on **carbon neutrality** and **net-zero emissions**.
- Major developments:
  - Smart grids and energy storage systems.
  - Electric vehicles powered by renewable energy.
  - Floating solar farms and offshore wind power.
- Countries like **India** launched missions such as:
  - National Solar Mission.
  - Wind–solar hybrid projects.
-

Fuel Cell

- Fuel Cell is a technology that uses a strong chemical reaction to generate electricity. The fuel cell generates electricity via redox reactions that convert the chemical energy of the fuel with an oxidizing agent into electricity.
- A fuel cell is a small device with two electrodes: a cathode and an anode. Inside the cell, these electrodes cause an electrochemical reaction.
- Fuel cells have a number of advantages over traditional combustion-based technologies that are currently used in many power plants and vehicles.
- They have higher efficiencies than combustion engines and can directly convert the chemical energy in fuel to electrical energy with efficiencies exceeding 60%.

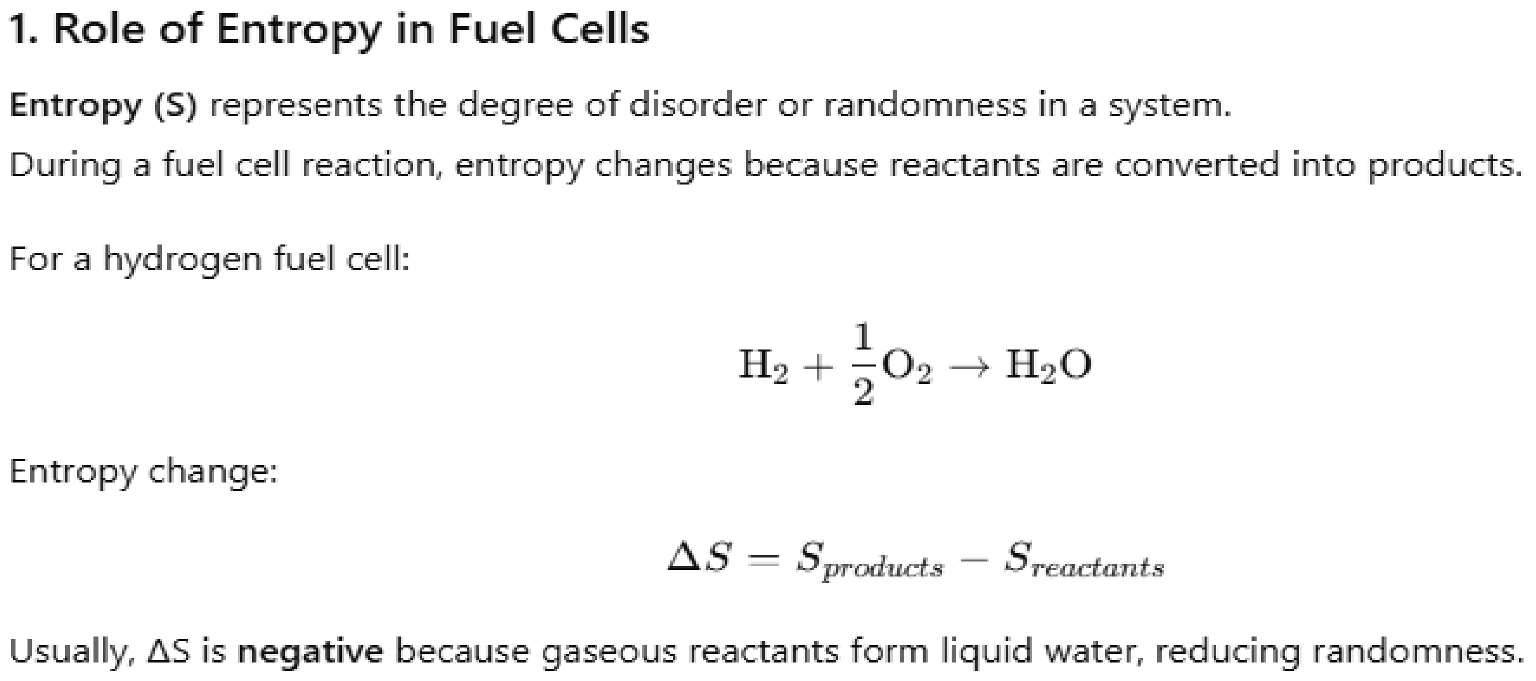
- First, flow fields direct hydrogen fuel to the anode. Hydrogen atoms are ionized (depleted of electrons) and now only have a positive charge.
- The oxygen then enters the fuel cell at the cathode and reacts with electrons returning from the electrical circuit as well as ionized hydrogen atoms. After picking up the electrons, the oxygen atom travels through the electrolyte to combine with the hydrogen ion.
- The chemical reaction is based on the combination of oxygen and ionized hydrogen.
- **Cathode Reaction**
- $O_2+2H_2O+4e^-\rightarrow 4OH^-$
- **Anode Reaction**
- $2H_2+4OH^-\rightarrow 4H_2O+4e^-$
- **Net Cell Reaction**
- $2H_2+O_2\rightarrow 2H_2O$



https://www.youtube.com/watch?v=JhOHowa8BHM

Entropy and the Theoretical Efficiency of Fuel Cells

- Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy. Their theoretical efficiency is fundamentally governed by **entropy (ΔS)** and **Gibbs free energy (ΔG)**, making thermodynamics central to understanding their performance.



1. Role of Entropy in Fuel Cells

Entropy (S) represents the degree of disorder or randomness in a system.
During a fuel cell reaction, entropy changes because reactants are converted into products.

For a hydrogen fuel cell:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Entropy change:

$$\Delta S = S_{products} - S_{reactants}$$

Usually, ΔS is **negative** because gaseous reactants form liquid water, reducing randomness.

2. Energy Distribution in a Fuel Cell

The total chemical energy released is:

$$\Delta H = \Delta G + T\Delta S$$

Where:

- ΔH = Enthalpy change (total energy available)
- ΔG = Gibbs free energy (useful electrical energy)
- TΔS = Energy lost due to entropy (heat)

So:

- Only **ΔG** can be converted into electricity.
- **TΔS** is unavoidable heat loss.

3. Theoretical (Maximum) Efficiency

The **maximum efficiency** of a fuel cell is:

$$\eta_{theoretical} = \frac{\Delta G}{\Delta H}$$

This represents the fraction of chemical energy that can be ideally converted into electrical energy.

---

4. Numerical Example (Hydrogen Fuel Cell at 25°C)

Standard values:

- ΔH = −286 kJ/mol
- ΔG = −237 kJ/mol

$$\eta_{theoretical} = \frac{237}{286} = 0.83 = 83\%$$

So, even in ideal conditions, **17% of energy is lost due to entropy.**

5. Effect of Temperature on Efficiency

From:

$$\Delta G = \Delta H - T\Delta S$$

As temperature increases:

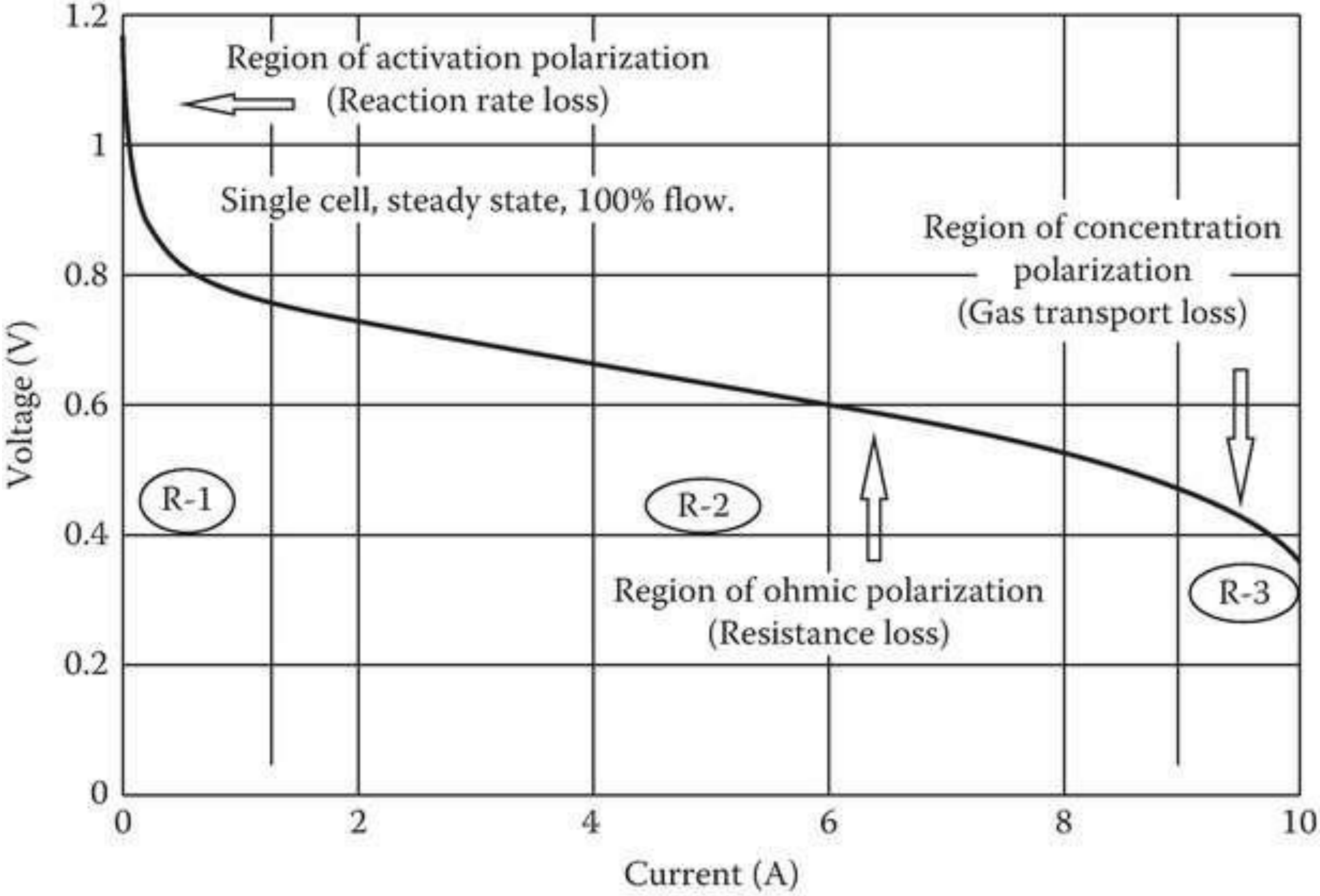
- $T\Delta S$ increases
- ΔG decreases
- Efficiency decreases

Hence:

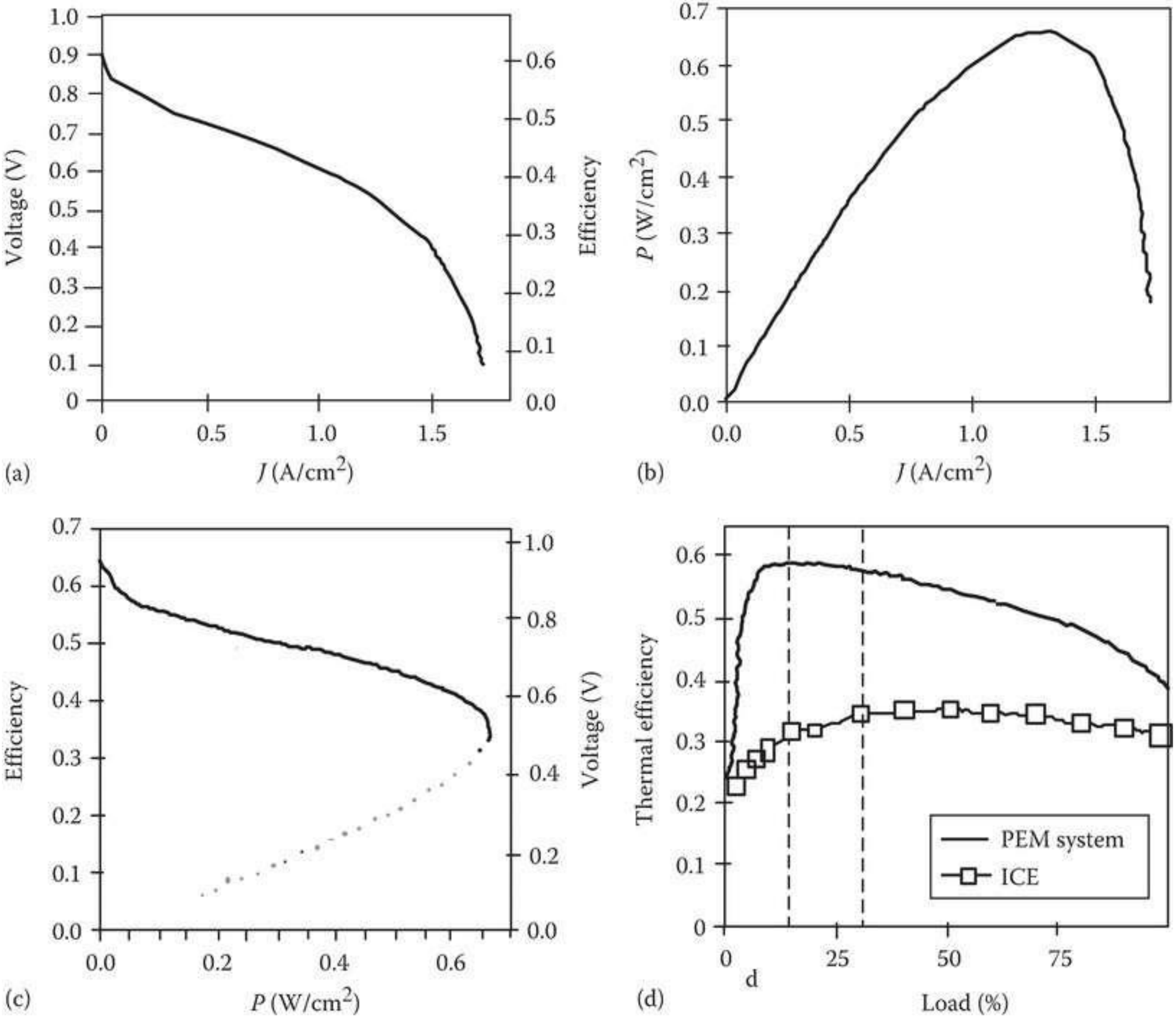
- **Low-temperature fuel cells** (PEMFC) have higher theoretical efficiency.
- **High-temperature fuel cells** (SOFC) have lower theoretical efficiency but better kinetics.

Electrical Characteristics of Real Fuel Cells

- *The properties and control characteristic curve of the fuel cell are examined for designing the overall power conversion system to obtain the required voltage and power output for various applications.*
- **Fuel Cell Losses**
- Several sources contribute to irreversible losses in a practical fuel cell. The losses, which are often called polarization losses, originate primarily from **three sources**:
- **(1)** Losses due to the rate of reaction,
- **(2)** Ohmic or resistance loss, and
- **(3)** Concentration polarization or gas transport loss.
- These losses result in a cell voltage (V) for a fuel cell that is less than its ideal potential, E (V = E − Losses).
- **Fuel Cell Characteristics Curve**
- A typical voltage-current characteristic of a fuel cell is shown in **Figure 1.** As can be seen, the actual voltage decreases as a function of the current drawn from the fuel cell.
- As shown, fuel cell I-V characteristic curve is divided into three regions: R-1, R-2, and R-3. The point at the boundary of regions R-2 and R-3 is known as **maximum power density point or knee/optimum point**.
- Loading the fuel cells above the maximum power point (MPP) current will shift the operating point right of the optimum point (region R-3) causing a sudden collapse of the fuel cell voltage to zero. Therefore, no power could be drawn from the cell.
- Extended operation in region R-3 may damage the fuel cell. Fuel cells are generally operated in the region R-2 of the characteristics shown in **Figure 1.**


Region of activation polarization
(Reaction rate loss)
Single cell, steady state, 100% flow.
Region of concentration polarization
(Gas transport loss)
R-1
R-2
R-3
Region of ohmic polarization
(Resistance loss)
Voltage (V)
Current (A)
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10

- **Figure 2a** is referred to as the performance curve showing the voltage as a function of the current density. The efficiency indicated on the secondary vertical axis is proportional to the cell voltage.
- The power density is shown in **Figure 2b** as a function of the current density. The efficiency as a function of power density is shown in **Figure 2c**. The efficiency increases at light load. The dotted line demonstrates above the maximum power regime.
- **Figure 2d** shows a typical efficiency characteristic of a complete fuel cell system in a vehicle, as a function of load power. It also compares with the thermal efficiency with a typical internal combustion engine (ICE) in a vehicle.



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Voltage (V)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Efficiency
0
0.5
1.0
1.5
(a)
J (A/cm^2)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
P (W/cm^2)
0.0
0.5
1.0
1.5
(b)
J (A/cm^2)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
Voltage (V)
0.0
0.2
0.4
0.6
(c)
P (W/cm^2)
0.6
0.5
0.4
0.3
0.2
0.1
0
Thermal efficiency
PEM system
ICE
0
25
50
75
d
(d)
Load (%)

Types of Fuel Cells

- **Hydrogen – Oxygen Fuel Cell**
- The hydrogen-oxygen fuel cell is one type of fuel cell. The half-reactions take place when hydrogen gas and oxygen gas are bubbled through two porous platinum-coated electrodes.
- Electrons flow from the negative pole to the positive pole via the external circuit. Their energy is used to power an electric motor or another device as they do so.
- A typical hydrogen fuel cell, for example, employs graphite electrodes embedded with platinum-based catalysts to accelerate the two half-cell reactions.

$H_2 + 1/2\ O_2 \rightarrow H_2$	$\Delta G_f = 229$ kJ/mol
$H_2 \rightarrow 2\ H^+ + 2\ e^-$	$E^0 = 0.00$ V
$O_2 + 4\ e^- + 4\ H^+ \rightarrow 2\ H_2O$	$E^0 = 1.2$V

Alkaline fuel cells

- These are devices in which the electrolyte is an aqueous solution of sodium hydroxide or potassium hydroxide. Almost always, the fuel is hydrogen gas, with oxygen (or oxygen in the air) acting as the oxidizer. However, if the by-product oxides were efficiently removed and the metal was fed continuously as a strip or powder, zinc or aluminum could be used as an anode.
- This was the fuel cell that served as the primary source of power for the Apollo space program.
- An aqueous alkaline solution is used in these cells to saturate a porous matrix, which is then used to separate the electrodes.
- Operating temperatures are quite low (approximately 90°C).
- These cells are extremely effective. Along with electricity, they generate heat and water.

Phosphoric acid fuel cells

- The electrolyte in these cells is orthophosphoric acid. Phosphoric acid which is used as an electrolyte in these fuel cells channels the H^+. On a small scale, phosphoric acid fuel cells have been proposed and tested for local municipal power stations as well as in remote-site generators.
- The electrodes are made of catalyzed carbon and are arranged in back-to-back pairs to form a series generation circuit.
- These cells operate at temperatures ranging from 150°C to 200°C.
- Because phosphoric acid is non-conductive, electrons must travel to the cathode via an external circuit.
- Because the electrolyte is acidic, the components of these cells corrode or oxidize over time.

