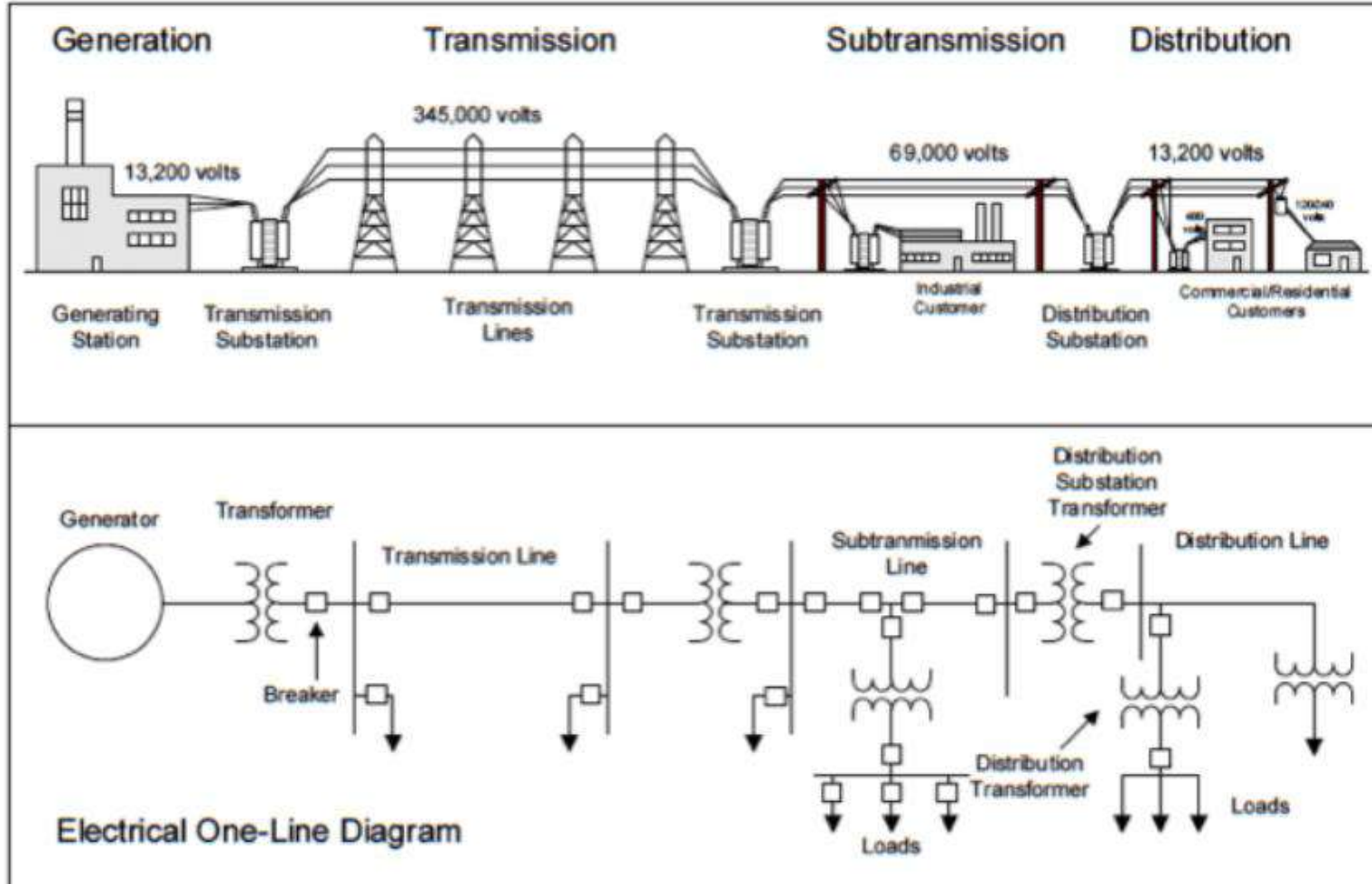


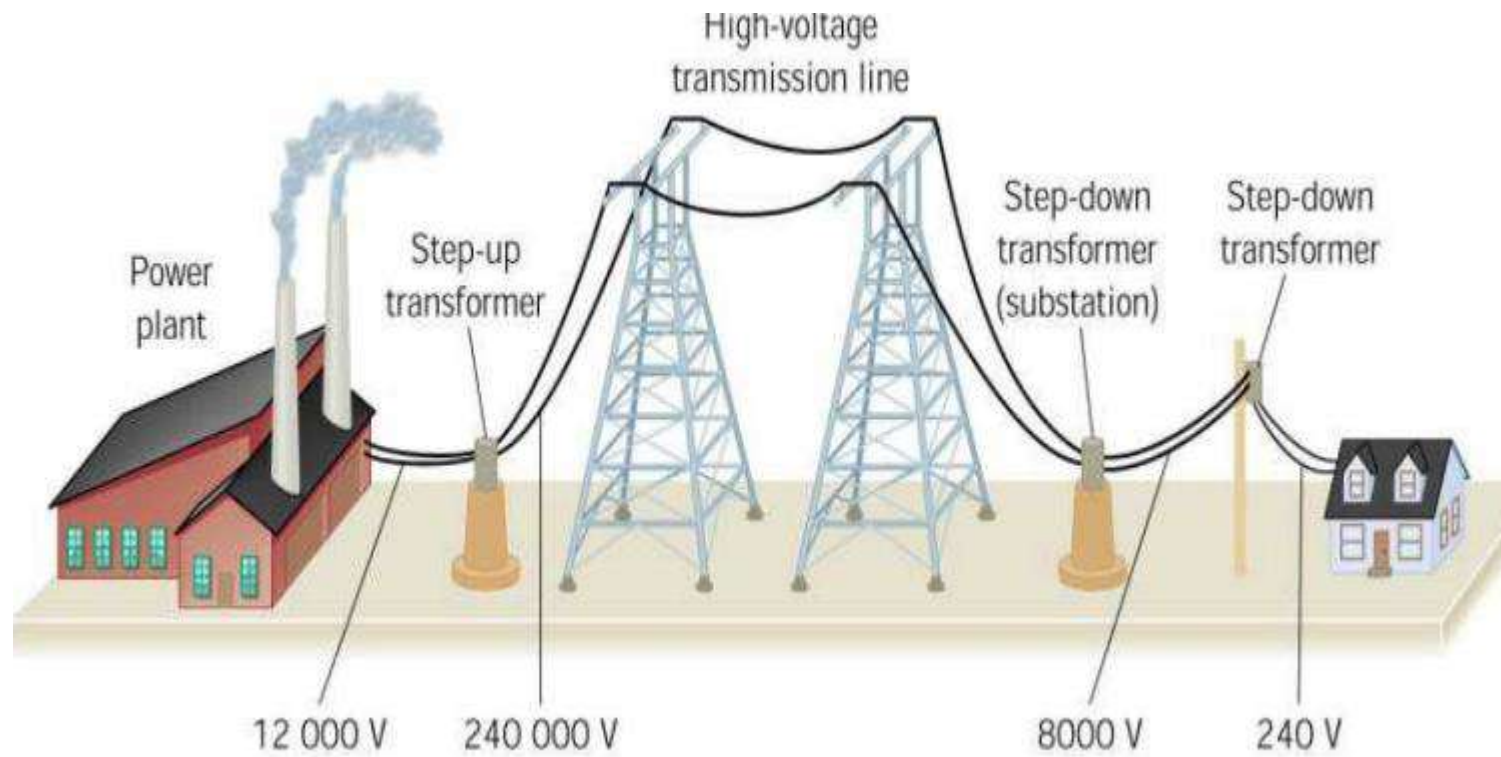
Comparison of conventional power system to microgrid