Molten carbonate fuel cells

- The fuel is made up of a mixture of hydrogen and carbon monoxide produced by water and fo ssil fuel. Molten potassium lithium carbonate serves as the electrolyte. Molten carbonate fuel cells should be useful in both small and large power plants.
- An operating temperature of approximately 650 °C (1,200 °F) is required.
- Because of the high operating temperature and the presence of the carbonate electrolyte, the anode, and cathode of this cell are prone to corrosion.
- These cells can also run on carbon-based fuels like natural gas and biogas.

Solid oxide fuel cells

- Solid oxide fuel cells are similar to molten carbonate devices in some ways. However, the majority of the cell materials are special ceramics containing nickel. The electrolyte is a yttria-treated ion-conducting oxide such as zirconia. As with molten carbonate cells, the fuel for these experimental cells is thus expected to be hydrogen combined with carbon monoxide. While the path of the internal reactions would be different, the cell products would be water vapor and carbon dioxide.
- Solid oxide fuel cells would be designed for use in central power plants where temperature variation could be efficiently controlled and fossil fuels were available.
- These fuel cells are extremely efficient and relatively inexpensive (theoretical efficiency can even approach 85%).
- These cells' operating temperatures are extremely high (lower limit of 600°C, standard operating temperatures lie between 800°C and 1000°C).
- Because of their high operating temperatures, solid oxide fuel cells are only suitable for stationary applications.

Methanol Fuel Cell

- Methanol is a liquid fuel that can be produced through fermentation from renewable resources. The electrochemical reactions described below are used in direct methanol fuel cells:
- Carbon dioxide, a greenhouse gas, is produced during the electrochemical reaction. The anodic reaction necessitates the use of an expensive, precious metal catalyst. A typical alloy is a ruthenium and palladium. However, another disadvantage of this fuel cell is methanol’s toxicity.
- Methanol is also compatible with hydrogen fuel cells. Steam reforming methanol at 250 degrees Celsius produces CO_2, H_2, and a trace of CO.

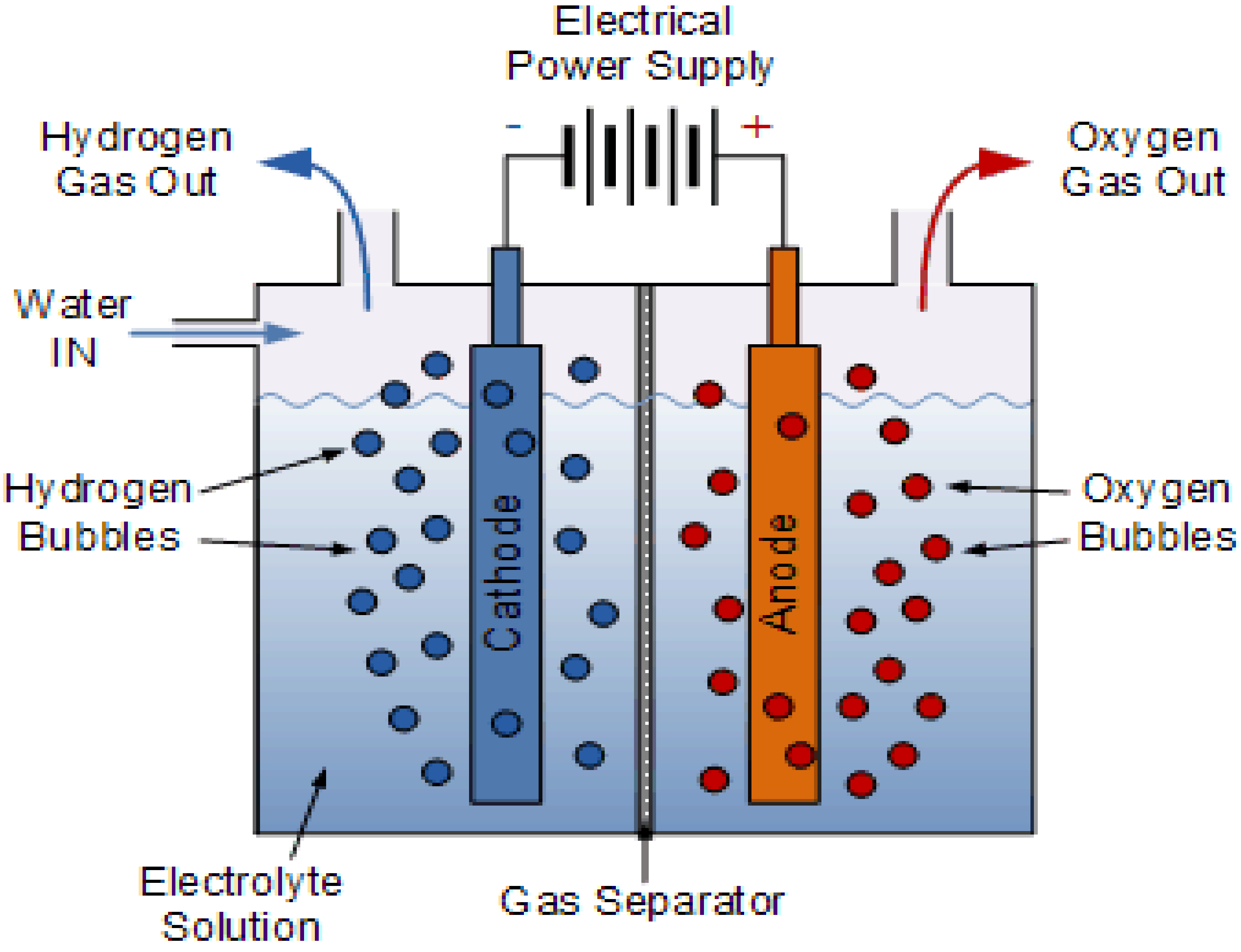
Fuel Cell Type	Electrolyte	Operating Temperature	Electrical Efficiency
Proton exchange membrane fuel cell (PEMFC)	Solid organic polymer polyper fluorosulphonic acid	50° C to 100° C	25% to 58%
Direct-methanol fuel cell (DMFC)	Polymer similar to PEMFC	50° C to 120° C	25% to 40%
Phosphoric acid fuel cell (PAFC)	Liquid phosphoric acid	150° C to 200° C	40% to 50%
Alkaline fuel cell (AFC)	Potassium hydroxide	100° C to 250° C	60% to 70%
Solid oxide fuel cell (SOFC)	Yttria-stabilized zirconia	600° C to 1,000° C	35% to 43%
Molten-carbonate fuel cell (MCFC)	Liquid solution of lithium sodium or potassium carbonates	600° C to 700° C	45% to 47%

Hydrogen Energy

- **Hydrogen Energy** can be used as alternative to the fossil fuel and many scientists around the world feel that hydrogen as a source of energy could be a permanent solution to the global crisis we are facing in our energy supplies.
- As Hydrogen (symbol, H) gas can be produced from water, it is therefore one of the lightest, most efficient, cost effective and cleanest fuel on the planet and as such has the great potential of being one of our primary fuels for powering our vehicles for a cleaner, greener future.
- Hydrogen is the simplest and most abundant element on Earth. A hydrogen atom consists of only one proton and one electron making it the first element in the periodic table, having an atomic number of just 1.
- But despite its simplicity and abundance, hydrogen does not occur naturally as a gas here on the Earth instead it is always combined with other elements.
- For example, water as H_2O. This is handy since over 72% of our planet is covered with water making the production of hydrogen as a source of energy highly sustainable, and a good candidate in our attempt to increase energy efficiency.

Producing Hydrogen Energy using Electrolysis

- Electrolysis is the process by which an electric current is passed through water and breaks the chemical bonds that exist between the hydrogen and oxygen atoms. The equipment used for doing this is called an “electrolyser”. An electrolyser basically consists of a positive element called the Anode (A), a negative element called the Cathode (K), both immersed in a liquid called an electrolyte which can carry a current.


Electrical
Power Supply
-
+
Hydrogen
Gas Out
Oxygen
Gas Out
Water
IN
Hydrogen
Bubbles
Cathode
Anode
Oxygen
Bubbles
Electrolyte
Solution
Gas Separator

- When an electrical voltage supply is connected to the two electrodes, an electrical current is passed through the conducting electrolyte causing electrons to flow from the anode (where oxidation occurs) to the cathode (where reduction occurs) breaking down the water into its constituent elements, of hydrogen and oxygen.
- A separator type membrane is used to separate the hydrogen's protons and electrons. In most cases water electrolysis is used to produce the hydrogen, but the electrolyte can also be a solution of water and acids or metal salts.
- The electrical current also breaks the molecular bonds between the atoms and once broken, the atomic particles (hydrogen and oxygen) become either positively or negatively charged and are free to move through the electrolyte.
- As the two electrodes are also positively and negatively charged from the battery supply, this attracts the free atoms towards them with the hydrogen atoms being attracted to the negative electrode forming bubbles of hydrogen gas.
- Generally, the positive hydrogen atoms gather at the anode (which is negative), while the negative oxygen ions reside at the cathode (which is positive). When the hydrogen and oxygen gases formed at either terminal and large enough they break free and rise to the surface were the hydrogen gas is collected and the oxygen gas is vented.
- Then we can see that electrolysis is a method of producing chemical energy (hydrogen and oxygen) by passing an electric current through a chemical substance called a watery electrolyte.

- **Benefits of Hydrogen Energy**
- **Environmental Sustainability:** When produced from renewable sources (green hydrogen), it produces zero harmful greenhouse gases, helping to combat climate change.
- **Energy Storage & Flexibility:** Acts as a long-duration energy storage medium to balance intermittent renewable sources like wind and solar.
- **High Efficiency:** Fuel cells coupled with electric motors are 2–3 times more efficient than internal combustion engines running on gasoline.
- **Energy Security:** Can be produced domestically from water, biomass, or natural gas, reducing reliance on imported fuels.
- **High Power Density:** Provides faster refueling and longer range for heavy-duty, long-distance transportation compared to batteries.

- **Primary Applications**
- **Transportation (Fuel Cells):** Powers fuel cell electric vehicles (FCEVs), including passenger cars, trucks, buses, trains, and ships.
- **Industrial Processes:** Used in refining petroleum, manufacturing fertilizer (ammonia), producing steel, and in glass/semiconductor manufacturing.
- **Power Generation:** Provides stationary electricity and heat for commercial, residential, and industrial use, including backup power for data centers.
- **Energy Storage & Grid Stability:** Stores excess renewable energy for later use, supporting grid reliability.
- **Heating:** Used for high-temperature industrial heating and potentially in residential heating systems.

problems associated with hydrogen energy

- **1. High Production Costs and Carbon Intensity**
- The "cleanliness" of hydrogen depends entirely on its production method, most of which are currently carbon-intensive or expensive.
- **Dominance of Fossil Fuels**: Approximately **99% of global hydrogen** (Gray Hydrogen) is currently produced from natural gas or coal, processes that emit more greenhouse gases than diesel or coal when the full lifecycle is considered.
- **Green Hydrogen Expense**: Producing hydrogen via electrolysis powered by renewables (Green Hydrogen) is currently **two to four times more expensive** than fossil-fuel-based methods ($2.28–$7.39/kg vs. $0.67–$1.31/kg).
- **Energy Efficiency**: The "well-to-wheel" efficiency is low. For instance, in transportation, converting electricity to hydrogen and then back to electricity in a fuel cell results in significant energy loss compared to using a battery-electric vehicle.

Storage and Transportation Hurdles

- Hydrogen's physical properties make it exceptionally difficult to handle compared to traditional fuels.
- **Low Energy Density**: Hydrogen has a very low volumetric energy density. To store a useful amount, it must be compressed to extremely high pressures (up to 700 bar) or liquefied at cryogenic temperatures (**-253°C**), both of which are energy-intensive processes.
- **Infrastructure Gaps**: Most existing pipelines and refueling stations are not compatible with hydrogen. Building a dedicated network is estimated to cost **over $500 billion** for even a partial transition in the U.S..
- **Hydrogen Embrittlement**: Hydrogen atoms can penetrate and weaken metals like steel, causing them to become brittle and prone to cracking or sudden failure.

- **3. Significant Safety Risks**
- Hydrogen presents unique hazards that complicate its use in public or residential settings.
- **High Flammability and Leakage**: It has a wide flammability range (4%–75% in air) and requires very low ignition energy—even a tiny static spark can trigger it. Its small molecular size also makes it highly prone to leaking through seals and materials.
- **Invisible Hazards**: Hydrogen burns with a **nearly invisible flame** and is odorless, making leaks and fires difficult to detect without specialized equipment.
- **Explosion Potential**: In confined spaces, leaked hydrogen can accumulate and lead to violent detonations with powerful shockwaves.

4. Environmental and Social Impacts

- **Resource Intensity**: Green hydrogen requires massive amounts of **fresh water** (roughly 9 liters of water per 1 kg of hydrogen), which poses challenges in water-scarce regions.
- **Pollutant Emissions**: While burning hydrogen doesn't produce CO2, it can produce **nitrogen oxides (NOx)**—a respiratory irritant—at rates up to six times higher than natural gas due to its high combustion temperature.
- **Global Warming Potential**: If hydrogen leaks into the atmosphere, it acts as an indirect greenhouse gas with a warming potential estimated to be **11 times greater than CO2**.
-

UNIT-IV

DISTRIBUTION SYSTEMS

1.Types of Electric Power Distribution Systems

The distribution system is classified as below;

1) According to the nature of the supply

- AC Distribution system
- DC Distribution system

2) According to a type of connection

- Radial system
- Ring system
- Interconnected system

3) According to a type of construction

- Overhead system
- Underground system

Let’s understand the classification of a distribution system in brief.

Classification According to Nature of Supply

There are two types of electric power; AC power and DC power. According to the type of power used in the distribution system, it is classified into AC distribution system and DC Distribution system.

AC Distribution System

In most of the conditions, the power consumer or load requires AC power. Therefore, the electric power is generated, transmitted, and distributed in the form of AC power. Because an AC voltage can be easily step up and step down with the help of a transformer.

According to the voltage level, the AC distribution system is further classified into two types;

- Primary distribution system
- Secondary distribution system

Primary Distribution System

The voltage level of a primary distribution system is higher than the utilization voltage level. In most cases, the primary distribution system uses a three-phase three-wire system and the voltage level is in the range of 3.3 kV, 6.6 kV, and 11 kV.

The primary distribution system supplies power to big consumers like industries or large commercial complexes, etc. The voltage level is stepped down at the utilization level by a step-down transformer. This transformer is placed near to the consumer premises.

The typical arrangement of a primary distribution system is as shown in the figure below.

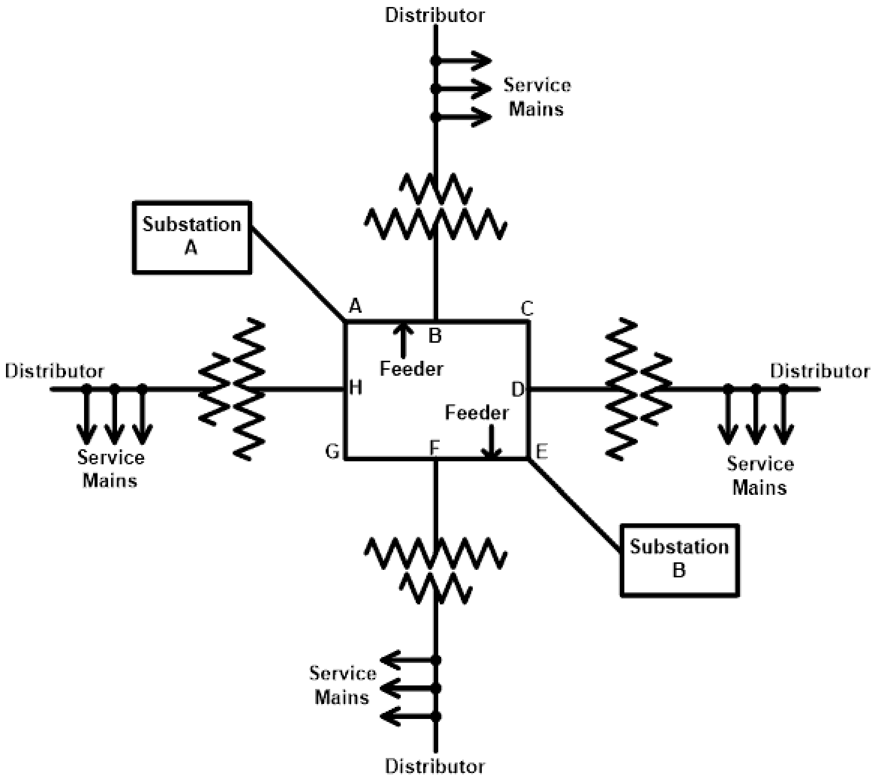


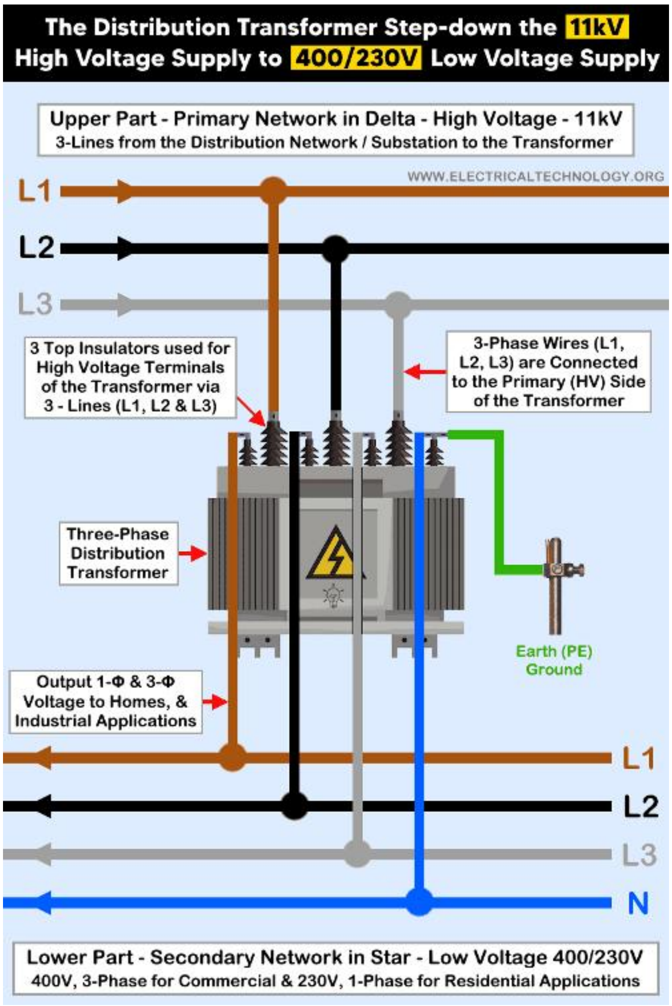
Fig-1: Primary Distribution System

Secondary Distribution System

In a secondary distribution system, the power is distributed at the utilization level. The primary distribution system ends with a transformer that is used to convert 11 kV to 415 V. And this power is directly distributed to the small consumers.

In most cases, the primary winding of this transformer is connected in delta connection and secondary winding is connected in star connection to provide a ground terminal. Therefore, the secondary distribution system uses a three-phase four-wire system.

Single-phase supply is taken by using any one phase with a neutral terminal that provides a voltage magnitude of 230V or 120V (according to country standards). For small shops and residential purposes, a single-phase supply is used.



Some consumers require three-phase supply like small scale industries, flour mills, etc. This type of consumer uses a three-phase supply by using R, Y, B, and N terminals. The arrangement for the secondary distribution network is shown in the figure below.

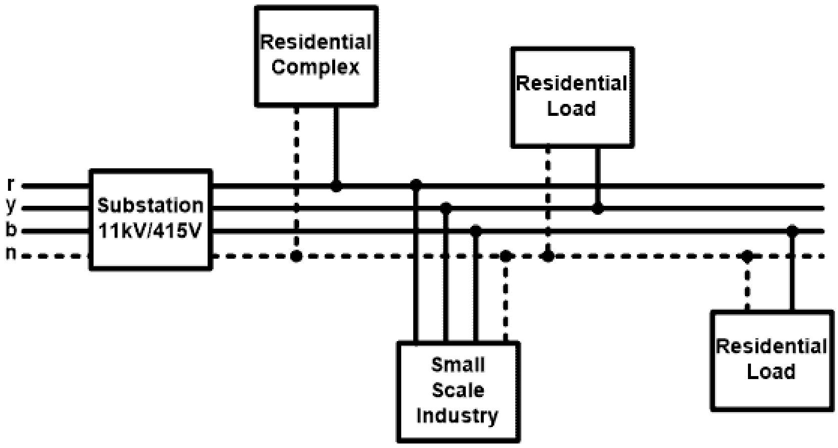


Fig-2: Secondary Distribution System

DC Distribution System

Most of the load connected to the power system is AC load. But there is a certain application where we required DC power. To fulfill these applications, we use DC power in the distribution system and this system is known as the DC distribution system.

In this condition, generated AC power is converted into DC power with the help of a rectifier or rotary converter. The applications where we need DC power are; traction purpose, DC motors, Battery charging, and electroplating.

According to the connection of DC system, it is classified into two types;

Two-wire DC Distribution System

This type of distribution system requires only two wires; one wire is at a positive potential level and the second wire is at a negative or zero potential levels. The wire connected with a positive potential level is known as a healthy wire.

The load is connected in parallel between two lines. Generally, the load connected in this system is lamp-load or motors. The load has only two terminals can be connected in this type of system. The connection diagram of this system is shown in the figure below.

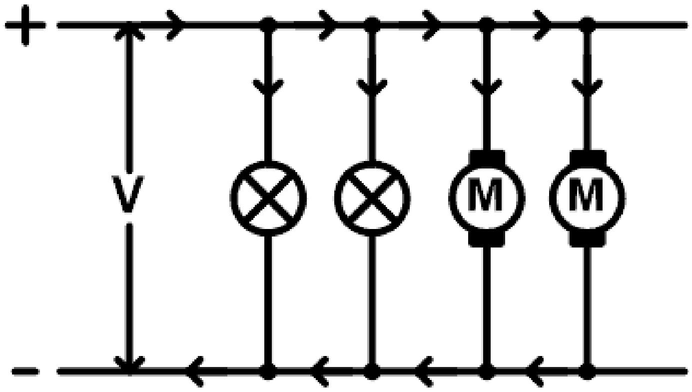


Fig-3: Two-wire DC Distribution System

Three-wire DC Distribution System

This type of distribution system requires three wires; two wires are healthy wires and one wire is the neutral wire. The main advantage of this system is that we have two voltage levels in this system.

Let say, two healthy wires are at a voltage level of +V and -V. The neutral wire is at zero potential networks. If a load is connected between one healthy wire and a neutral wire, the available voltage is V volt. And if a load is connected between both healthy wires, the available voltage is 2V volt.

Hence, the load requires a higher voltage that is connected between healthy wires, and the load requires a lower voltage that is connected between one healthy wire and a neutral wire. The connection diagram of a three-wire distribution system is as shown in the figure below.

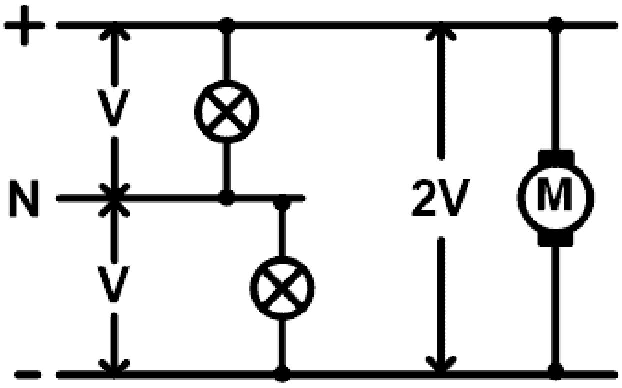


Fig-4: Three-wire DC Distribution System

Classification According to Method of Connection

The distribution system is classified into three types according to the method of connection;

- Radial system
- Ring main system
- Interconnected distribution system

Radial System

In a radial system, a separate feeder is used to feed power from the substation to each area. And this feeder feeds power to a distributor in one direction only. The design of the radial system is simple and easy to implement in the system.

The initial cost of this system is less compared to other systems. But the reliability of this system is very low. If one feeder is out of step condition, the entire system will stop. This type of system is only used for a short-distance distribution system.

The consumer far from the feeder may suffer poor voltage regulation and voltage fluctuation with a variation of load. Due to this advantage, this type of system is only used to supply the load which is near to the feeder. The single line diagram of the radial system is shown in the figure below.

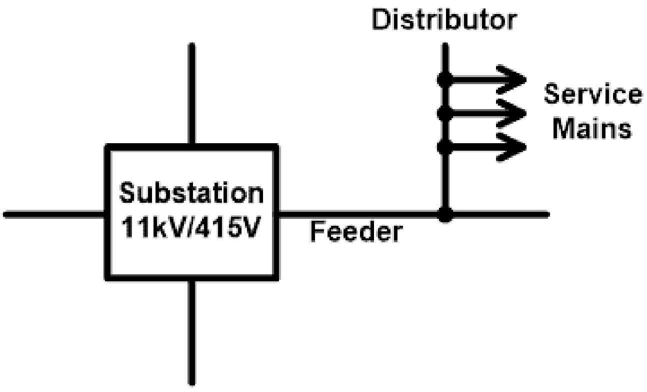


Fig-5: Radial System

Ring Main System

In the ring main system, the distribution transformer is connected in a loop and supplied by a substation from one end. It means each distribution transformer has two different ways to connect with the substation. A single-line diagram of the ring main system is shown in the figure below.

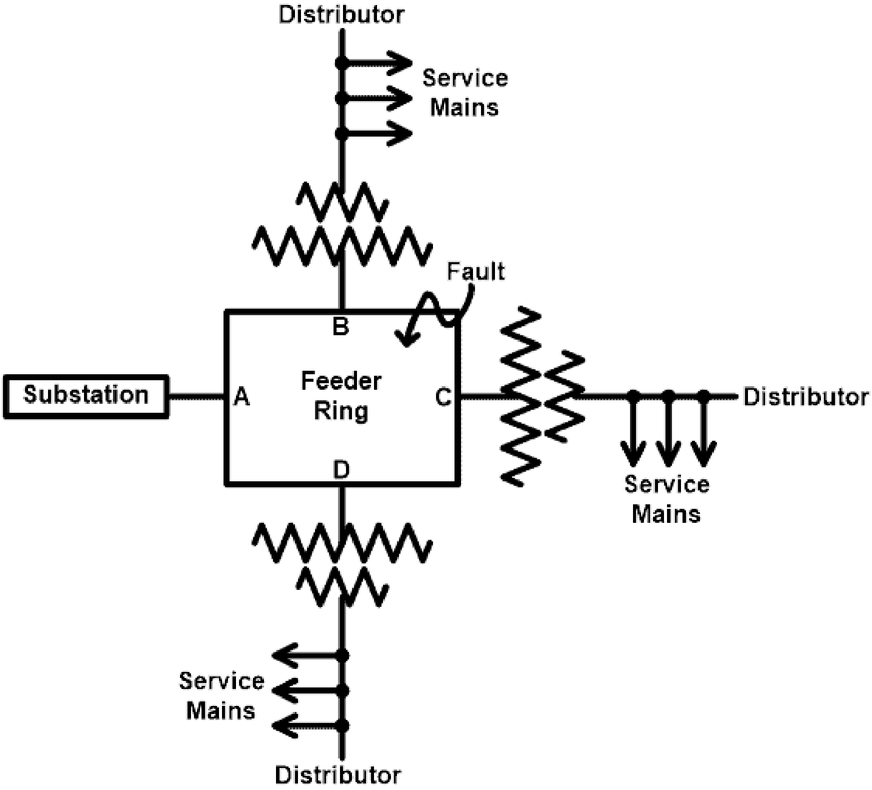


Fig-6: Ring Main System

We can compare this arrangement with two feeders connected in parallel. For example, if a fault occurs between B and C points. In this condition, the part between B and C will isolate from the system. And substation supply power in two different ways.

It makes the system more reliable. And there is less voltage fluctuation at the consumer’s end. Each part of the ring carries less current. So, less conductor material is required compared to radial system.

Interconnected Distribution System

In an interconnected distribution system, a loop is supplied by more than one substation at different points. This system is also known as a grid distribution system. The single-line diagram of the interconnected system is shown in the figure below.

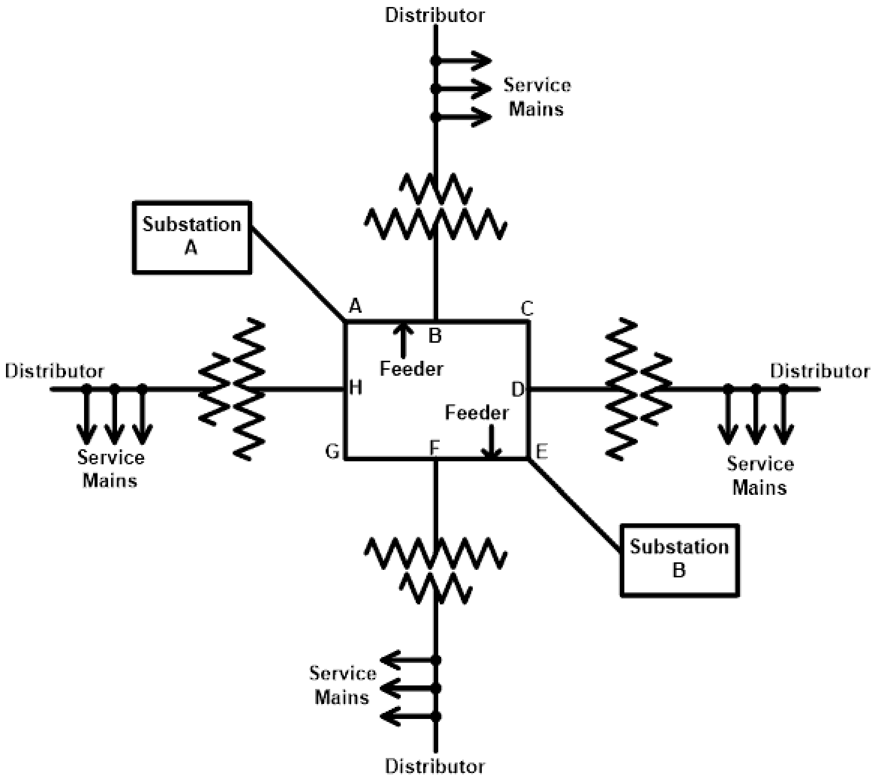


Fig-7: Interconnected Distribution System

As shown in the above figure, loop ABCDEFGHA is supplied by two substations at points A and E. Due to this type of arrangement, the reliability of the system increases compared to the ring main and radial system.

The design of the interconnected system is very difficult and the initial cost of the system is also high as a greater number of substations are required in a system. But this system has the advantage of good power quality and a more efficient system. This system reduces reserve power capacity.

Classification of Distribution System According to Type of Construction

According to the construction of distribution system is classified into two types;

- Underground distribution system
- Overhead distribution system

Underground Distribution System

As the name suggests, in this type of system, the conductors are placed under the surface of streets or sidewalks. The underground distribution system is safer than the overhead distribution system. But the initial cost of the underground system is very high. Because it requires trenching, conduits, manholes, and special cables.

In this system, the cables lie under the streets. Hence, there are fewer chances of the fault and it gives a good appearance as cables are invisible. When a fault occurs in the underground system, it is difficult to locate and also it is difficult to repair. The life of an underground system is very long. The useful life of this system is more than 50 years.

Overhead Distribution System

In the overhead distribution system, the conductors are mounted on wooden, concrete, or steel poles. This system is also known as a conventional system for the distribution network. The conductor is placed on the poles, there are more chances of fault and hazards compared to the underground distribution system.

But the initial cost of the overhead system is less. The overhead transmission system is more flexible compared to the underground system. Because this system is permanently placed once installed. Hence, it is easy for load expansion and laying a new line. The conductors are placed over the surface. So, the appearance of this system is not good as an underground distribution system.

In the overhead system, the conductors are placed with taking proper space. Hence, the air is used as an insulation medium. So, it does not require special insulated cables. The current carrying capacity of the overhead system is higher compared to the underground system.

It is easy to install the overhead system. And also, when a fault occurs, it is easy to locate and repair a fault. Hence, the maintenance cost of the overhead system is very less. There are chances of interference with a communication system. The useful life of an overhead system is more than 25 years.

Compression between Underground Cables and Overhead Lines

Underground Cables	Overhead Lines
Protected from storms and lightning	Unprotected from wind, birds, and lightning
Faults are frequent	Relatively few faults occur
Fault detection is difficult	The fault is easily traced
Fault finding and repair costs are high	Repair costs are relatively low
Risk of public accidents is low	Risk of public accidents exists
Installation and laying cables are difficult	They are easier to install
The cost of laying cables is very high	The installation is less costly
Appears visually more attractive and	The visual appearance is not pleasing

aesthetically pleasing	
Do not interfere with communication cables	Interference with communication lines
There is no problem of crossing the road	The crossing problem occurs
Low Inductive Voltage drop	High voltage drop
Not suitable to be used for long distances	They can be used for even longer distances
Preferred to use in densely populated areas	Not recommended to use in densely populated areas
Reliable and strong	Strong and reliable
Less space is required to accommodate the same level of transmission voltage	Requires more space due to supporting structures and lines
Low current carrying capacity	Current carrying capacity is relatively high
Low inductive reactance	High inductive reactance
High capacitive reactance	Low capacitive reactance
Useful life expectancy is longer	Useful life is comparably low
Difficult to draw tapings	Tapings can be easily drawn
Due to excessive voltage drop, they are relatively less preferred for voltage regulation	Due to the close proximity of cable conductors, it results in lower inductive drop, making the cable preferable for voltage

	regulation in AC systems

2.Requirements of a Distribution System:

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the good Requirements of a Distribution System are :

1. **Proper voltage**
2. **Availability of power on demand**
3. **Reliability**

1.Proper voltage: One important Requirements of a Distribution System is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumers terminals are within permissible limits. The statutory limit of voltage variations is ± 6% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

2.Availability of power on demand: Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the Requirements of a Distribution System must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

3.Reliability: Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by

- **interconnected system**
- **reliable automatic control system**
- **providing additional reserve facilities.**

3.Design Considerations in Distribution System:

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

1.Feeders: A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

2.Distributors: A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer’s terminals (± 6% of rated value). The size and length of the distributor should be such that voltage at the consumer’s terminals is within the permissible limits.

4.TYPES OF CABLES

1 Based on Voltage Rating

1. **Low Tension (LT) Cables**
    - Voltage rating: Up to 1 kV
    - Used in domestic and commercial wiring.
2. **High Tension (HT) Cables**
    - Voltage rating: 1 kV – 11 kV
    - Used in distribution systems.
3. **Super Tension (ST) Cables**
    - Voltage rating: 22 kV – 33 kV
4. **Extra High Tension (EHT) Cables**
    - Voltage rating: 33 kV – 66 kV
5. **Extra Super Voltage (ESV) Cables**
    - Above 132 kV
    - Used in power transmission.

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2 Based on Number of Cores

1. **Single-core cable**
2. **Two-core cable**
3. **Three-core cable**
4. **Four-core cable**
5. **Multicore cable**

Used depending on single-phase or three-phase supply.

3️⃣ Based on Insulation Material

1. **PVC (Polyvinyl Chloride) Cables**
    - Most common for house wiring
    - Moisture and chemical resistant
2. **XLPE (Cross-linked Polyethylene) Cables**
    - High thermal capacity
    - Used in HT and EHT systems
3. **Rubber Insulated Cables**
    - Flexible
    - Used in portable equipment
4. **PILC (Paper Insulated Lead Covered) Cables**
    - Used in old underground systems
5. **Mineral Insulated Cables**
    - Fire resistant
    - Used in hospitals and industries

4️⃣ Based on Construction

1. **Belted Cables**
    - Used up to 11 kV
2. **Screened Cables**
    - H-type
    - SL-type
3. **Pressure Cables**
    - Oil-filled cables
    - Gas-pressure cables

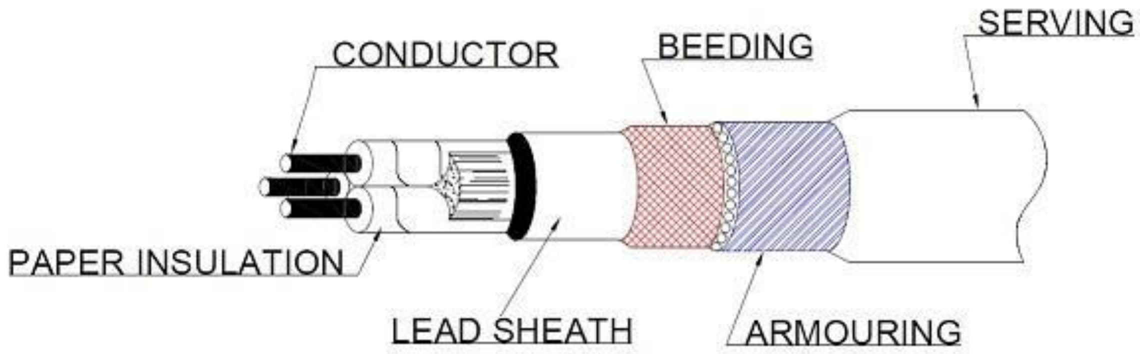
5️⃣ Based on Application

1. **Power Cables** – For transmission and distribution
2. **Control Cables** – For control circuits
3. **Instrumentation Cables** – For signal transmission
4. **Communication Cables** – Telephone, data
5. **Submarine Cables** – Laid underwater
6. **Aerial Bunched Cables (ABC)** – Overhead distribution

6 Special Purpose Cables

- Fire-resistant cables
- Armoured cables
- Flexible cables
- Coaxial cables
- Optical fiber cables

5.CONSTRUCTION OF CABLES



Cores or Conductors

The number of core or conductors in a cable depends upon its use. For example, a three core cable is used for three phase system. The conductors are made of tinned copper or aluminum and are stranded to provide flexibility.

Insulation

A suitable thickness of insulation is provided on each core or conductor so that the conductors of underground cable may withstand the operating or designed voltage. The thickness of insulation on the core increases as the operating or design voltage is increased. Normally the insulation materials are made of impregnated paper, varnish cambric or rubber mineral compound.