By Dr. Rajdip Dey
EE Department
NIT Durgapur

Traditional System



Traditional System

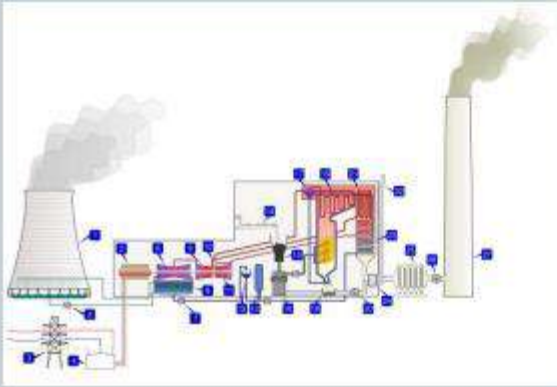


Components of Traditional System

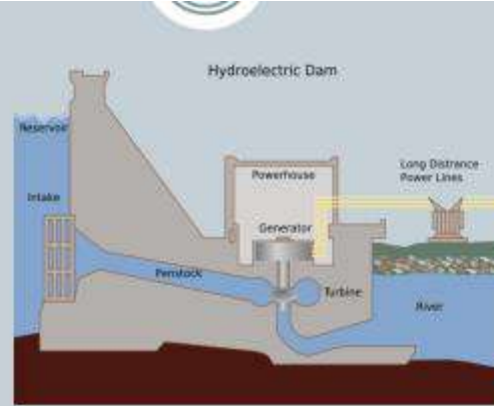
A typical power generation, transmission and distribution system has these components:

- **Power Generation Plants**
- **Substations**
 - Step-up Transmission Substation
 - Step-down Transmission Substation
 - Distribution Substation
 - Underground Distribution Substation
 - Substation Functions
 - Substation Equipment
- **Transmission Lines**
 - Overhead Transmission Lines
 - Sub transmission Lines
 - Underground Transmission Lines
- **Distribution Systems**
 - Industrial Customer
 - Commercial Customer
 - Residential Customer
 - Transportation Customer

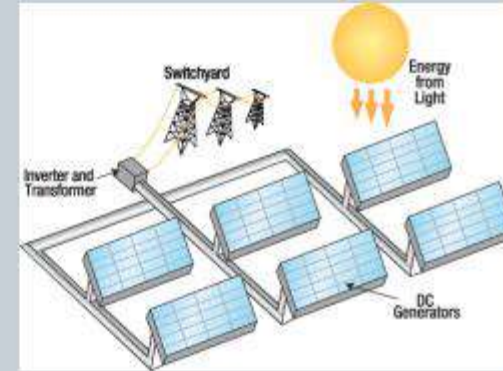
Generation System



Thermal Power Plant diagram



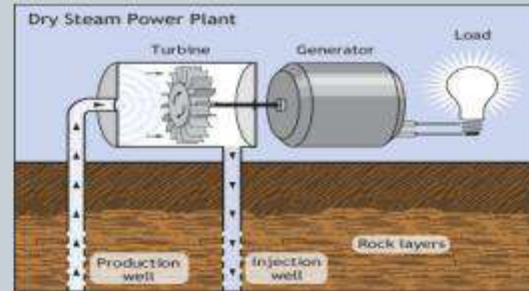
Hydro Plant diagram



Photovoltaic Power Plant

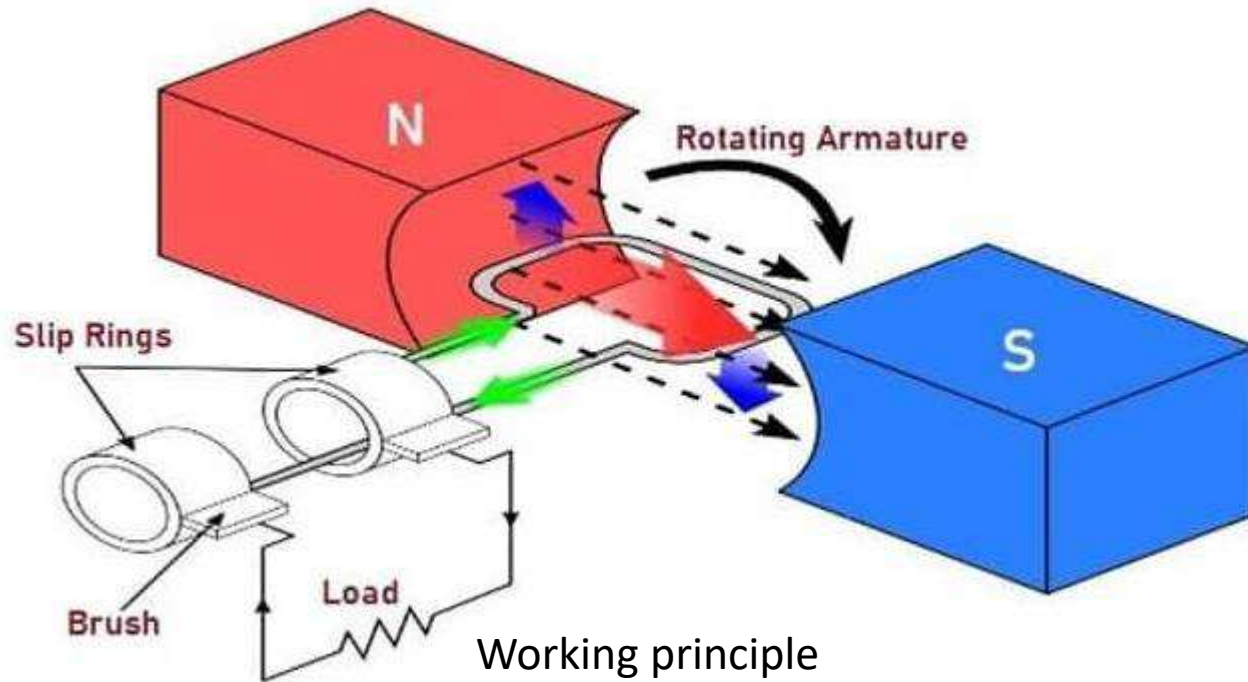


Wind Power Plant

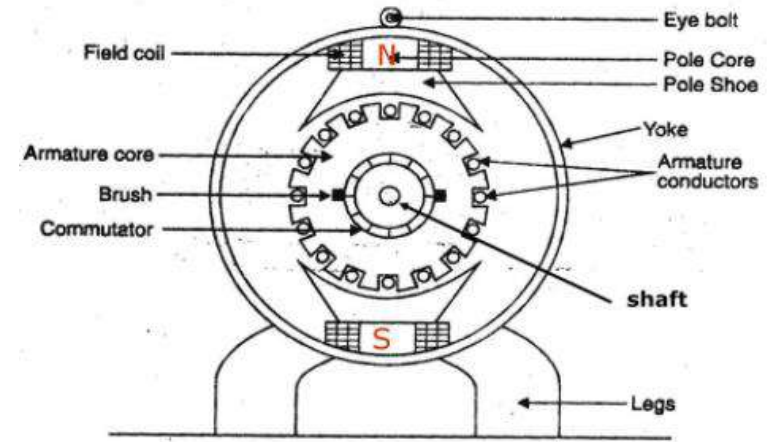


Geothermal Power Plant

Generator



Any change in the magnetic field of a coil of wire will cause an emf to be induced in the coil. This emf induced is called induced emf and if the conductor circuit is closed, the current will also circulate through the circuit and this current is called induced current.