Metallic Sheath

Metallic sheath surrounds the insulation on the core. It is provided to protect the insulation from moisture, gases, oil, liquids etc. present in the soil and atmosphere. It is normally made of lead or aluminum.

Bedding

Bedding surrounds the sheath. It is made of fibrous materials like jute or hessian tape. The purpose of bedding is to protect the sheath from mechanical injury due to armouring. You can think it like a shock absorber.

Armouring

Armouring is provided over the bedding to protect the cable from mechanical injury during its handling and lying. It consists of one or two layers of galvanized steel wire or steel tape. In some cable, armouring is not provided.

Serving

To protect the armouring from atmospheric condition, a layer of fibrous material like jute is applied on the armouring. This layer is called serving.

Thus, we observe that the main working part of underground cable are core / conductor and Sheath. Other parts of cable, just protect the conductor and sheath from mechanical injury or chemical attack. This does not mean that, they are not important. Bedding, Armouring and Servings are very important parts of cable else cable won�t work as its insulation will degrade.

6.Insulation Resistance of a Single-Core Cable

- The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current.

- The path for leakage current is radial through the insulation. The opposition offered by insulation to leakage current is known as insulation resistance of the cable.

- For satisfactory operation, the insulation resistance of the cable should be very high.

- Consider a single-core cable of conductor radius r1 and internal sheath radius r2 as shown in Fig. 11.12. Let l be the length of the cable and ρ be the resistivity of the insulation.

- Consider a very small layer of insulation of thickness dx at a radius x. The length through which leakage current tends to flow is dx and the area of X-section offered to this flow is 2π x l. ∴ Insulation resistance of considered layer

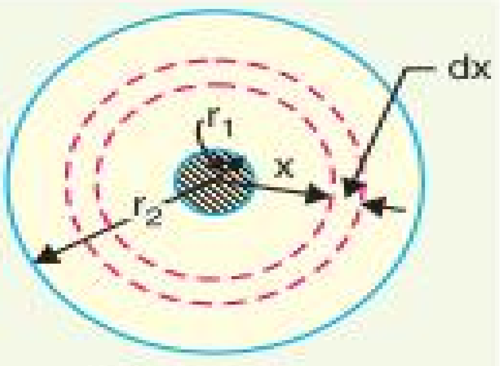


Fig. 11.12

∴ Insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_1}^{r_2} \frac{1}{x} dx$$

$$\therefore \qquad R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$

7.Capacitance of a Single-Core Cable

- A single-core cable can be considered to be equivalent to two long co-axial cylinders.
- The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential.
- Consider a single core cable with conductor diameter d and inner sheath diameter D (Fig. 11.13).
- Let the charge per metre axial length of the cable be Q coulombs and ε be the permittivity of the insulation material between core and lead sheath.
- Obviously *$\varepsilon = \varepsilon 0 \, \varepsilon r$ where εr is the relative permittivity of the insulation.
- Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is $= 2 \pi x \times 1 = 2 \pi x$ m 2

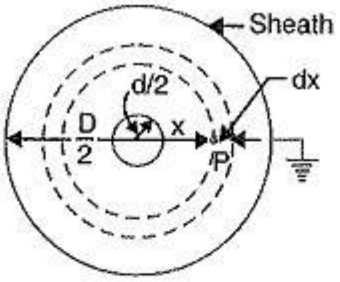


Fig. 11.13

∴ Electric flux density at any point P on the considered cylinder is

$$D_x = \frac{Q}{2\pi x} \text{ C/m}^2$$

Electric intensity at point P, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}$ volts/m

The work done in moving a unit positive charge from point P through a distance dx in the direc-ion of electric field is $E_x\,dx$. Hence, the work done in moving a unit positive charge from conductor o sheath, which is the potential difference V between conductor and sheath, is given by :

$$V = \int_{d/2}^{D/2} E_x\,dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}\,dx = \frac{Q}{2\pi\varepsilon_0\,\varepsilon_r} \log_e \frac{D}{d}$$

Capacitance of the cable is

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\,\varepsilon_0\varepsilon_r}\log_e \frac{D}{d}} \text{ F/m}$$

$$= \frac{2\pi\,\varepsilon_o\varepsilon_r}{\log_e(D/d)} \text{ F/m}$$

$$= \frac{2\pi\times 8\cdot 854\times 10^{-12}\times\varepsilon_r}{2\cdot 303\,\log_{10}(D/d)} \text{ F/m}$$

$$= \frac{\varepsilon_r}{41\cdot 4\,\log_{10}(D/d)}\times 10^{-9} \text{ F/m}$$

If the cable has a length of l metres, then capacitance of the cable is

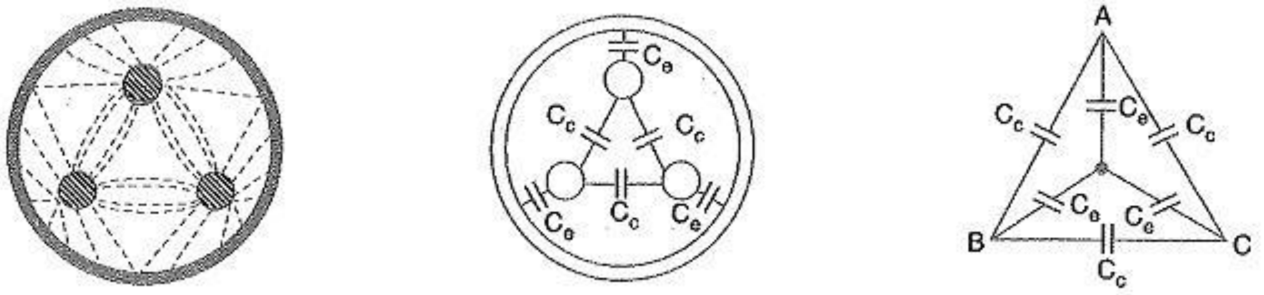
$$C = \frac{\varepsilon_r\ l}{41\cdot 4\,\log_{10}\frac{D}{d}}\times 10^{-9} \text{ F}$$

8.Capacitance of 3 Core Cables:

The Capacitance of 3 Core Cables is much more important than that of overhead line because in cables

(i) conductors are nearer to each other and to the earthed sheath
(ii) they are separated by a dielectric of permittivity much greater than that of air.

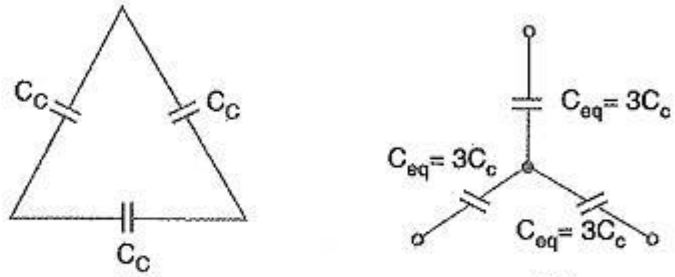
Fig. 11.18 shows a system of capacitances in a 3-core belted cable used for 3-phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig. 11.18 (i). These electrostatic fields give rise to core-core capacitances C_c and conductor-earth capacitances C_e as shown in Fig. 11.18 00. The three C_c are delta connected whereas the three C_e are star connected, the sheath forming the star point [See Fig. 11.18 (W)].



(i) (ii) (iii)

Fig. 11.18

They lay of a belted cable makes it reasonable to assume equality of each C_c and each C_e. The three delta connected capacitances C_c [See Fig. 11.19 (0] can be converted into equivalent star connected Capacitance of 3 Core Cables as shown in Fig. 11.19 (ii). It can be easily shown that equivalent star capacitance C_{eq} is equal to three times the delta-capacitance C_c i.e. $C_{eq}=3C_c$.



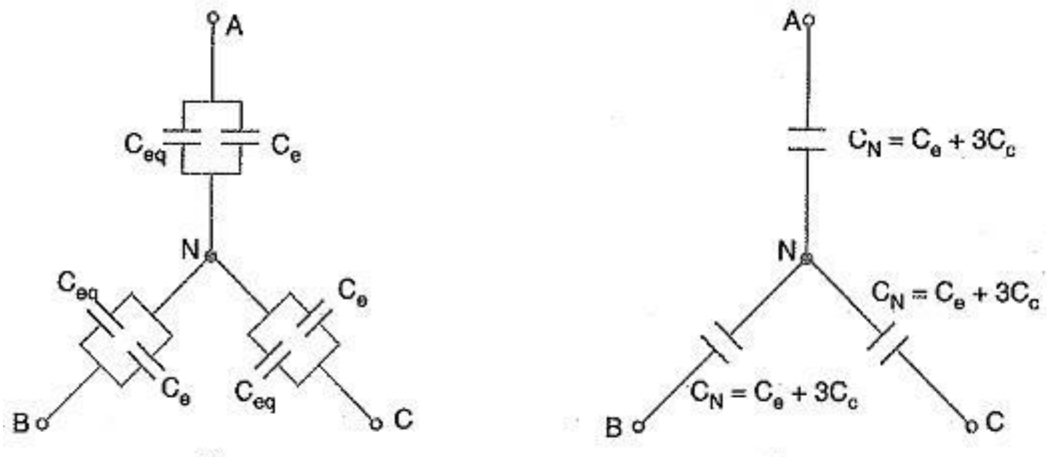
(i) (ii)

Fig. 11.19

The system of Capacitance of 3 Core Cables shown in Fig.11.18

(iii) reduces to the equivalent circuit shown in Fig. 11.20 (i).

Therefore, the whole cable is equivalent to three star-connected capacitors each of Capacitance of 3 Core Cables [See Fig. 11.20 (ii)],



(*i*) (*ii*)

Fig. 11.20

$$C_N = C_e + C_{eq}$$
$$= C_e + 3C_c$$

If V_{ph} is the phase voltage, then charging current I_C is given by ;

$$I_C = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$
$$= 2\pi f V_{ph} C_N$$
$$= 2\pi f V_{ph} (C_e + 3C_c)$$

Measurements of C_e and C_c

Although core-core capacitance C_c and core-earth capacitance C_e can be obtained from the empirical formulas for belted cables, their values can also be determined by measurements. For this purpose, the following two measurements are required :

(i) In the first measurement, the three cores are bunched together (i.e. commoned) and the capacitance is measured between the bunched cores and the sheath. The bunching eliminates all the three capacitors C_c, leaving the three capacitors C_e in parallel. Therefore, if C_1 is the measured capacitance, this test yields :

$$C_1 = 3\,C_e$$
$$C_e = \frac{C_1}{3}$$

Knowing the value of C_1, the value of C_e can be determined.

(ii) In the second measurement, two cores are bunched with the sheath and capacitance is measured between them and the third core. This test yields $2C_c + C_e$. If C_2 is the measured Capacitance of 3 Core Cables, then,

$$C_2 = 2C_c + C_e$$

As the value of C_e is known from first test and C_2 is found experminentally, therefore, value of C_c can be determined.

It may be noted here that if value of $C_N (= C_e + 3C_c)$ is desired, it can be found directly by another test. In this test, the capacitance between two cores or lines is measured with the third core free or connected to the sheath. This eliminates one of the capacitors C_e so that if C_3 is the measured Capacitance of 3 Core Cables, then,

$$\begin{aligned} C_3 &= C_c + \frac{C_c}{2} + \frac{C_e}{2} \\ &= \frac{1}{2}(C_e + 3C_c) \\ &= \frac{1}{2}C_N \end{aligned}$$

Current Carrying Capacity of Underground Cables

The safe current-carrying capacity of an underground cable is determined by the maximum permissible temperature rise. The cause of temperature rise is the losses that occur in a cable which appear as heat. These losses are

- **Copper losses in the conductors**
- **Hysteresis losses in the dielectric**
- **Eddy current losses in the sheath**

The safe working conductor temperature is 65°C for armoured cables and 50°C for lead-sheathed cables laid in ducts. The maximum steady temperature conditions prevail when the heat generated in the cable is equal to the heat dissipated. The heat dissipation of the conductor losses is by conduction through the insulation to the sheath from which the total losses (including dielectric and sheath losses) may be conducted to the earth. Therefore, in order to find permissible current loading, the thermal resistivities of the insulation, the protective covering and the soil must be known.

9.Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity e_r of any layer is inversely proportional to its distance from the centre. Under such conditions, the value of potential gradient at any point in the dieletric is constant and is independent of its distance from the centre. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. However, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity ; the dielectric of highest permittivity being used near the core.

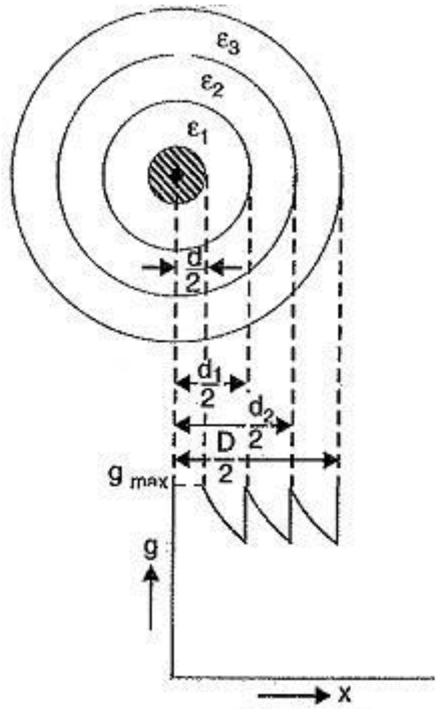


Fig. 11.15

The capacitance grading can be explained beautifully by retelling to Fig. 11.15. There are three dielectrics of outer diameter d_1, d_2 and D and of relative permittivity ε_1,ε_2 and ε_3 respectively. If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1\dagger}{\varepsilon_3 d_2}$$

$$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\,dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\varepsilon_0\varepsilon_1 x}dx$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1}\log_e\frac{d_1}{d} = \frac{g_{max}}{2}d\log_e\frac{d_1}{d}\left[\because \frac{Q}{2\pi\varepsilon_0\varepsilon_1} = \frac{{}^*g_{max}}{2}d\right]$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by ;

$$V_2 = \frac{g_{max}}{2}d_1\log_e\frac{d_2}{d_1}$$

$$V_3 = \frac{g_{max}}{2}d_2\log_e\frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ &= \frac{g_{max}}{2}\left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2}\right] \end{aligned}$$

If the cable had:homogeneous dielectric then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

Obviously, V > V′ i.e., for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable. Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable. The following points may be noted :

- **As the permissible values of g_{max} are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.**
- **If the maximum stress in the three dielectrics is not the same, then,**

$$V = \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3max}}{2} d_2 \log_e \frac{D}{d_2}$$

The principal disadvantage of this method is that there are a few high grade dielectrics of reasonable cost whose permittivities vary over the required range.

10.Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into, various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at suitable potentials which are inbetween the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

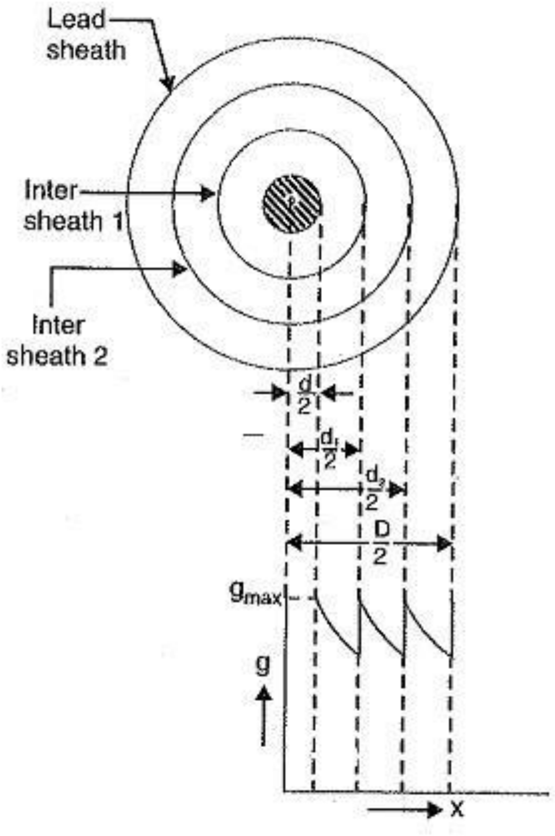


Fig. 11.17

Consider a cable of core diameter d and outer lead sheath of diameter D. Suppose that two intersheaths of diameters d_1 and d_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let V_1, V_2 and V_3 respectively be the voltage between core and intersheath I, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each intersheath, therefore each sheath can be treated like a homogeneous single core cable.

Maximum stress between core and intersheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same i.e.,

$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\frac{V_1}{\frac{d}{2}\log_e\frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e\frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e\frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase i.e. Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

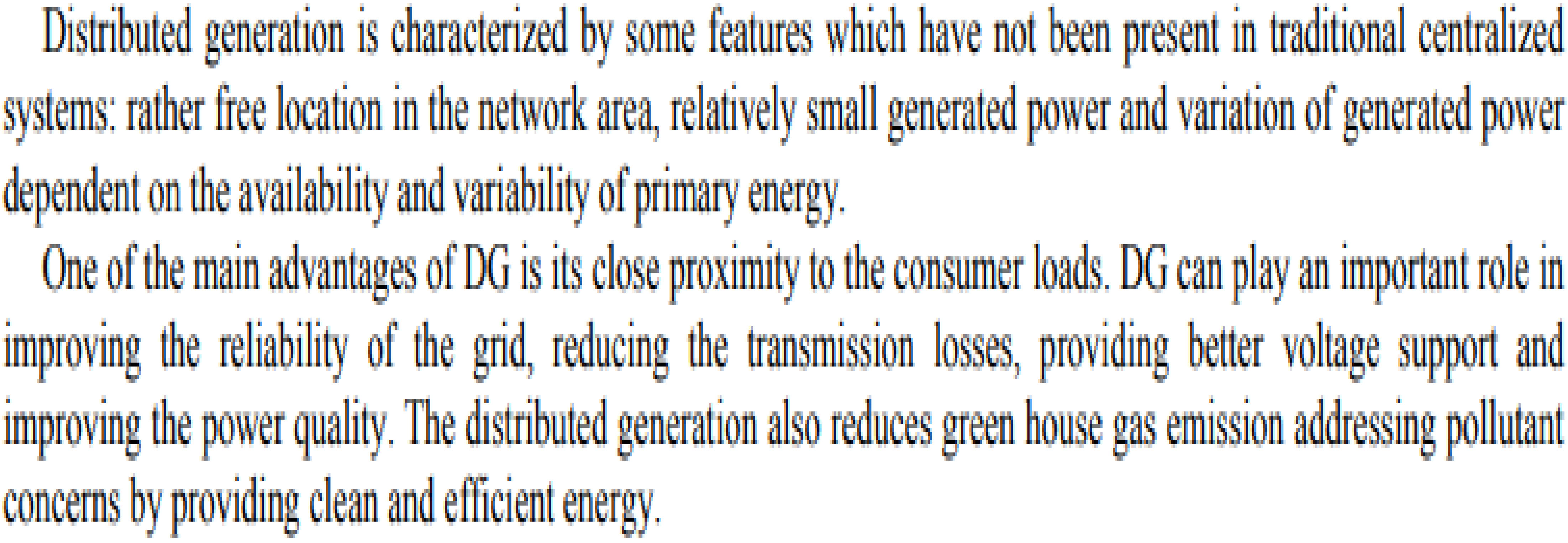
Intersheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the intersheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the intersheaths due to charging currents. For these reasons, intersheath grading is rarely used.

UNIT-V

UNIT – V: GRID INTEGRATION OF DGS AND TECHNICAL IMPACTS OF DGS

DG Impact on - Transmission and Distribution systems, De-regulation – Impact of DGs upon protective relaying –Impact of DGs upon transient and dynamic stability of existing distribution systems

DG Impact on - Transmission and Distribution systems



Distributed generation is characterized by some features which have not been present in traditional centralized systems: rather free location in the network area, relatively small generated power and variation of generated power dependent on the availability and variability of primary energy.

One of the main advantages of DG is its close proximity to the consumer loads. DG can play an important role in improving the reliability of the grid, reducing the transmission losses, providing better voltage support and improving the power quality. The distributed generation also reduces green house gas emission addressing pollutant concerns by providing clean and efficient energy.

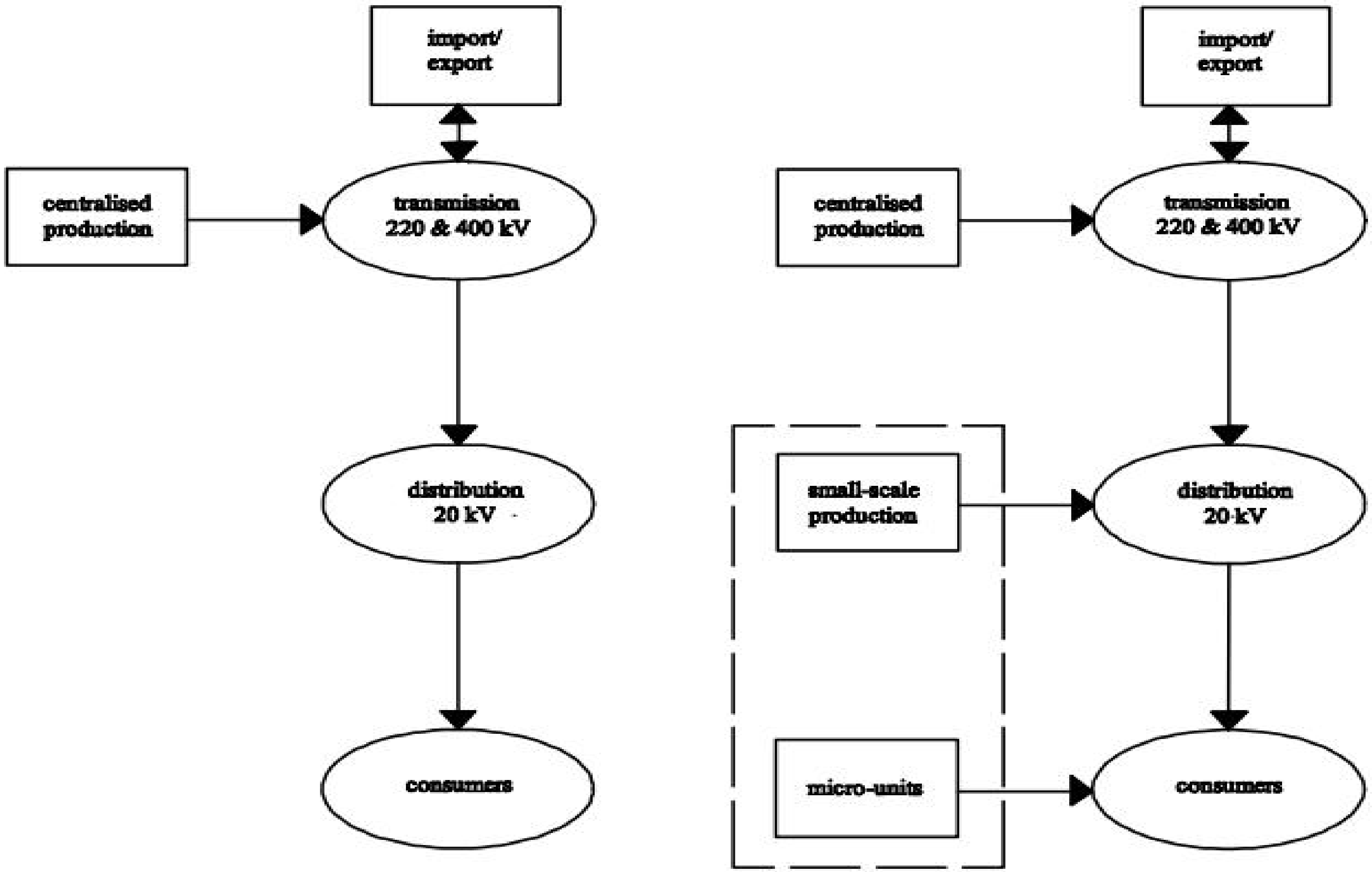


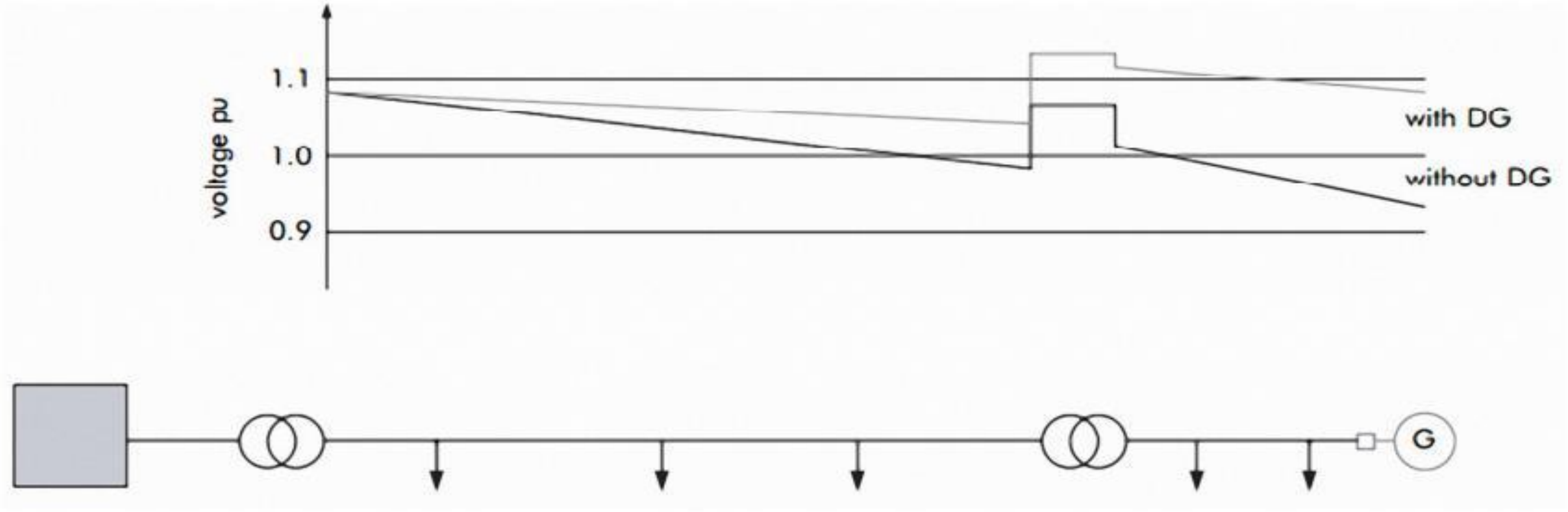
Fig. 1. A unidirectional centrally delivered power generation system (left) and a bidirectional system with distributed generation (right)

Operation and control

Change of short circuit capacity

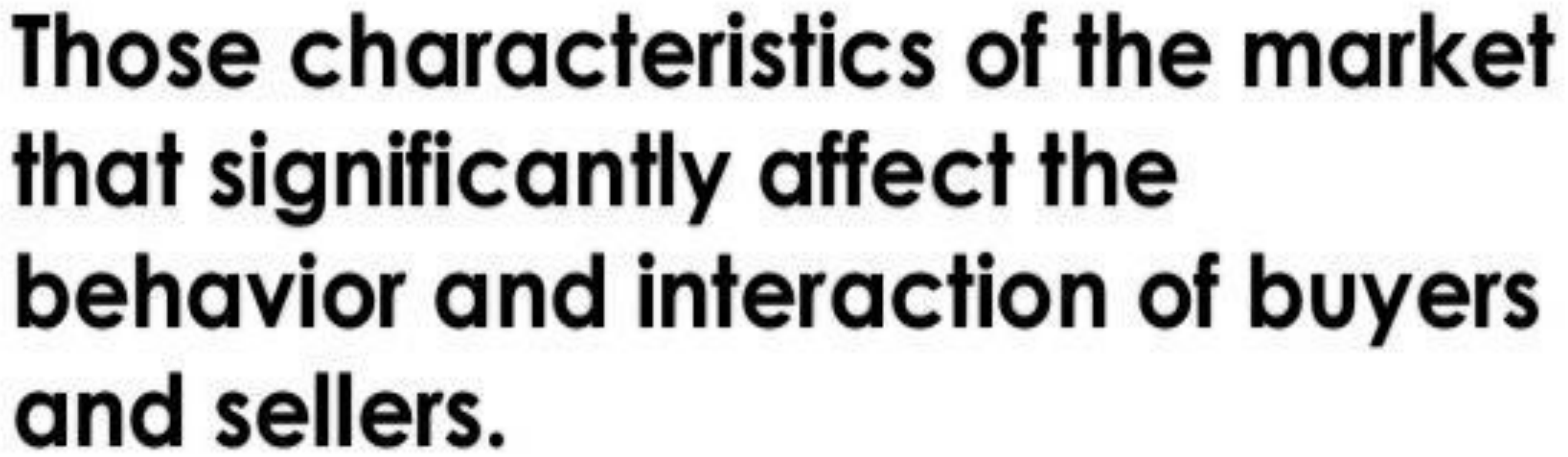
Stability

Voltage level of integration and interconnection



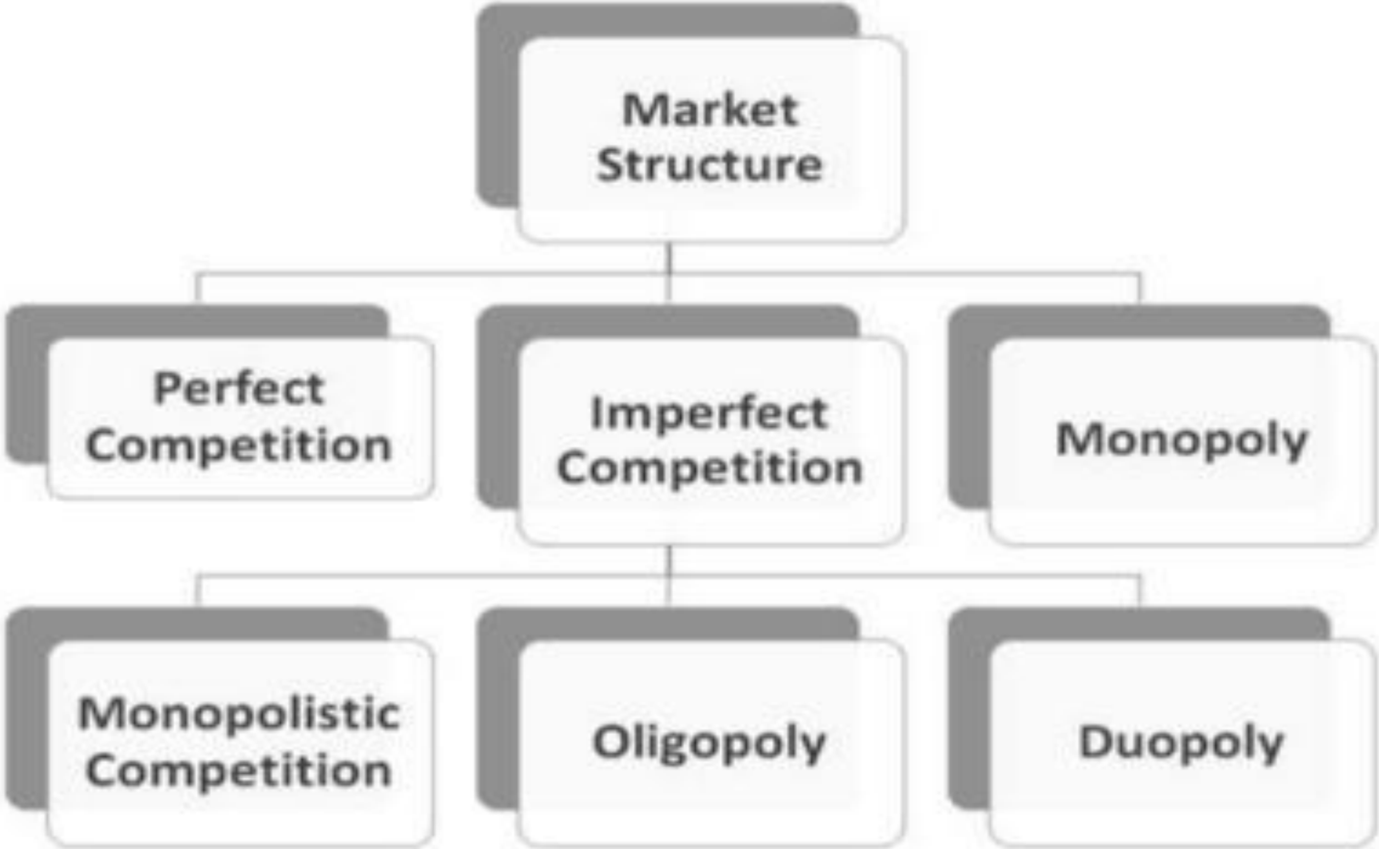
Deregulation

What is Market Structure?



Those characteristics of the market that significantly affect the behavior and interaction of buyers and sellers.

Market Structure



Market Structure

Perfect Competition

Imperfect Competition

Monopoly

Monopolistic Competition

Oligopoly

Duopoly

Deregulation in Power Industry

The goal of changing the way of operation, i.e. re-regulation, or deregulation, as we say, is to enhance competition and bring consumers new choices and economic benefits.

Under Deregulation, the former vertically integrated utility, which performed all the functions involved in power, i.e. generation, transmission, distribution and retail sales, is dis-aggregated into separate companies devoted to each function. The electricity bill for the end consumer now involves at least two components: one from the distribution and transmission network-operator responsible for the network and services, and the other from the company that generates the electrical energy.

- **Regulation:** *Regulation means that the Government has set down laws and rules that put limits on and define how a particular industry or company can operate.*

- **Deregulation:** *Deregulation in power industry is a restructuring of the rules and economic incentives that government set up to control and drive the electric power industry.*

Under deregulated environment, the electric utility will always try to innovate something for the betterment of service and in turn save its costs and maximize the profit. By means of this, the utility will try to ensure that it will maintain its customer base in spite of competition.

Some other forces supporting the main reasons for motivating the deregulation can also be enlisted as follows:

1. Overstaffing in the regulated electric industry.
2. Global economic crisis
3. Political and ideological changes
4. Managerial inefficiency in the regulated company
5. Lack of public resources for the further development
6. More demanding environment issues
7. Pressure of financial institutes

A typical structure of a vertically integrated electric utility is shown in figure (1).

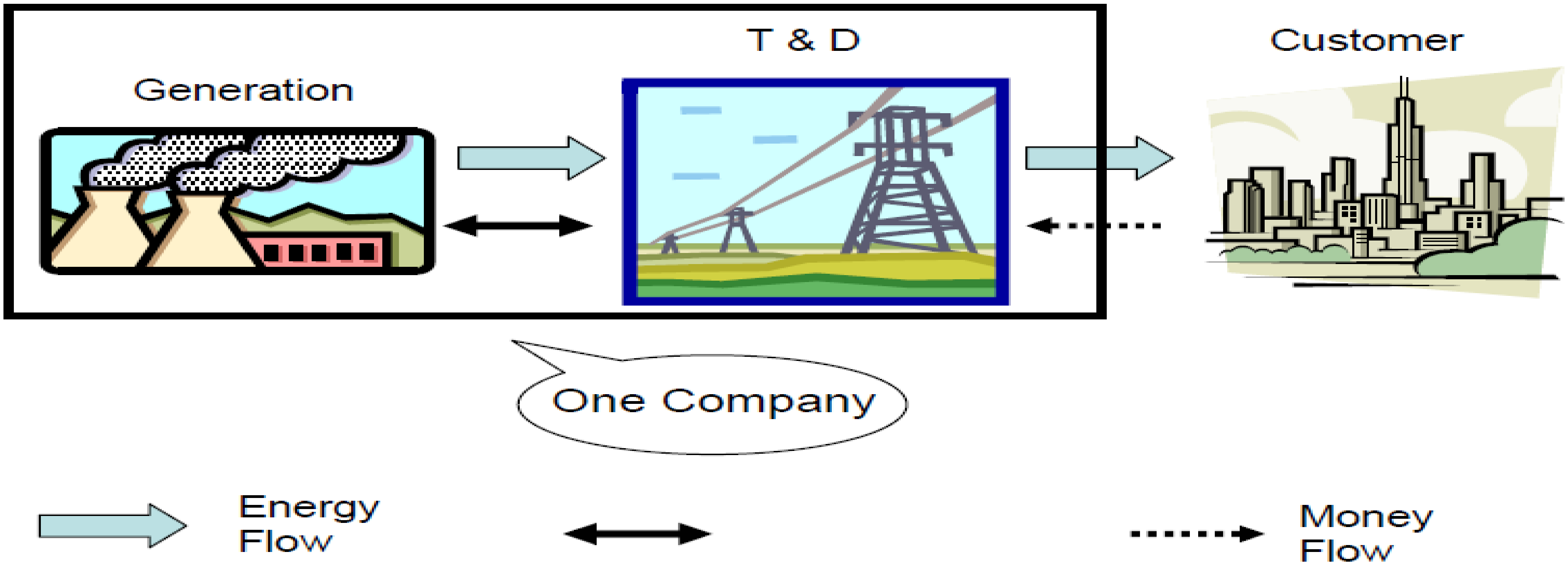


Figure 1

In figure (1), the money flow is unidirectional, i.e. from the consumer to the electric company. Similarly, the information flow exists only between the generators and the transmission systems.

The utilities being vertically integrated, it was often difficult to segregate the costs involved in generation, transmission or distribution. So, the utilities often charged their customers an average tariff rate depending on their aggregated cost during a period.

Under deregulation, the vertically integrated utility, one giant company that generates, transmits, distributes and sells electricity in coordinated manner will become thing of the past. To function in an open access system, such utilities will have to rearrange their operational organization to match the unbundled functions they must perform. Each part of the company will need to work in its new form. Generation will have to compete in the competitive power generation market place. T & D will have to operate as an open provider of delivery services. Competition will be present in retailing.

Generally, the governments advocating deregulation want competition in energy production, and they want to see significant levels of customer choice in the retail market for electricity. At the same time, it recognizes that it is best to have only one transmission and one distribution system in any one area. Therefore, the purpose of deregulation is to restructure the electric industry so that power production and retail sales are competitive, while delivery is still a regulated, monopoly franchise business.

Figure (2) shows the typical structure of a deregulated electricity system with links of information and money flow between various players.