Cross section diagram

Method to change the magnetic field:

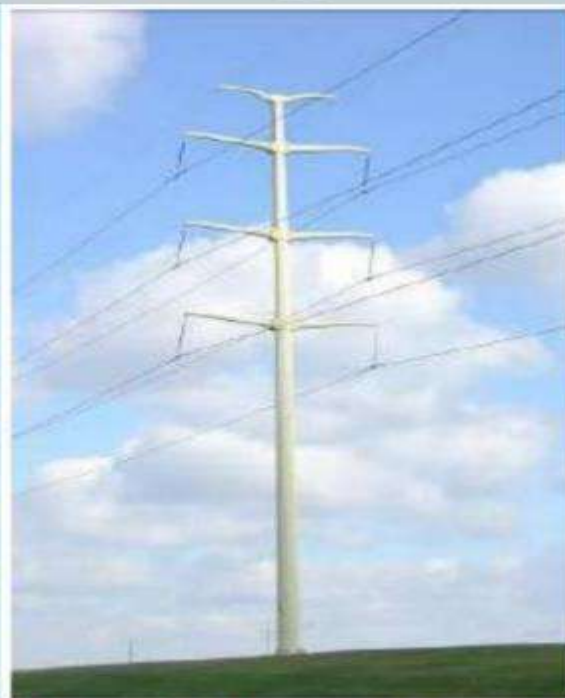
1. By moving a magnet towards or away from the coil
2. By moving the coil into or out of the magnetic field
3. By changing the area of a coil placed in the magnetic field
4. By rotating the coil relative to the magnet

Transmission System

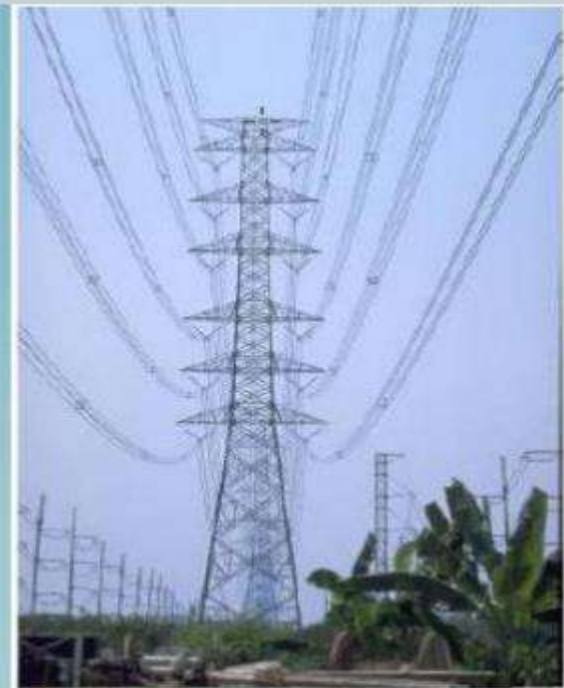
It refers to the part of electricity delivery that moves bulk electricity from the generation sites over long distances to substations closer to areas of demand for electricity.