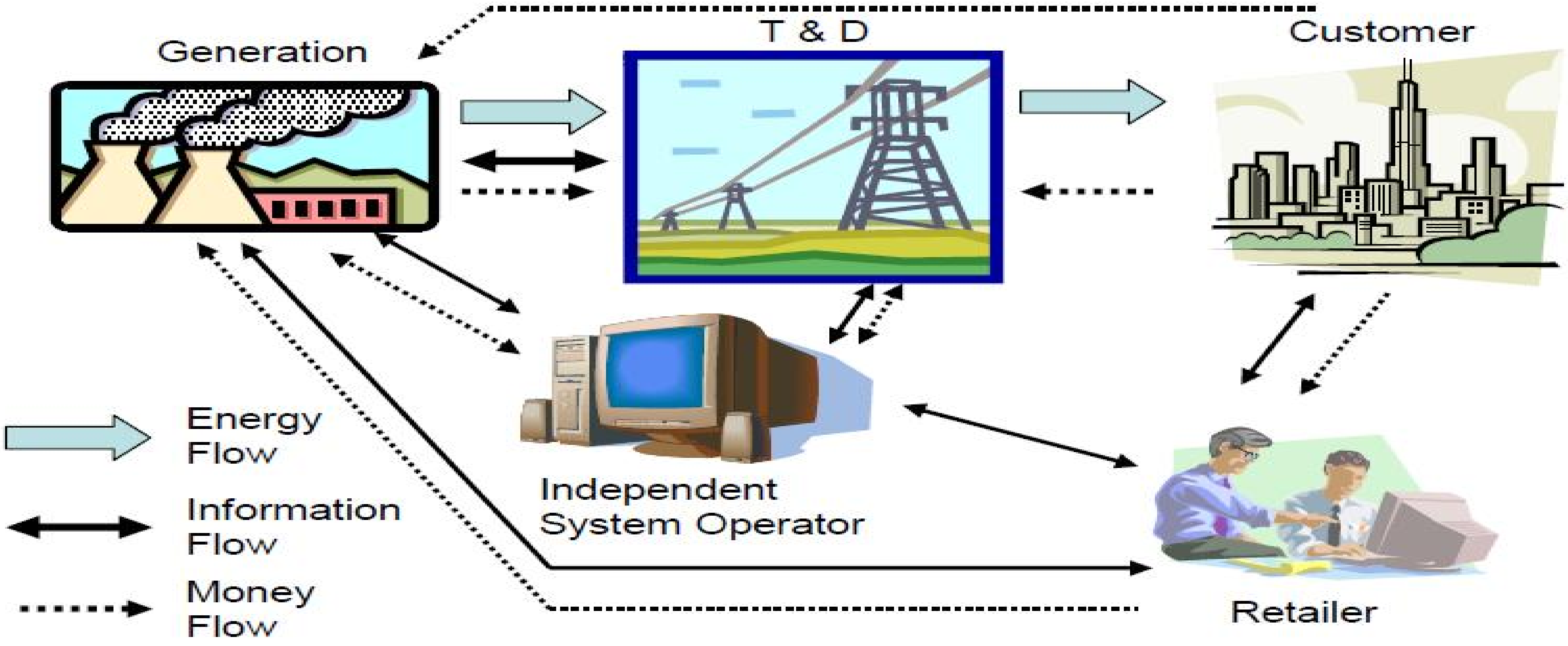


Figure 2

1. **Genco** (Generating Company): Genco is an owner-operator of one or more generators that runs them and bids the power into the competitive marketplace. Genco sells energy at its sites in the same manner that a coal mining company might sell coal in bulk at its mine.

2. **Transco** (Transmission Company): Transco moves power in bulk quantities from where it is produced to where it is delivered. The Transco owns and maintains the transmission facilities, and may perform many of the management and engineering functions required to ensure the system can continue to do its job. In most deregulated industry structures, the Transco owns and maintains the transmission lines under monopoly franchise, but does not operate them. That is done by Independent System Operator (ISO). The Transco is paid for the use of its lines.

3. **Disco** (Distribution Company): It is the monopoly franchise owner-operator of the local power delivery system, which delivers power to individual businesses and homeowners. In some places, the local distribution function is combined with retail function, i.e. to buy wholesale electricity either through the spot market or through direct contracts with gencos and supply electricity to the end use customers. In many other cases, however, the disco does not sell the power. It only owns and operates the local distribution system, and obtains its revenues by 'renting' space on it, or by billing for delivery of electric power.
4. **Resco** (Retail Energy Service Company): It is the retailer of electric power. Many of these will be the retail departments of the former vertically integrated utilities. Others will be companies new to the electric industry that believe they are good at selling services. Either way, a resco buys power from gencos and sells it directly to the consumers.

5. **Independent System Operator** (ISO): The ISO is an entity entrusted with the responsibility of ensuring the reliability and security of the entire system. It is an independent authority and does not participate in the electricity market trades. It usually does not own generating resources, except for some reserve capacity in certain cases. In order to maintain the system security and reliability, the ISO procures various services such as supply of emergency reserves, or reactive power from other entities in the system.
6. **Customers**: A customer is entity, consuming electricity. In deregulated markets, the customer has several options for buying electricity. It may choose to buy electricity from the spot market by bidding for purchase, or may buy directly from a genco or even from the local distribution company.

Impact of DGs upon protective relaying

The protection of conventional distribution systems is a straightforward task due to their radial configurations with the main source in-feed. In this regard, the protection system in such systems includes fuses, auto reclosers, and overcurrent relays

In the presence of DG, conventional distribution systems would no longer be radially configured, causing many challenges to protection systems which may ultimately lead to losing protection system coordination.
The challenges of the protection systems in the presence of DG would be as listed below :
• Unsynchronized reclosing • Avoiding automatic reclosing • Undesired islanding • Contribution to the short-circuit level • Protection system blinding • Nuisance tripping of generating units • Maloperation of feeder protection

- DG can cause malfunctioning of protection systems during faults. For instance, if a fault occurs at one of the feeders adjacent to DG units, an undesired tripping command by protection relays may be triggered.
- As such, it should be noted that the location of DG units in distribution systems (as well as their number and penetration level), highly impacts protection systems

- Overcurrent relays are the most commonly used as primary protection in distribution systems and in some cases as backup protection in transmission and sub-transmission networks.
- In presence of DG, the short-circuit levels would change and some challenging issues would arise. Therefore, adaptive relay coordination is necessary for distribution system protection

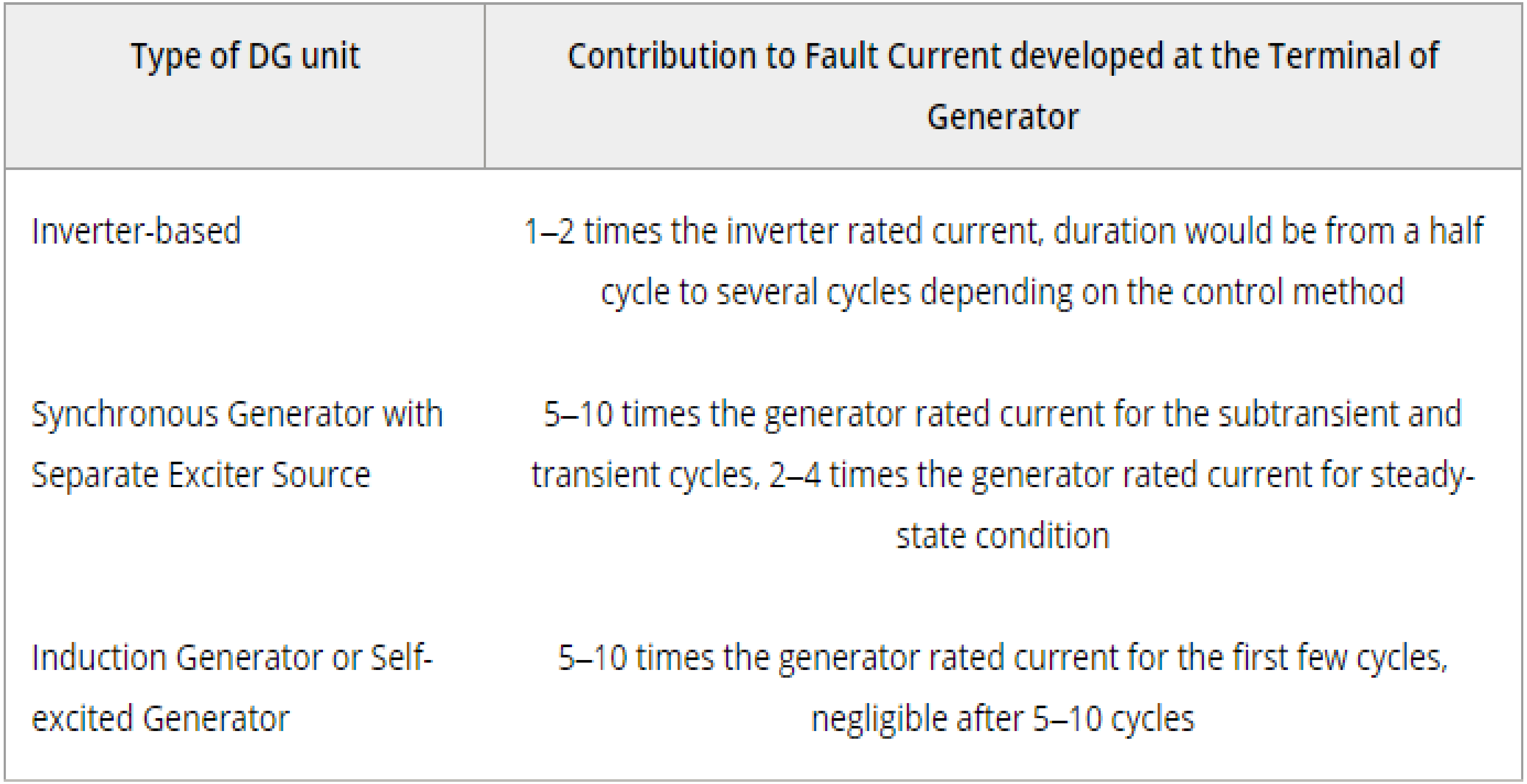
- The contribution of a single DG unit may not significantly affect the fault current. However, in the case of several DG units connected to the system, the fault current and accordingly the protection system will be highly affected

- When using inverse time overcurrent protection, the fault-clearing time may become unacceptably long.
- The rise in the short circuit level and change in the direction of fault current flow in the distribution network influence the protection coordination between relays installed in the distribution network(DN), and thus disturb the functionality, selectivity and reliability of protection scheme.

- Losing protection coordination with DG mainly results in the false tripping command and blinding of the protection system. The protection system becomes blind when the sensitivity of relays decreases, and the false tripping command occurs when the protective device sends a tripping command for a fault on a feeder while the fault has occurred on another feeder

The contribution of a DG unit to a fault current is related to the type of DG unit, which can be characterized as synchronous generators, induction generators and inverter-based units. However, the response of each type to a fault and its contribution to the fault current varies.

Table 1. Contribution of Different DG types to Fault Current



Type of DG unit	Contribution to Fault Current developed at the Terminal of Generator
Inverter-based	1–2 times the inverter rated current, duration would be from a half cycle to several cycles depending on the control method
Synchronous Generator with Separate Exciter Source	5–10 times the generator rated current for the subtransient and transient cycles, 2–4 times the generator rated current for steady-state condition
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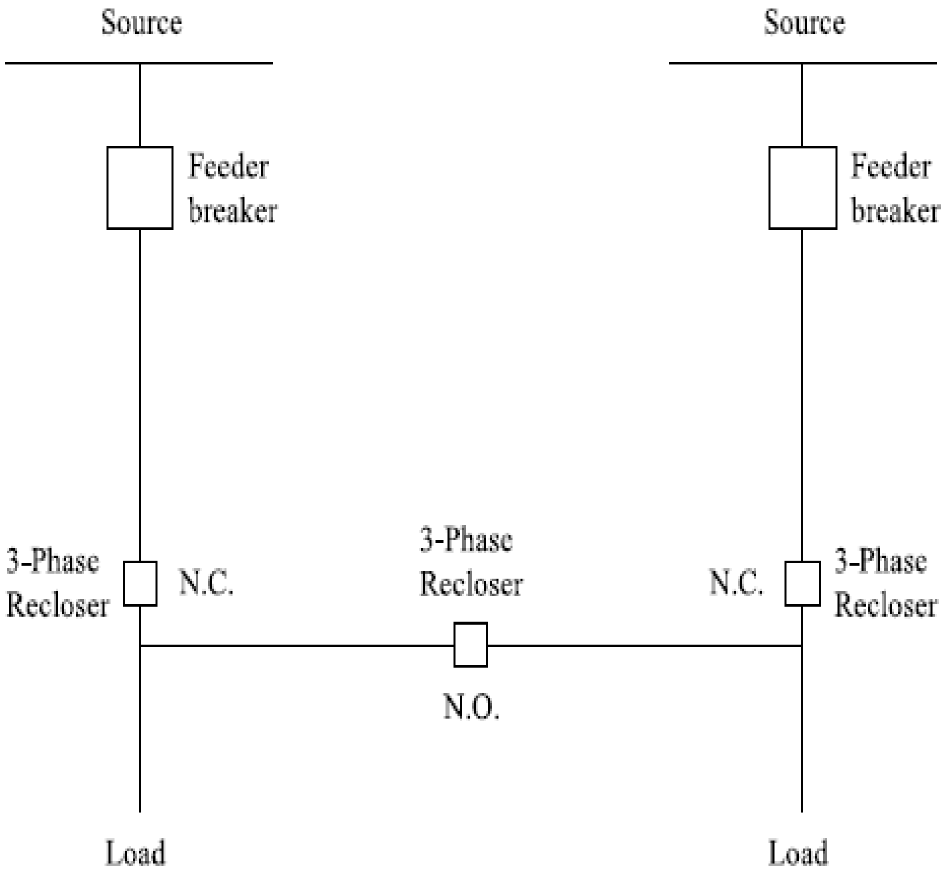
Source
Source
Feeder breaker
Feeder breaker
3-Phase Recloser
N.C.
3-Phase Recloser
N.O.
N.C.
3-Phase Recloser
Load
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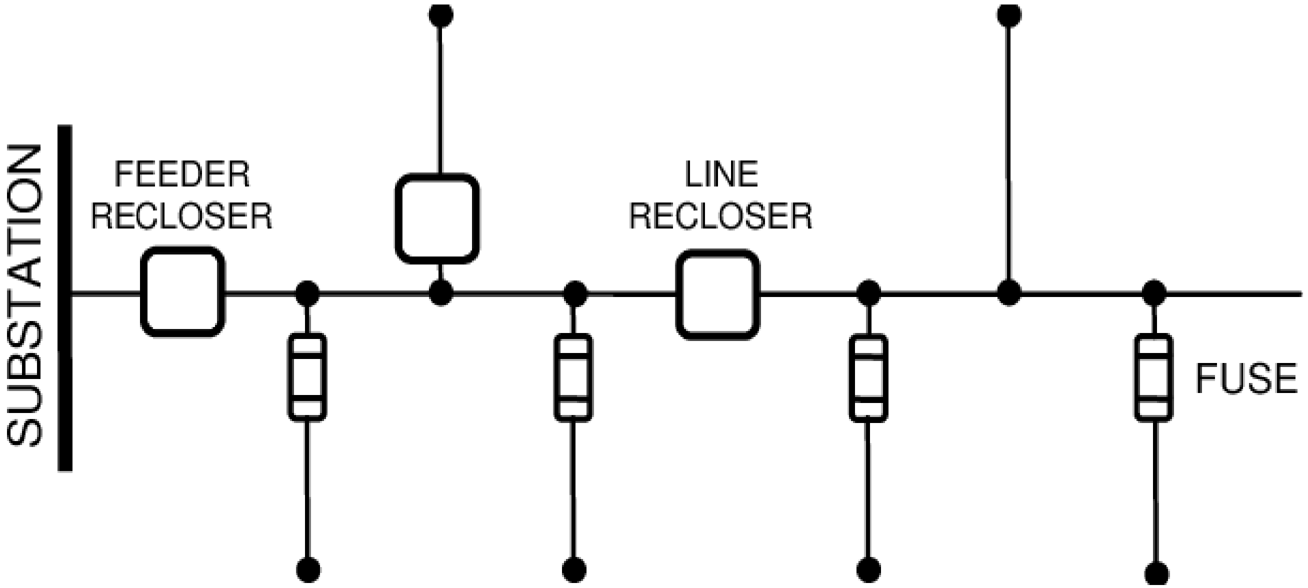
SUBSTATION
FEEDER RECLOSER
LINE RECLOSER
FUSE

Impact of distributed generation penetration on Stability

- Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.
- Three categories have been proposed, i.e., rotor angle stability, voltage stability and frequency stability.
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It is well recognized that the system steady state voltage rise plays an important role on limiting the penetration level of DG. Thus many methods are proposed to cope with this voltage rise effect:

- if available, tuning the OLTC at the CCP of the transmission and distribution system;
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Market Facts & Key Issues

- **Market Growth:** The distributed energy market was valued at approximately
- billion in 2024, with a projected CAGR of
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- **Key Drivers:** Rising demand for renewable energy (solar, wind), need for higher reliability (fewer blackouts), and declining technology costs.
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- **Grid Instability:** High penetration of DG creates bidirectional power flows that existing, aging infrastructure cannot manage, leading to voltage instability and capacity limitations.
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- **Economic Impact on Utilities:** DG can jeopardize the revenue models of distribution companies, requiring new regulatory frameworks for cost recovery.
- **Safety & Protection:** Changes in protection schemes and potential for islanding (when a DG unit continues to power a location even when grid power is lost).

Challenges of DG

- **Regulatory Hurdles:** Stringent,, inconsistent, or slow interconnection policies ("fit and forget") hinder rapid deployment and cause long wait times.
- **High Initial Investment:** Despite long-term savings, high upfront capital costs for solar, wind, and storage remain a major barrier for residential and small commercial users.
- **Optimization & Location:** Finding the optimal, capacity and location for DG units to maximize benefits and minimize,, losses,.
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Limitations of Distributed Generation (DG):

- **System Stability & Reliability Issues:** Integrating DG shifts systems from passive to active, causing potential reliability issues and stability problems within distribution networks.
- **Voltage Profile Disturbance:** Improper DG placement or high penetration can cause overvoltage or undervoltage, leading to fluctuations, especially if numerous small DGs cause circulation currents.
- **Protection Coordination & Fault Currents:** DG adds to short-circuit levels, increasing fault currents that can cause unintentional protective device tripping and complicate existing protection schemes.
- **Reverse Power Flow:** Large-scale DG integration disrupts traditional radial power flow, causing power to flow back towards the substation, which can overload infrastructure.
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- **Operational & Cost Factors:** High initial investment, maintenance requirements, and potential noise/environmental impacts are significant barriers, particularly for diesel or gas-based systems.
- **Power Quality Issues:** Electronically coupled DG units (like photovoltaics) can inject harmonic distortions into the grid.

Voltage Control Techniques for DG

- Voltage control techniques for Distributed Generation (DG) manage voltage variations in distribution networks caused by high penetration of, for example, solar or wind, using active power curtailment, reactive power control and tap-changing transformers.
- Key methods include direct inverter control, multi-agent cooperative control, and network-wide coordination to optimize voltage stability and power quality.