Single Circuit,



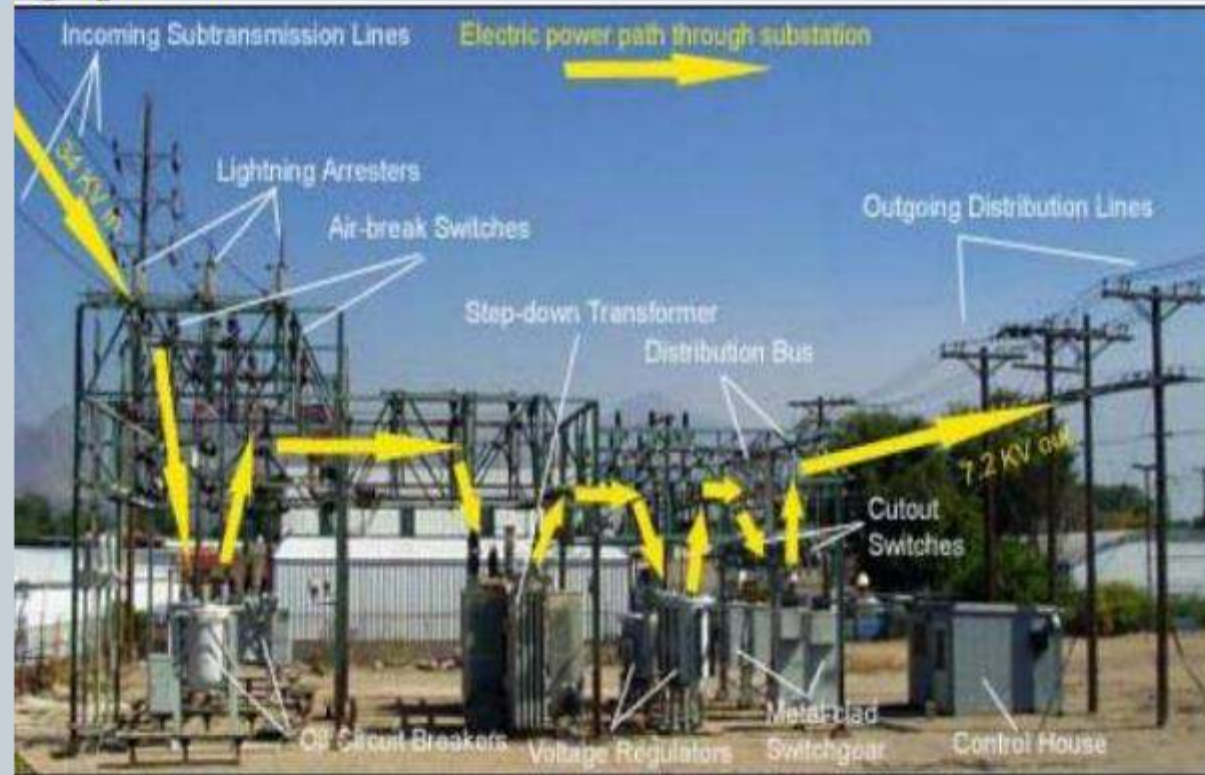
Double Circuit



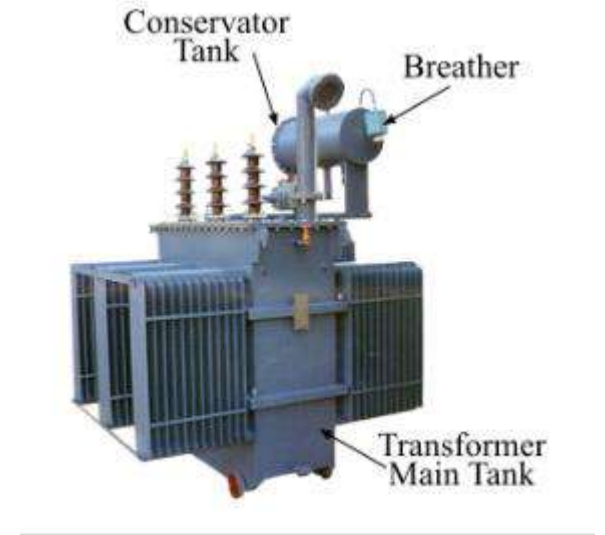
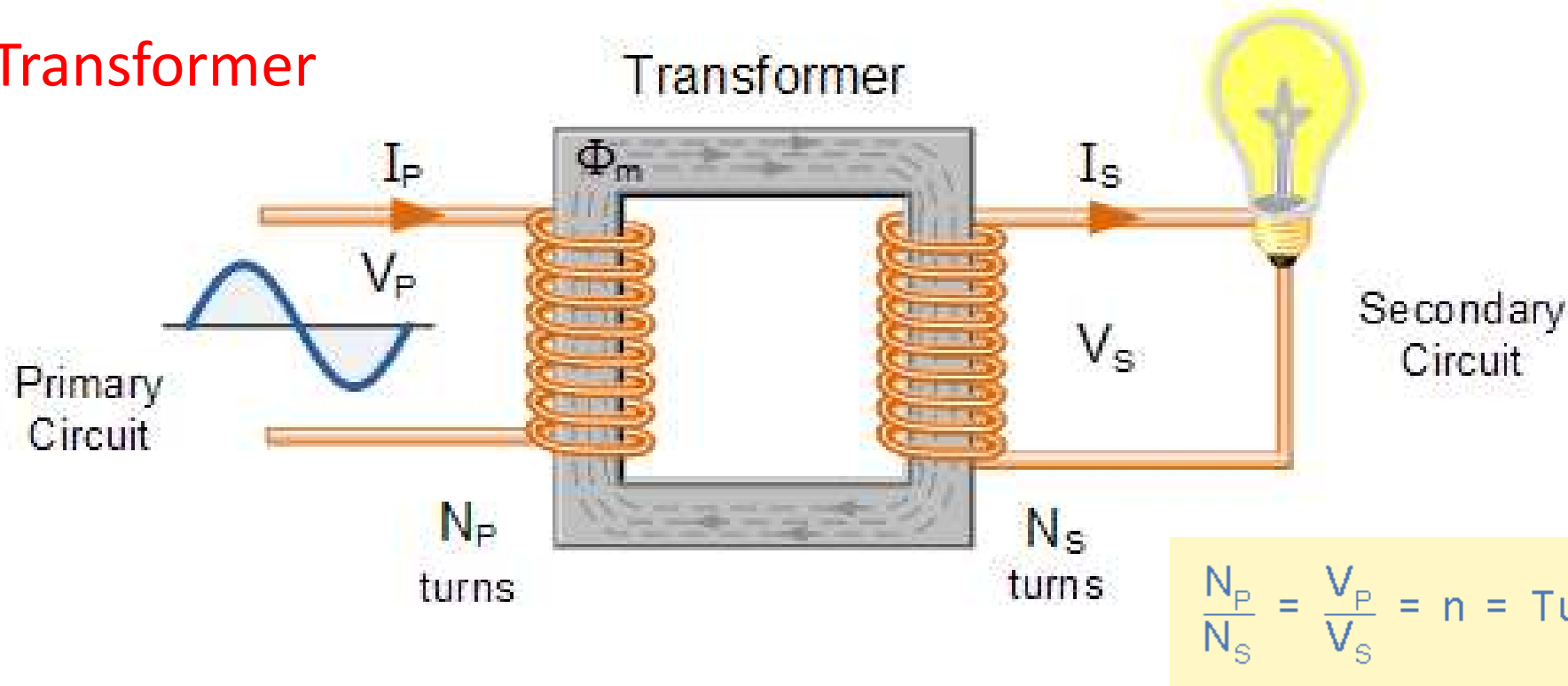
Multiple Circuit

Substation

Substations are the places where the level of voltage undergoes change with the help of transformers. Apart from transformers a substation houses switches (called circuit breakers), meters, relays for protection and other control equipment.

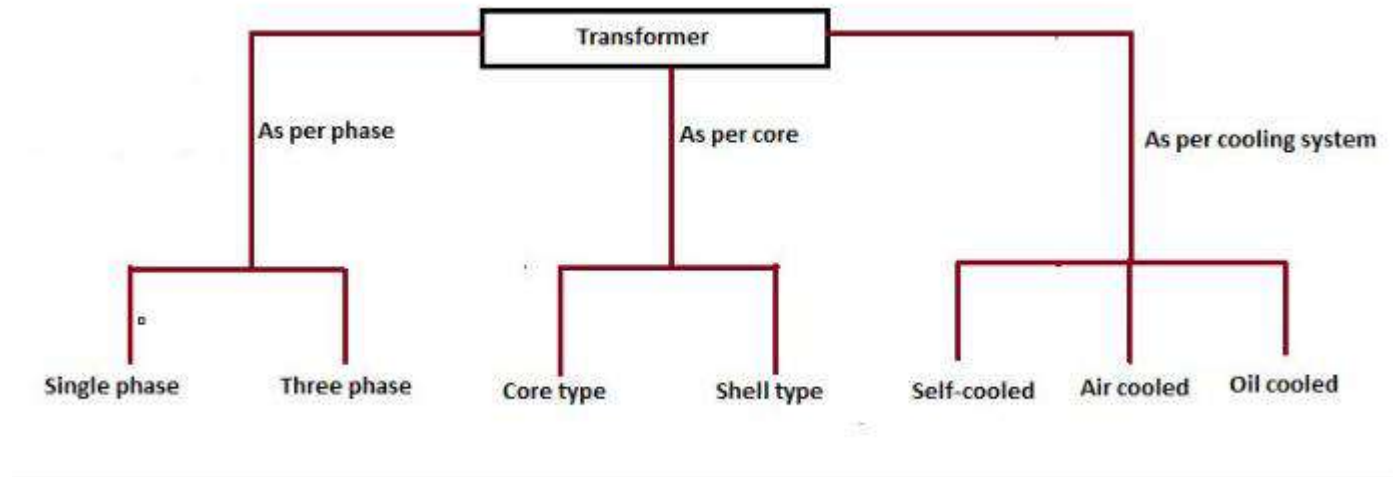


Transformer



According to the principle of mutual inductance, when an alternating voltage is applied to the primary winding of the transformer, an alternating flux ϕ_m which is called as the mutual flux is produced in the core. This alternating flux links both the windings magnetically and induces EMFs E_1 in the primary winding and E_2 in the secondary winding of the transformer according to Faraday's law of electromagnetic induction. The EMF (E_1) is called as primary EMF and the EMF (E_2) is known as secondary EMF. If a load is now connected across the secondary winding, the EMF E_2 will cause a load current I_2 to flow through the load. Therefore, a transformer enables the transfer of power from one electric circuit to another with a change in voltage level.

Classification of Transformer



Based on Voltage Levels

Commonly used transformer type, depending upon voltage they are classified as:

- **Step-up Transformer:** They are used between the power generator and the power grid. The secondary output voltage is higher than the input voltage.
- **Step down Transformer:** These transformers are used to convert high voltage primary supply to low voltage secondary output.

Based on the Medium of Core Used

In a transformer, we will find different types of cores that are used.

- **Air core Transformer:** The flux linkage between primary and secondary winding is through the air. The coil or windings are wound on the non-magnetic strip.
- **Iron core Transformer:** Windings are wound on multiple iron plates stacked together, which provides a perfect linkage path to generate flux.

Based on the Winding Arrangement

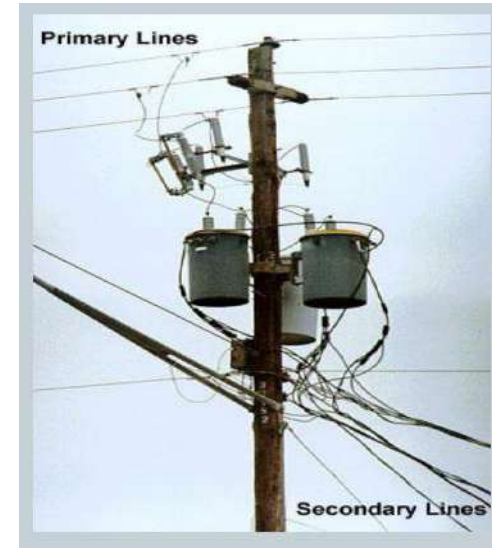
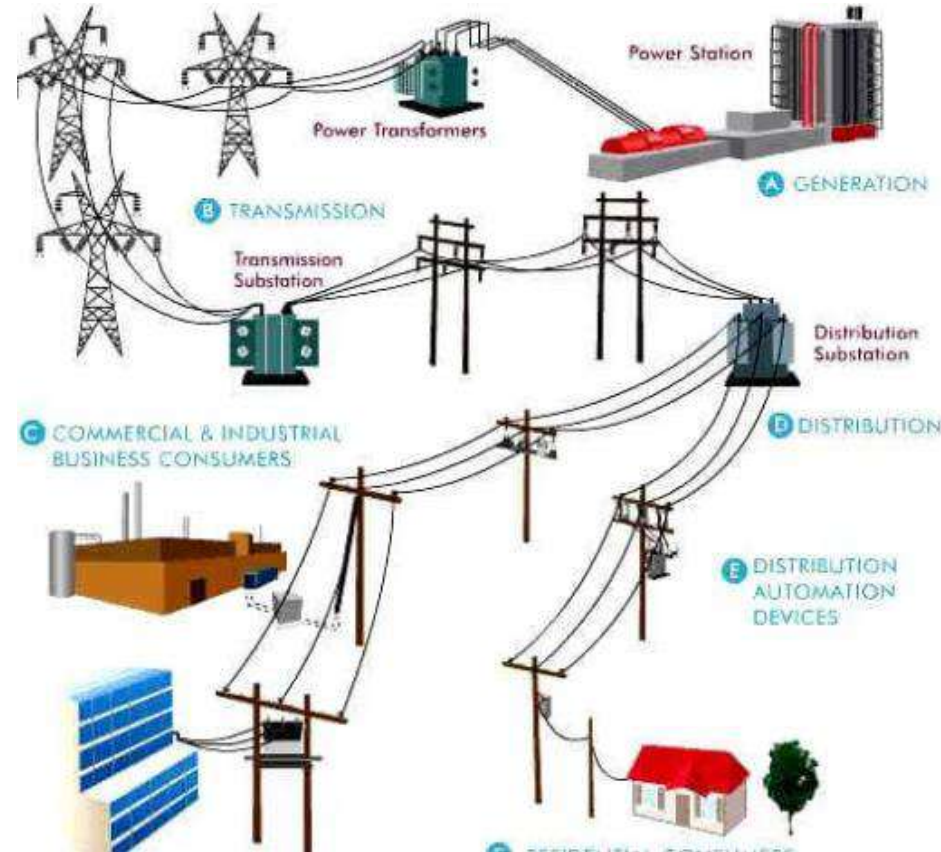
- **Autotransformer:** It will have only one winding wound over a laminated core. The primary and secondary share the same coil. Auto also means "self" in language Greek.

Based on Install Location

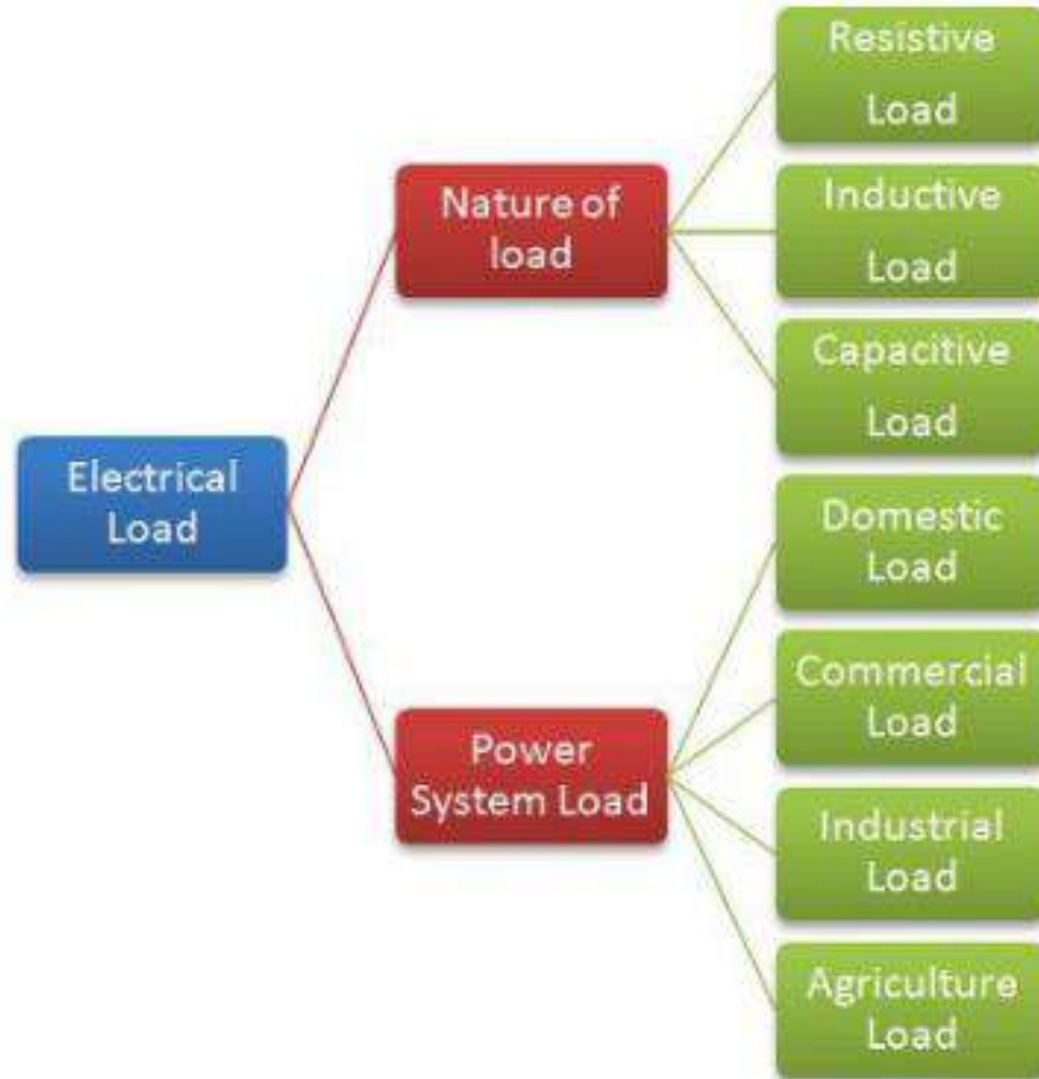
- **Power Transformer:** It is used at power generation stations as they are suitable for high voltage application.
- **Distribution Transformer:** Mostly used at distribution lanes for domestic purposes. They are carrying low voltages. It is very easy to install and characterized by low magnetic losses.
- **Measurement Transformers:** These are further classified. They are mainly used for measuring current, power.
- **Protection Transformers:** They are used for component protection purposes. In circuits, sensitive components must be protected from voltage fluctuation etc. Protection transformers ensure protection.