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reactive power control of dg

- Reactive power control of Distributed Generation (DG) involves managing reactive power (Q) to regulate voltage, reduce system losses, and prevent overvoltage caused by reverse power flow in distribution grids.
- Key techniques include Local Voltage-Reactive power (Q-V) droop control, PF(P,V) method (adjusting power factor based on active power and voltage), and adaptive virtual impedance for microgrids.
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- **Key Aspects of DG Reactive Power Control:**
- **Voltage Regulation & Overvoltage Protection:** DGs often cause excessive voltage rise in distribution lines. Reactive power control, such as absorbing or injecting
- , helps maintain voltage within acceptable limits.
- **Active Power Reduction Prevention:** By controlling reactive power, DG units can avoid reducing their active power (P) output, which is often required to manage voltage, thus increasing overall energy efficiency.
- **Control Methods:**
  - **Local Control:** Uses local measurements at the Point of Common Coupling (PCC) to adjust reactive power based on voltage levels (Q-V) or active power output (P-V).
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- **Voltage Flicker:** Rapid, fluctuating power output from intermittent DG sources can cause light flickering and disturb voltage-sensitive equipment.
- **Switching Transients & Faults:** The integration and removal of DG units, especially during faults or switching events, can create voltage surges that exceed normal operating levels.
- **Frequency Variations:** If the DG capacity is large compared to the grid, it can lead to instability in the network frequency.

Mitigation Techniques

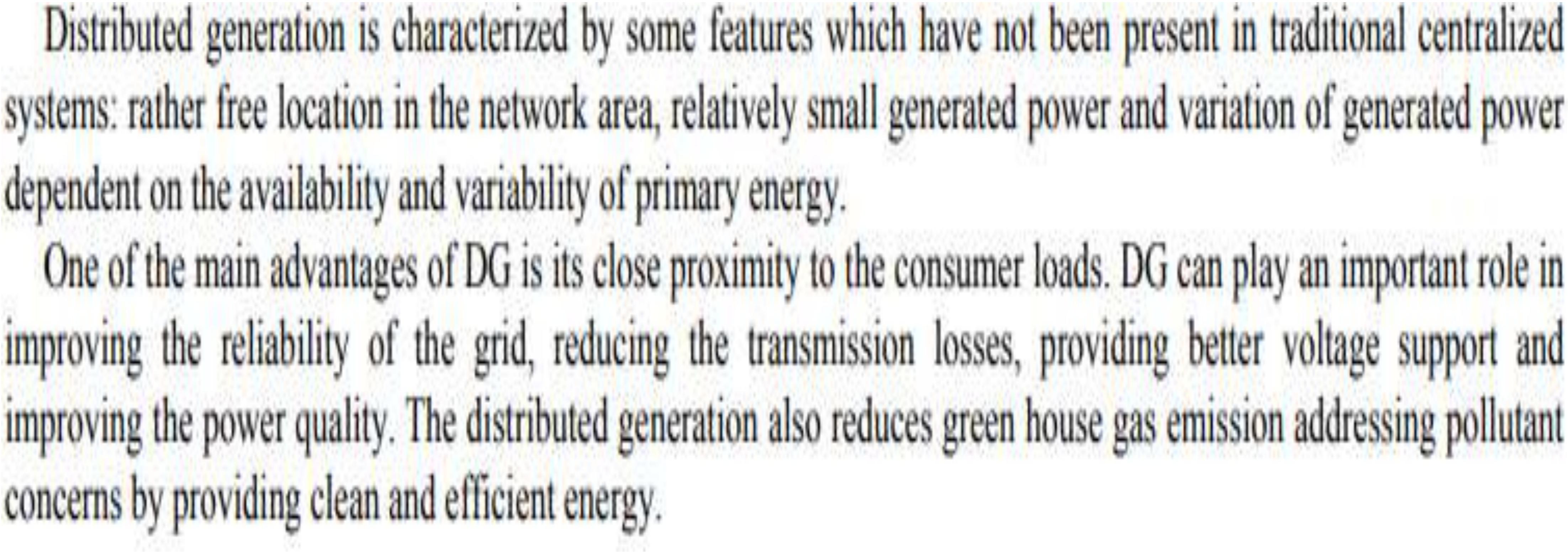
- **Filtering:** Use active or passive filters to reduce harmonic distortions.
- **Voltage Regulation:** Installing on-load tap changers and voltage regulators on feeders with high DG penetration.
- **Reactive Power Control:** Utilizing inverters to manage reactive power and stabilize voltage levels.
- **Energy Storage:** Incorporating battery storage to mitigate the intermittency of renewable sources.
- **Advanced Inverters:** Utilizing smart inverters with enhanced grid-support functionality.

UNIT-V

UNIT – V: GRID INTEGRATION OF DGS AND TECHNICAL IMPACTS OF DGS

DG Impact on - Transmission and Distribution systems, De-regulation – Impact of DGs upon protective relaying –Impact of DGs upon transient and dynamic stability of existing distribution systems

DG Impact on - Transmission and Distribution systems



Distributed generation is characterized by some features which have not been present in traditional centralized systems: rather free location in the network area, relatively small generated power and variation of generated power dependent on the availability and variability of primary energy.

One of the main advantages of DG is its close proximity to the consumer loads. DG can play an important role in improving the reliability of the grid, reducing the transmission losses, providing better voltage support and improving the power quality. The distributed generation also reduces green house gas emission addressing pollutant concerns by providing clean and efficient energy.

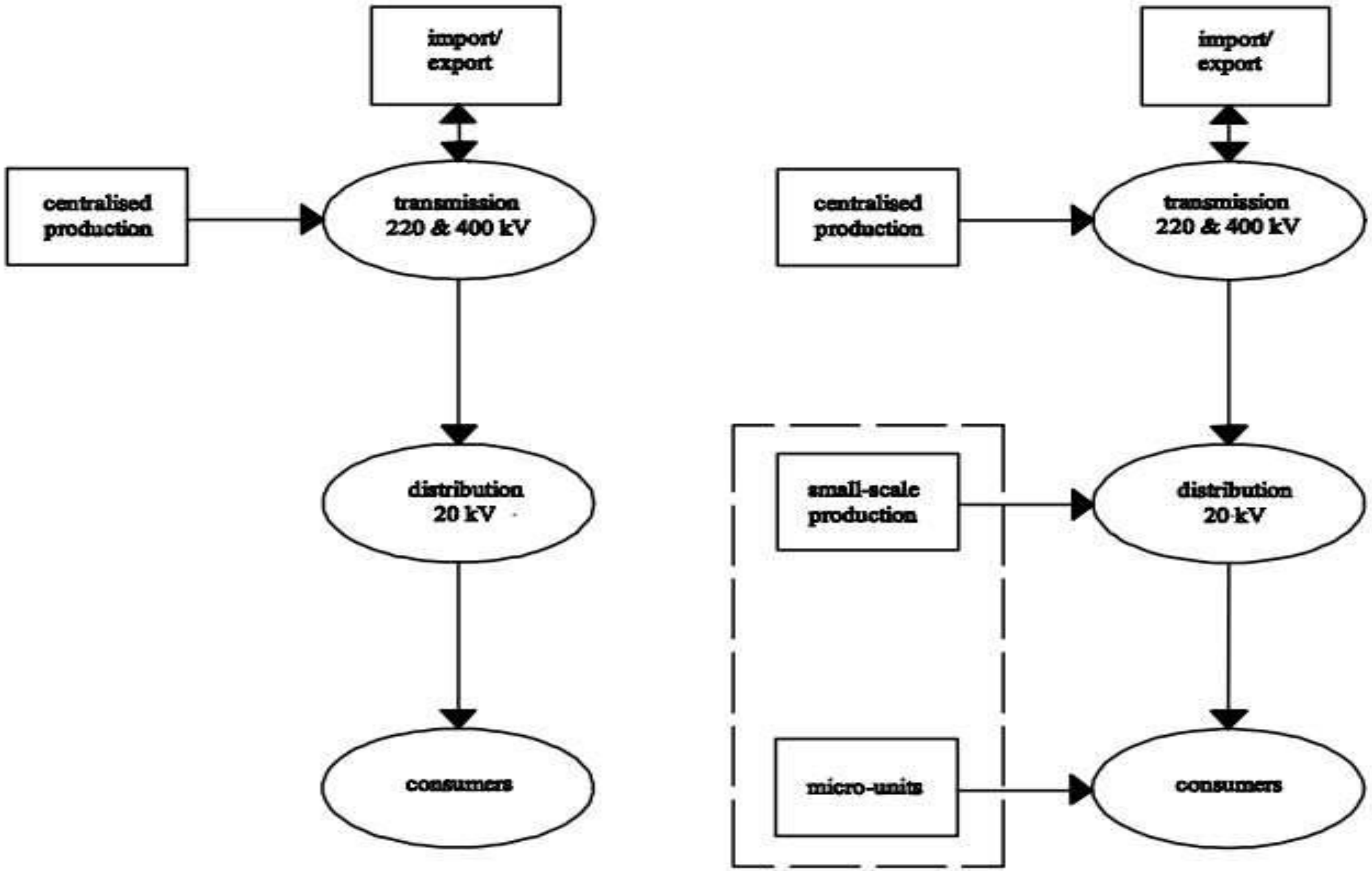


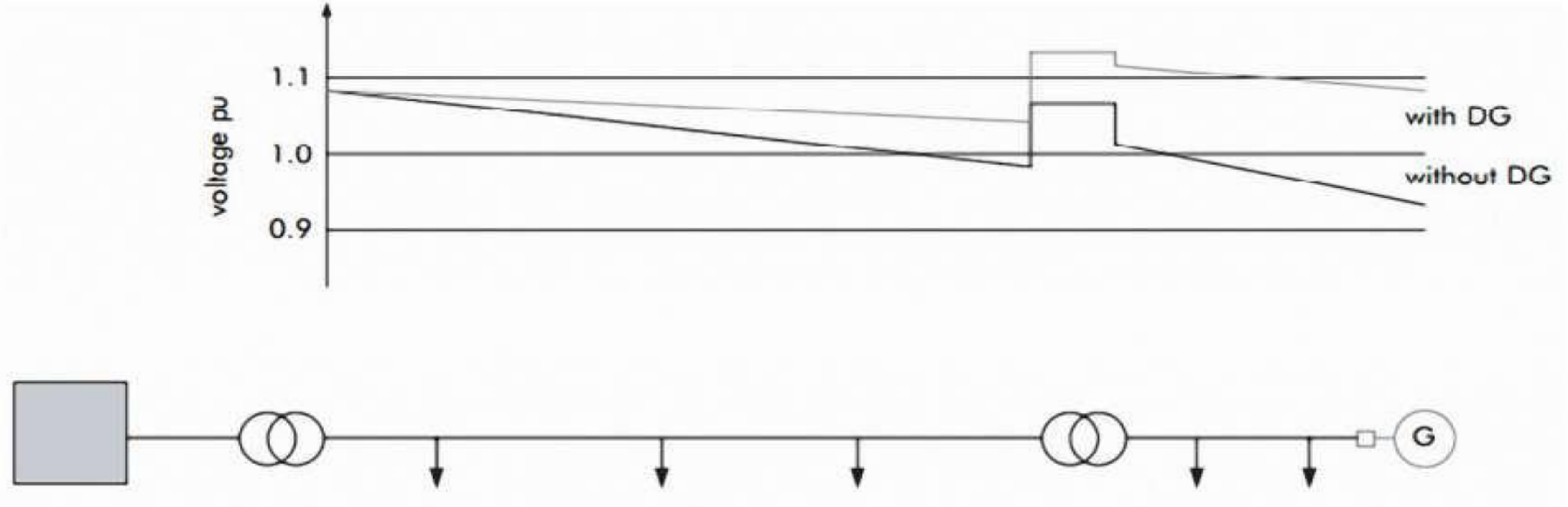
Fig. 1. A unidirectional centrally delivered power generation system (left) and a bidirectional system with distributed generation (right)

Operation and control

Change of short circuit capacity

Stability

Voltage level of integration and interconnection

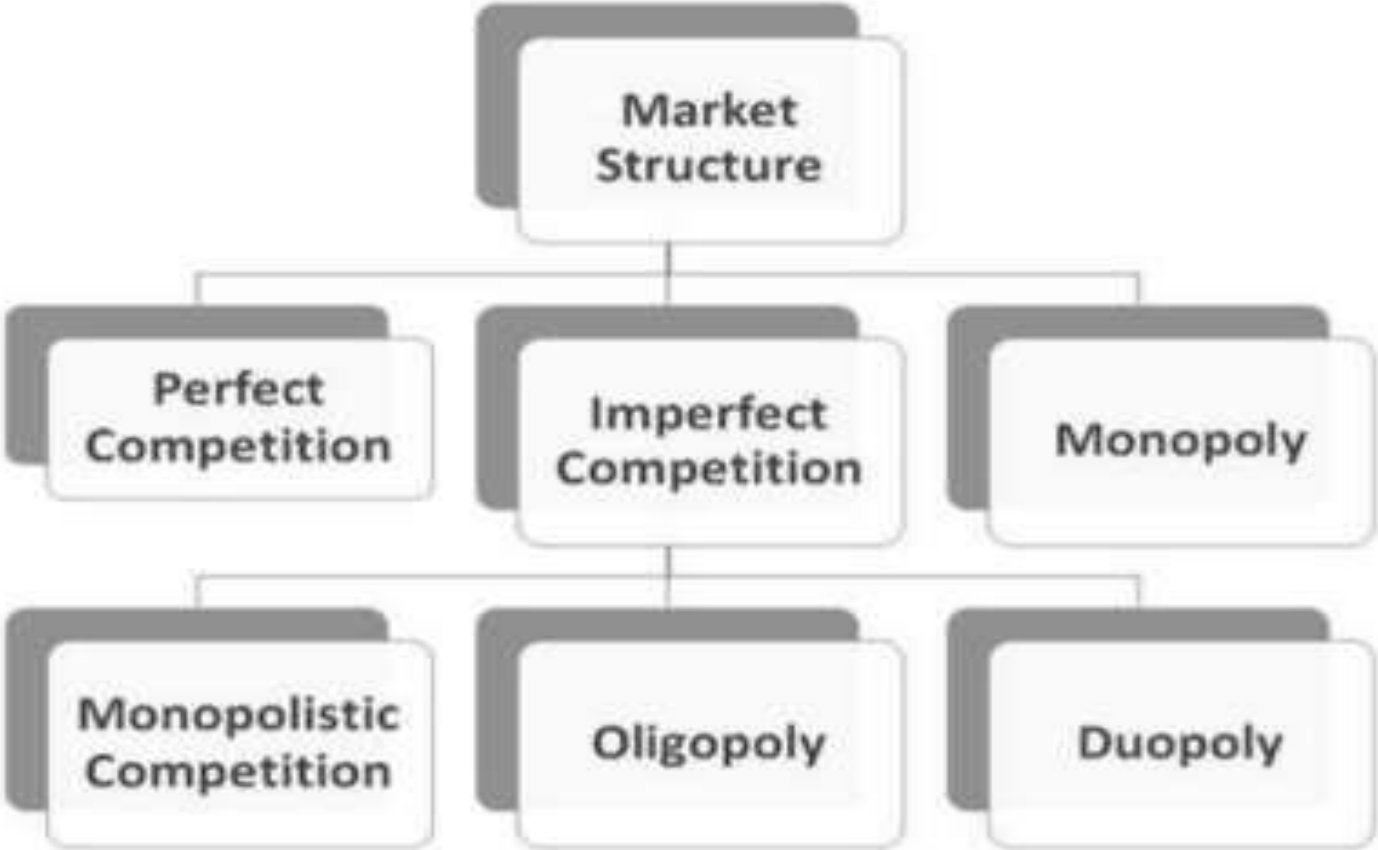


Deregulation

What is Market Structure?

Those characteristics of the market that significantly affect the behavior and interaction of buyers and sellers.

Market Structure



Market Structure

Perfect Competition

Imperfect Competition

Monopoly

Monopolistic Competition

Oligopoly

Duopoly

Deregulation in Power Industry

The goal of changing the way of operation, i.e. re-regulation, or deregulation, as we say, is to enhance competition and bring consumers new choices and economic benefits.

Under Deregulation, the former vertically integrated utility, which performed all the functions involved in power, i.e. generation, transmission, distribution and retail sales, is dis-aggregated into separate companies devoted to each function. The electricity bill for the end consumer now involves at least two components: one from the distribution and transmission network-operator responsible for the network and services, and the other from the company that generates the electrical energy.

- **Regulation:** *Regulation means that the Government has set down laws and rules that put limits on and define how a particular industry or company can operate.*

- **Deregulation:** *Deregulation in power industry is a restructuring of the rules and economic incentives that government set up to control and drive the electric power industry.*

Under deregulated environment, the electric utility will always try to innovate something for the betterment of service and in turn save its costs and maximize the profit. By means of this, the utility will try to ensure that it will maintain its customer base in spite of competition.

Some other forces supporting the main reasons for motivating the deregulation can also be enlisted as follows:

1. Overstaffing in the regulated electric industry.
2. Global economic crisis
3. Political and ideological changes
4. Managerial inefficiency in the regulated company
5. Lack of public resources for the further development
6. More demanding environment issues
7. Pressure of financial institutes

A typical structure of a vertically integrated electric utility is shown in figure (1).

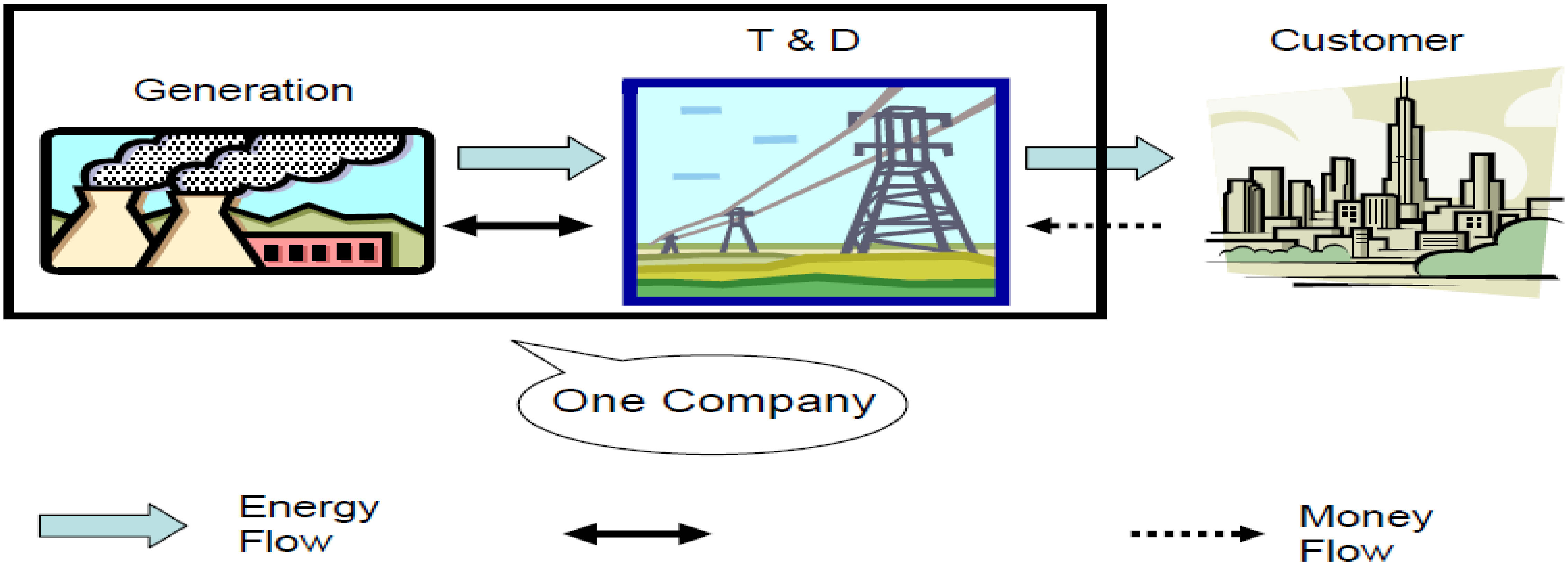


Figure 1

In figure (1), the money flow is unidirectional, i.e. from the consumer to the electric company. Similarly, the information flow exists only between the generators and the transmission systems.