Distribution System

A distribution system originates at a distribution substation and includes the lines, poles, transformers and other equipment needed to deliver electric power to the customer at the required voltages.



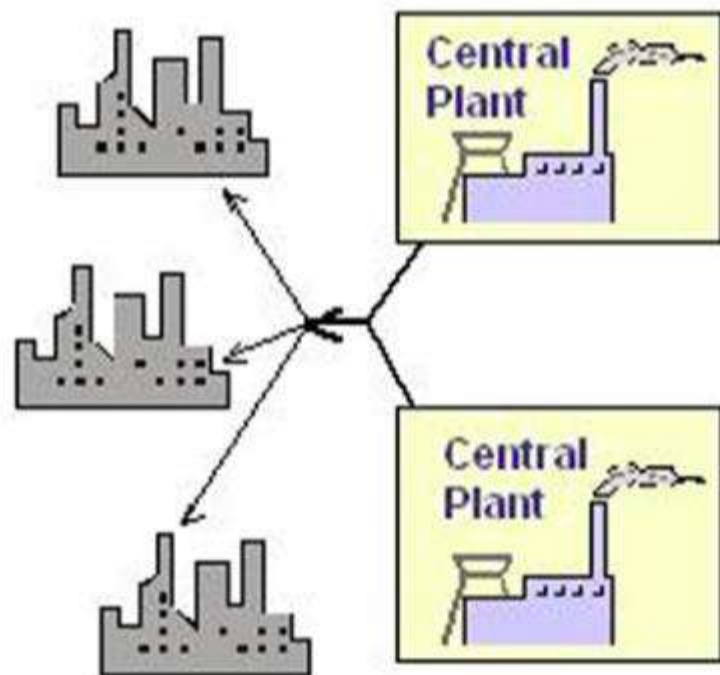
Load



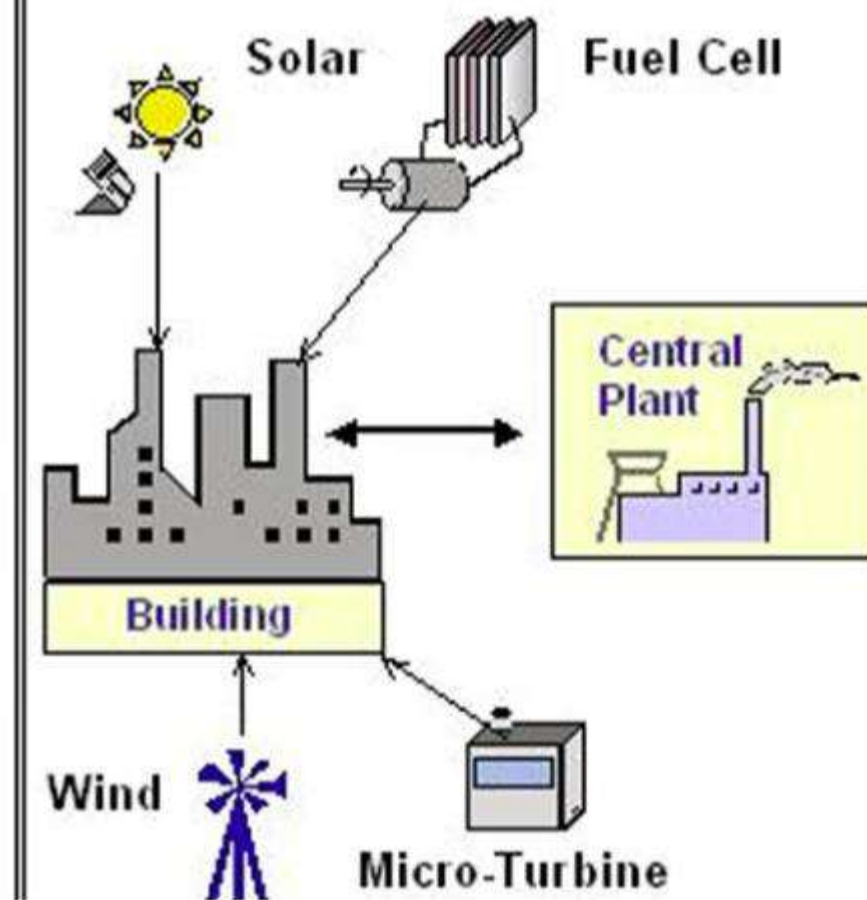
Comparison of traditional system with microgrid

Characteristics	Traditional Power Grid	Smart Grid
Topology	Mainly radial	Network
Generation	Centralized (due to the governmental view)	distributed (due to the private view)
Efficiency	Low efficiency	Relatively high efficiency
Control	Limited	More extensive
Reliability	Based on static, offline models	Real-time predictions
Distribution	One-way distribution	Two-way distribution From alternative energy
Monitoring	Manual (due to the lack of sensors)	Self-monitoring using digital technology
Response to Disturbances	Response after faults to prevent further damage	Responds to faults by focusing on prediction
Technology	Electromechanical infrastructure	Digital infrastructure and communication
Restoration	Manual (due to the lack of controller)	Self-healing
Assets Management	Low data relationship with asset management	Planning for an asset with extensive monitoring of their information
Equipment	Failure and blackout	Adaptive and islanding
Customer Choices	Fewer choices	Many choices
Active Participation Consumer	Consumers do not participate	Consumers participate actively
Provision of Power Quality	Slow response to power quality	Rapid resolution of power quality
Resiliency against Cyber-Attack and Natural Disasters	Vulnerability to natural and human destructive actions	High resilience to cyber-attack and natural disasters
New Products, Services, and Markets	Limited opportunity and the market for consumers	Integrated market and the right to choose for customers
Reaction Time	Slow reaction time	Extremely quick reaction time
System Communications	Limited to power companies	Expanded and real-time
Sensors	Few sensors	Multiple sensors throughout

Central Generation



Distributed Generation



Comparison of generations

Value	Distributed Generations	Centralized Generations	Recommendation for CG and DG options
Continuous Power	Operated to allow a facility to generate some or all of its power on a relatively continuous basis. Important DG characteristics for continuous power include: ▪ High electric efficiency, ▪ Low emissions.	Though operated to provide continuous power, its characteristics results in: ▪ Low electric efficiency as a result of high losses at the transmission system ▪ High emissions	For continuous power production, more DG need to be penetration in CG based networks to reduce emissions and increase efficiency.
Premium Power	It provides electricity service at a higher level of reliability and power quality than typically available from the grid.	Provision of power at low reliability and power quality cannot be guaranteed due to inherent high power losses.	Providing premium power would also need DG penetration in the CG network leading to better reliability and low losses.
Cost	Low variable cost Low maintenance costs	High variable cost High maintenance cost	With respect to cost, DG based networks is preferable.
Peaking Power	Operated between 50-3000 hours per year to reduce overall electricity costs.	It is operated unintermittently at various peak powers.	Combined CG and DG.
Resiliency	More resilient since it serves low power demands continuously. (avoiding, surviving and recovering from disruptions)	Less resilient but serves high power demands continuously.	Combined CG and DG.
Sustainability	Sources of power makes it more sustainable	Sources of power results in less sustainability	More of CG is preferable.

Sustainability improves the quality of our lives, protects our ecosystem and preserves natural resources for future generations.

Comparison of generations based on cost

Component Cost	Centralized Generation (CG)	Distributed Generation (DG)	
Cost of Capital	Lower Cost per unit	Higher cost per unit Saved cost of system design due to reduced capacity Saved cost of system design due to use of waste heat in cogeneration	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Fixed Operation and Maintenance Cost	Higher	Lower	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Variable Operation and Maintenance Cost	Lower	Higher	
Fuel	Same as DG	Same as CG	
Transmission	High voltage transmission is mandatory High losses and transmission failure	Only distribution required Reduced capital cost	This approach would lead to a reduced cost for the power grid system with the combined CG and DG.
Expense for Unserved Energy	High	Low	

Distributed energy System

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Distributed Energy System

- Distributed resource (DR) refers to a combined DG and energy storage (ES) system, that is, $DR = DG + ES$.
- It includes all DG technologies and can store energy in a battery, flywheel, regenerative fuel cell, superconducting magnetic storage device, and so on.
- Distributed energy resources (DER) is generation of electricity or heat at the distribution level for local use.
- It includes all DR technologies, and systems connected to a utility grid with which users can sell surplus power to utilities.

Distributed Energy System cont.....

- Distributed generation (DG) is any small electric power system independent of traditional utility grids, which is located on the user side to meet end-users demands.

- The DG comprises (Fig.1) of sources such as:

- ❖ Internal combustion engine
- ❖ Micro turbine, fuel cell
- ❖ Small hydropower system,
- ❖ Photovoltaic (PV) generation
- ❖ Wind generation
- ❖ Waste generation, and
- ❖ Biomass generation

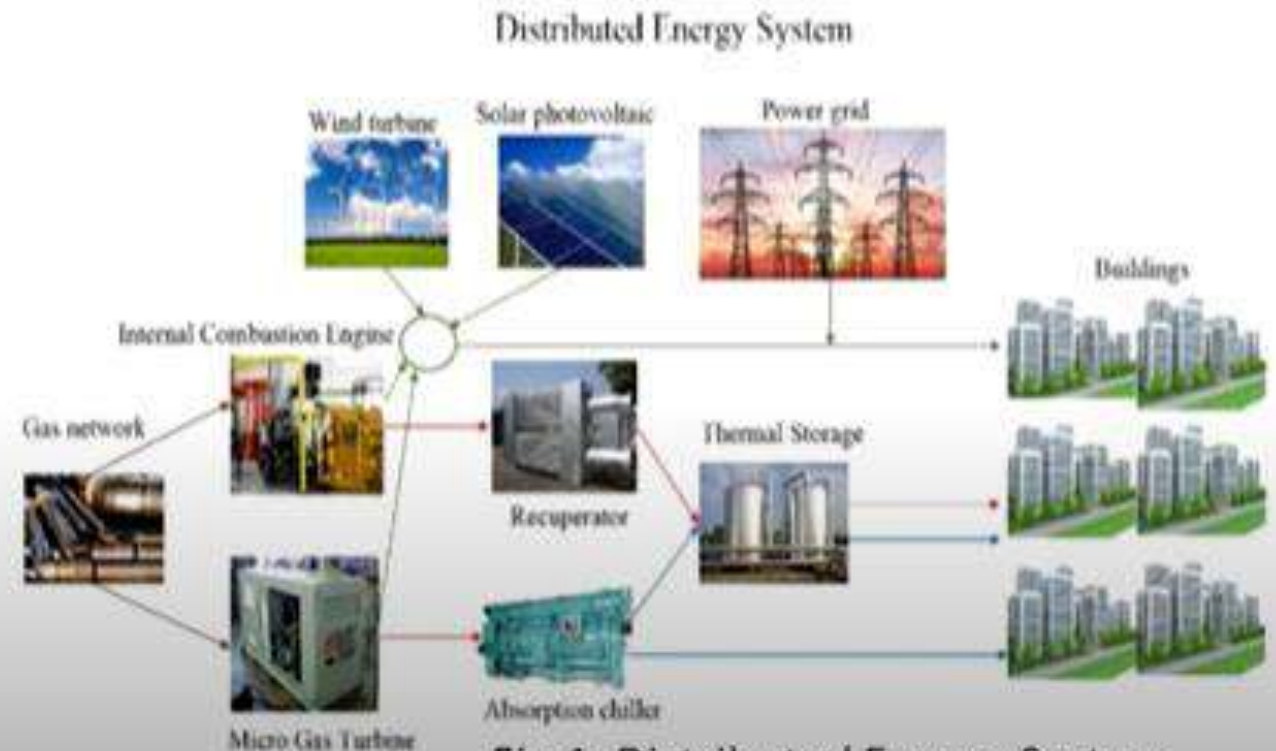


Fig.1: Distributed Energy System

Characteristics of Distributed Energy System

1. Comprehensive and efficient energy use

- ❖ With small size and high flexibility, a distributed energy system can satisfy the load demand and also solve the difficulty of long-distance transmission of cooling or heating sources.
- ❖ The efficiency of distributed energy can reach above 80% without transmission loss.

2. An improvement to grid security and stability

- ❖ Deploying a distributed energy system on the user side as a supplement to the macrogrid can significantly enhance reliability and continuity of power supply to critical loads in the event of grid collapse or disasters such as an earthquake, snowstorm, sabotage, or war.

3. Small capacity, small area, low initial investment, no long-distance transmission loss and investment on transmission and distribution (T&D) network, and Ability to meet special demands.

❖ This obviates the need for long-distance transmission and distribution and causing no feeder loss, requiring no investment on T&D network, and contributing to good economy and flexible, energy-efficient, and comprehensive services for end users.