The utilities being vertically integrated, it was often difficult to segregate the costs involved in generation, transmission or distribution. So, the utilities often charged their customers an average tariff rate depending on their aggregated cost during a period.

Under deregulation, the vertically integrated utility, one giant company that generates, transmits, distributes and sells electricity in coordinated manner will become thing of the past. To function in an open access system, such utilities will have to rearrange their operational organization to match the unbundled functions they must perform. Each part of the company will need to work in its new form. Generation will have to compete in the competitive power generation market place. T & D will have to operate as an open provider of delivery services. Competition will be present in retailing.

Generally, the governments advocating deregulation want competition in energy production, and they want to see significant levels of customer choice in the retail market for electricity. At the same time, it recognizes that it is best to have only one transmission and one distribution system in any one area. Therefore, the purpose of deregulation is to restructure the electric industry so that power production and retail sales are competitive, while delivery is still a regulated, monopoly franchise business.

Figure (2) shows the typical structure of a deregulated electricity system with links of information and money flow between various players.

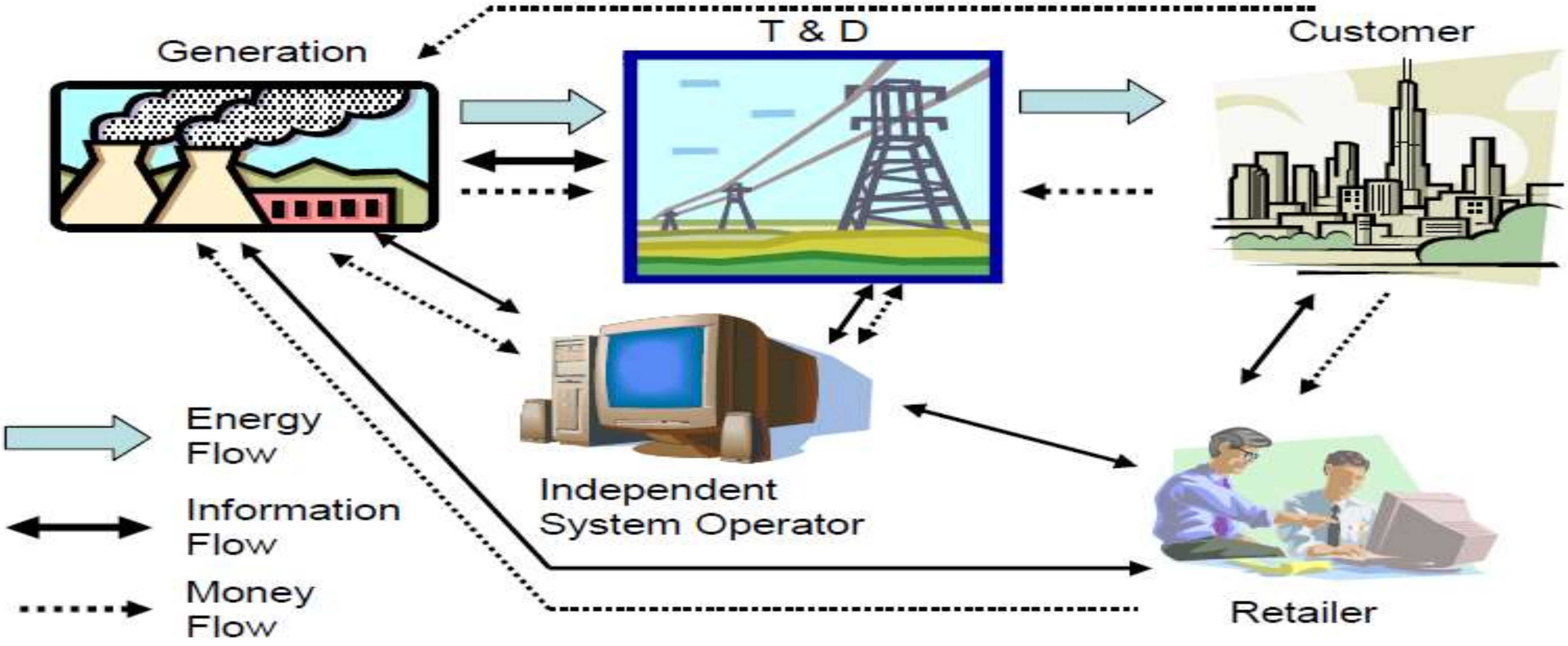


Figure 2

1. **Genco** (Generating Company): Genco is an owner-operator of one or more generators that runs them and bids the power into the competitive marketplace. Genco sells energy at its sites in the same manner that a coal mining company might sell coal in bulk at its mine.

2. **Transco** (Transmission Company): Transco moves power in bulk quantities from where it is produced to where it is delivered. The Transco owns and maintains the transmission facilities, and may perform many of the management and engineering functions required to ensure the system can continue to do its job. In most deregulated industry structures, the Transco owns and maintains the transmission lines under monopoly franchise, but does not operate them. That is done by Independent System Operator (ISO). The Transco is paid for the use of its lines.

3. **Disco** (Distribution Company): It is the monopoly franchise owner-operator of the local power delivery system, which delivers power to individual businesses and homeowners. In some places, the local distribution function is combined with retail function, i.e. to buy wholesale electricity either through the spot market or through direct contracts with gencos and supply electricity to the end use customers. In many other cases, however, the disco does not sell the power. It only owns and operates the local distribution system, and obtains its revenues by 'renting' space on it, or by billing for delivery of electric power.
4. **Resco** (Retail Energy Service Company): It is the retailer of electric power. Many of these will be the retail departments of the former vertically integrated utilities. Others will be companies new to the electric industry that believe they are good at selling services. Either way, a resco buys power from gencos and sells it directly to the consumers.

5. **Independent System Operator** (ISO): The ISO is an entity entrusted with the responsibility of ensuring the reliability and security of the entire system. It is an independent authority and does not participate in the electricity market trades. It usually does not own generating resources, except for some reserve capacity in certain cases. In order to maintain the system security and reliability, the ISO procures various services such as supply of emergency reserves, or reactive power from other entities in the system.
6. **Customers**: A customer is entity, consuming electricity. In deregulated markets, the customer has several options for buying electricity. It may choose to buy electricity from the spot market by bidding for purchase, or may buy directly from a genco or even from the local distribution company.

Impact of DGs upon protective relaying

The protection of conventional distribution systems is a straightforward task due to their radial configurations with the main source in-feed. In this regard, the protection system in such systems includes fuses, auto reclosers, and overcurrent relays

In the presence of DG, conventional distribution systems would no longer be radially configured, causing many challenges to protection systems which may ultimately lead to losing protection system coordination.

The challenges of the protection systems in the presence of DG would be as listed below : • Unsynchronized reclosing • Avoiding automatic reclosing • Undesired islanding • Contribution to the short-circuit level • Protection system blinding • Nuisance tripping of generating units • Maloperation of feeder protection

- DG can cause malfunctioning of protection systems during faults. For instance, if a fault occurs at one of the feeders adjacent to DG units, an undesired tripping command by protection relays may be triggered.
- As such, it should be noted that the location of DG units in distribution systems (as well as their number and penetration level), highly impacts protection systems

- Overcurrent relays are the most commonly used as primary protection in distribution systems and in some cases as backup protection in transmission and sub-transmission networks.
- In presence of DG, the short-circuit levels would change and some challenging issues would arise. Therefore, adaptive relay coordination is necessary for distribution system protection

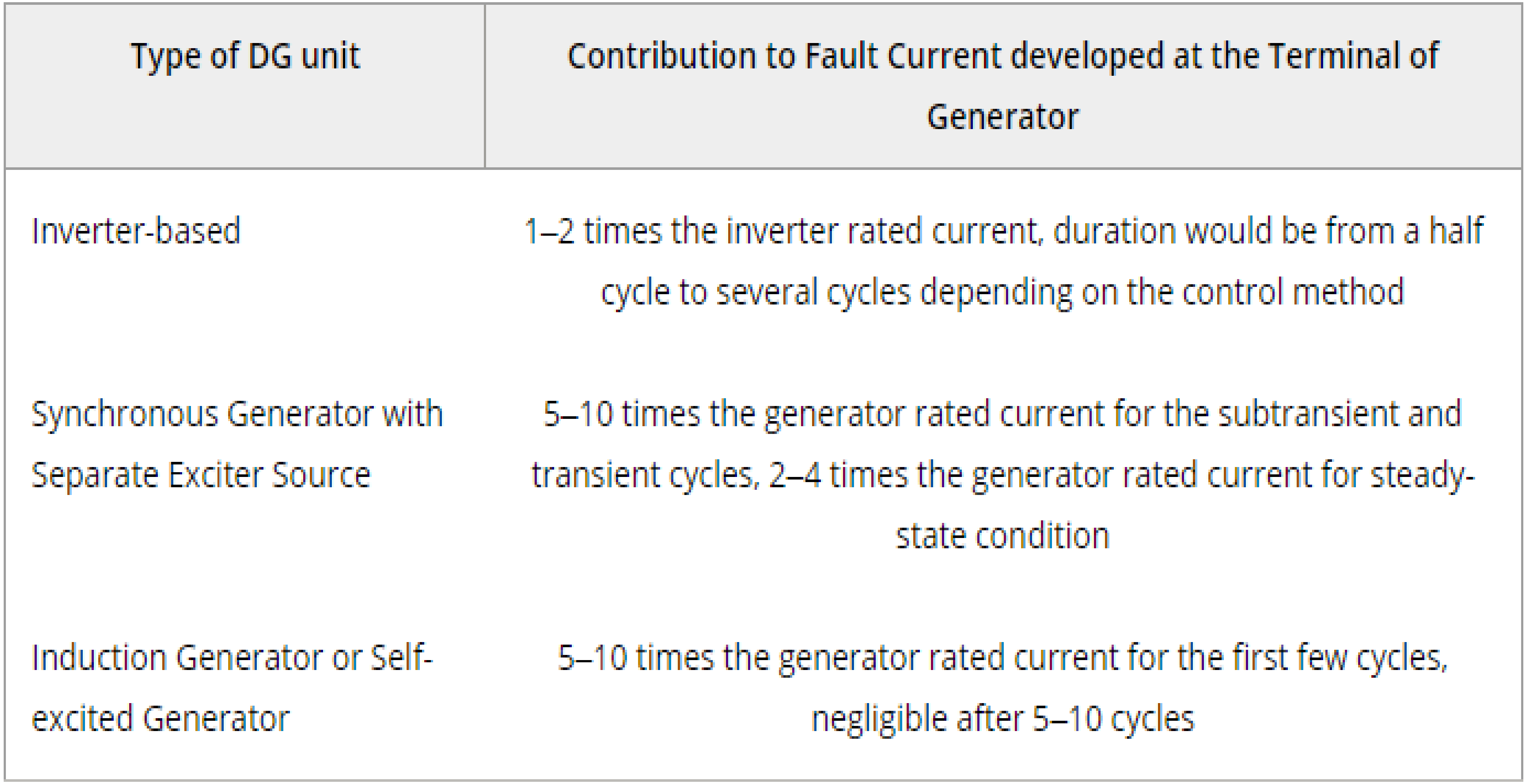
- The contribution of a single DG unit may not significantly affect the fault current. However, in the case of several DG units connected to the system, the fault current and accordingly the protection system will be highly affected

- When using inverse time overcurrent protection, the fault-clearing time may become unacceptably long.
- The rise in the short circuit level and change in the direction of fault current flow in the distribution network influence the protection coordination between relays installed in the distribution network(DN), and thus disturb the functionality, selectivity and reliability of protection scheme.

- Losing protection coordination with DG mainly results in the false tripping command and blinding of the protection system. The protection system becomes blind when the sensitivity of relays decreases, and the false tripping command occurs when the protective device sends a tripping command for a fault on a feeder while the fault has occurred on another feeder

The contribution of a DG unit to a fault current is related to the type of DG unit, which can be characterized as synchronous generators, induction generators and inverter-based units. However, the response of each type to a fault and its contribution to the fault current varies.

Table 1. Contribution of Different DG types to Fault Current



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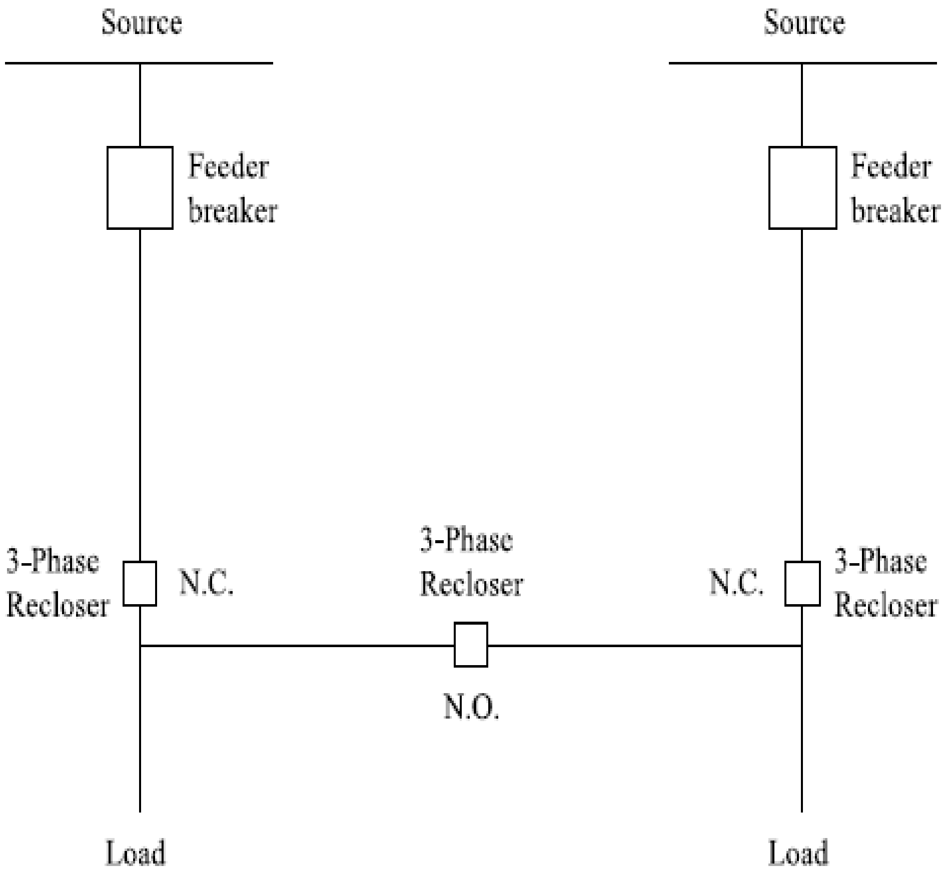
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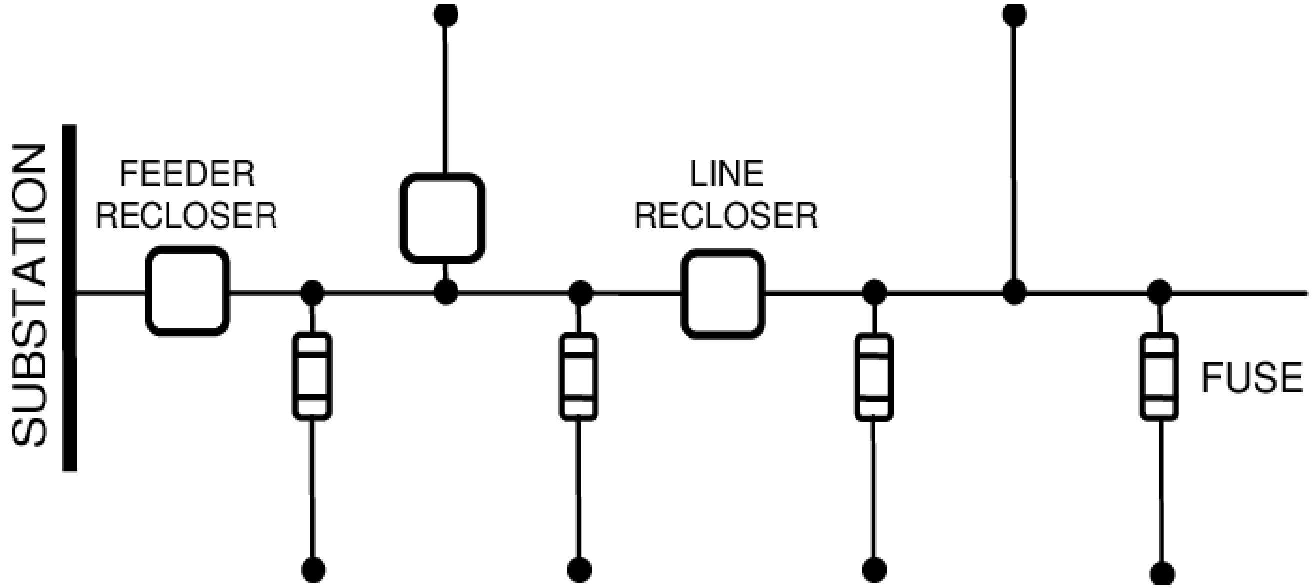
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- **Harmonic Distortion:** Power electronic inverters in DG units convert DC to AC, often injecting harmonics (high-order frequencies) into the system, causing overheating in transformers and equipment malfunction.
- ontrollers.

- **Voltage Flicker:** Rapid, fluctuating power output from intermittent DG sources can cause light flickering and disturb voltage-sensitive equipment.
- **Switching Transients & Faults:** The integration and removal of DG units, especially during faults or switching events, can create voltage surges that exceed normal operating levels.
- **Frequency Variations:** If the DG capacity is large compared to the grid, it can lead to instability in the network frequency.

Mitigation Techniques

- **Filtering:** Use active or passive filters to reduce harmonic distortions.
- **Voltage Regulation:** Installing on-load tap changers and voltage regulators on feeders with high DG penetration.
- **Reactive Power Control:** Utilizing inverters to manage reactive power and stabilize voltage levels.
- **Energy Storage:** Incorporating battery storage to mitigate the intermittency of renewable sources.
- **Advanced Inverters:** Utilizing smart inverters with enhanced grid-support functionality.