4. Environmental friendliness, diversified energy mix, a new way to utilize renewable energy.

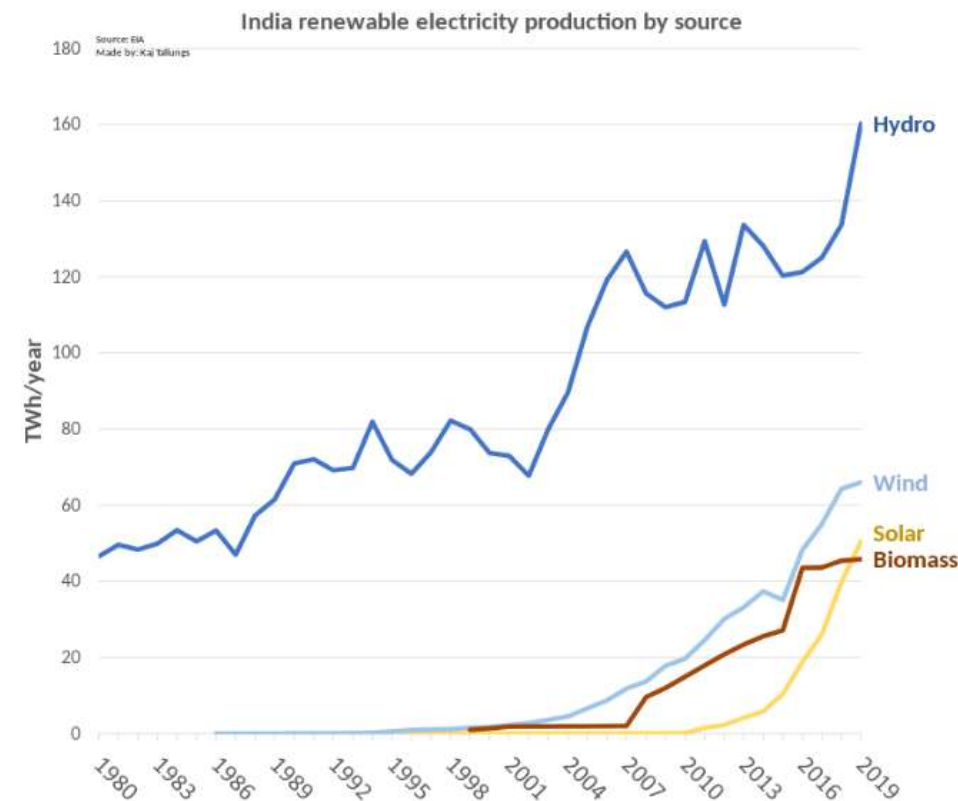
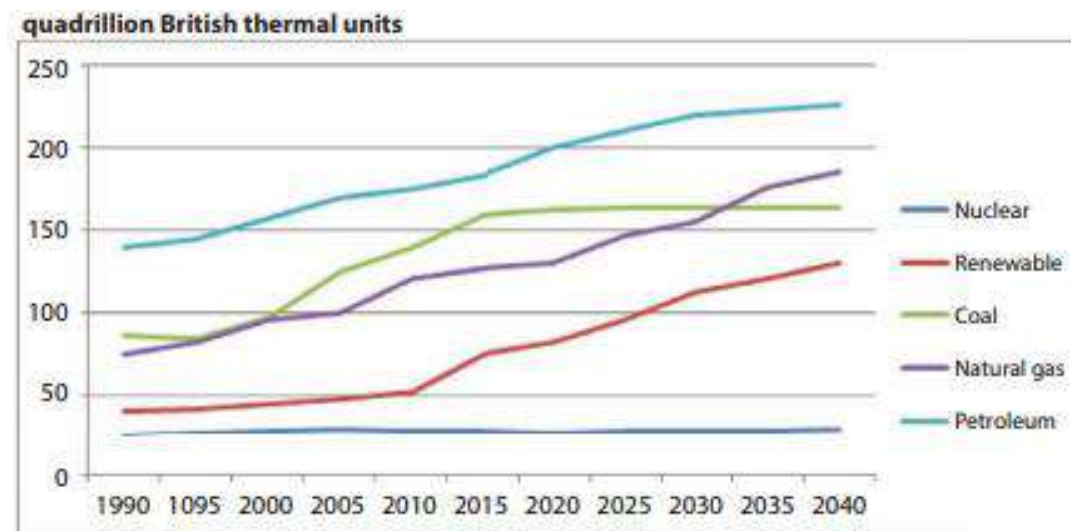
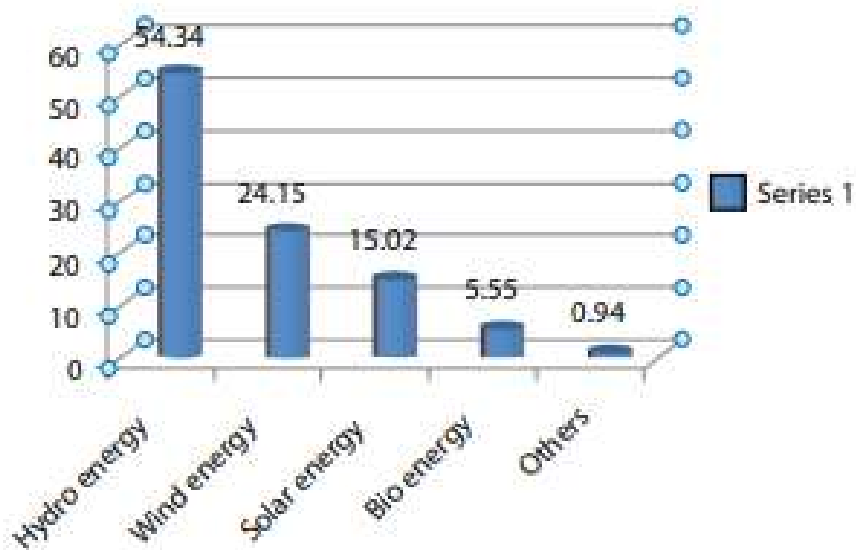
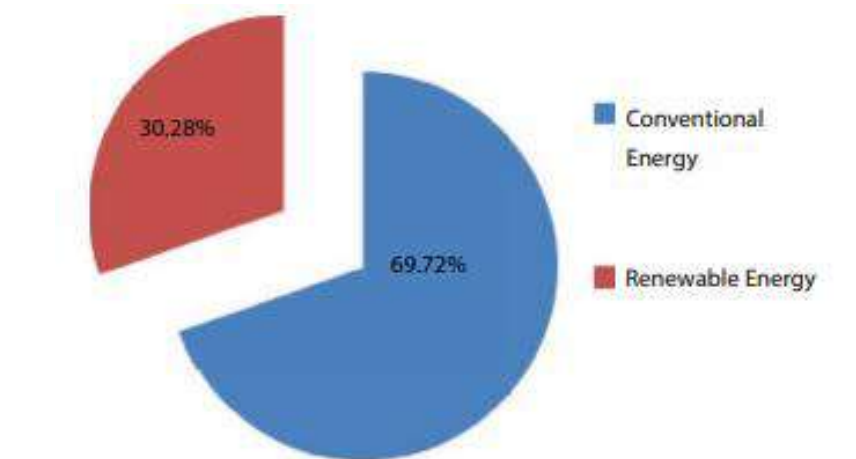
❖ Using clean fuels as the energy source, a distributed energy system is environmentally friendly.

❖ They have smaller capacity and is suitable for integration of renewable energy.

Advantages of Distributed Energy System

Technical side	Economic side
Reduces line losses	Defers investment for facilities upgrades
Voltage profile improvement	Reduces operation and maintenance cost
Reduces emissions of pollutants	Enhances productivity
Increases overall energy efficiency	Reduces health care cost by improving environment
Enhances system reliability and security	Increases overall efficiency by reducing fuel costs
Improves power quality	Reduces reserve requirements and the associated costs
Relieves transmission and distribution congestion	Lowers operating costs due to peak shaving

Renewable energy sources



Renewable Energy

Advantages

Disadvantages

Easily Regenerated [2]

Weather Dependency [7]

Boost Economic Growth [3]

High Installation Cost [8]

Easily Available [4]

Noise caused by Wind Energy [9]

Support Environment [5]

Fluctuation problem (Solar) [10]

Low Maintenance Cost [6]

Intermittency Issue (Wind) [11]



Type of Energy	Source	Advantage	Disadvantage
Solar Energy	Sunlight	Infinite resource Environmental friendly	Expensive Large space
Wind Energy (Wind Power)	Wind	Rapid growth Low operational costs	Environmental issue Noise problem
Geothermal Energy	Underground heat of Earth	Potential infinite	Limited area (Volcanic activity)
Biomass Energy	Decaying plant or animal waste	Carbon neutral Cost effective	Expensive Requires space
Hydropower (or Hydroelectric Power)	Gravitational force of falling or flowing water	Reliable Flexible	Expensive Environmental issues Limited reservoir
Tidal Energy	Movement tide	Predictable Long lifespans	Environmental issue Expensive
Wave Energy	Movement of seawater	Ideal for island	Environmental issue Expensive

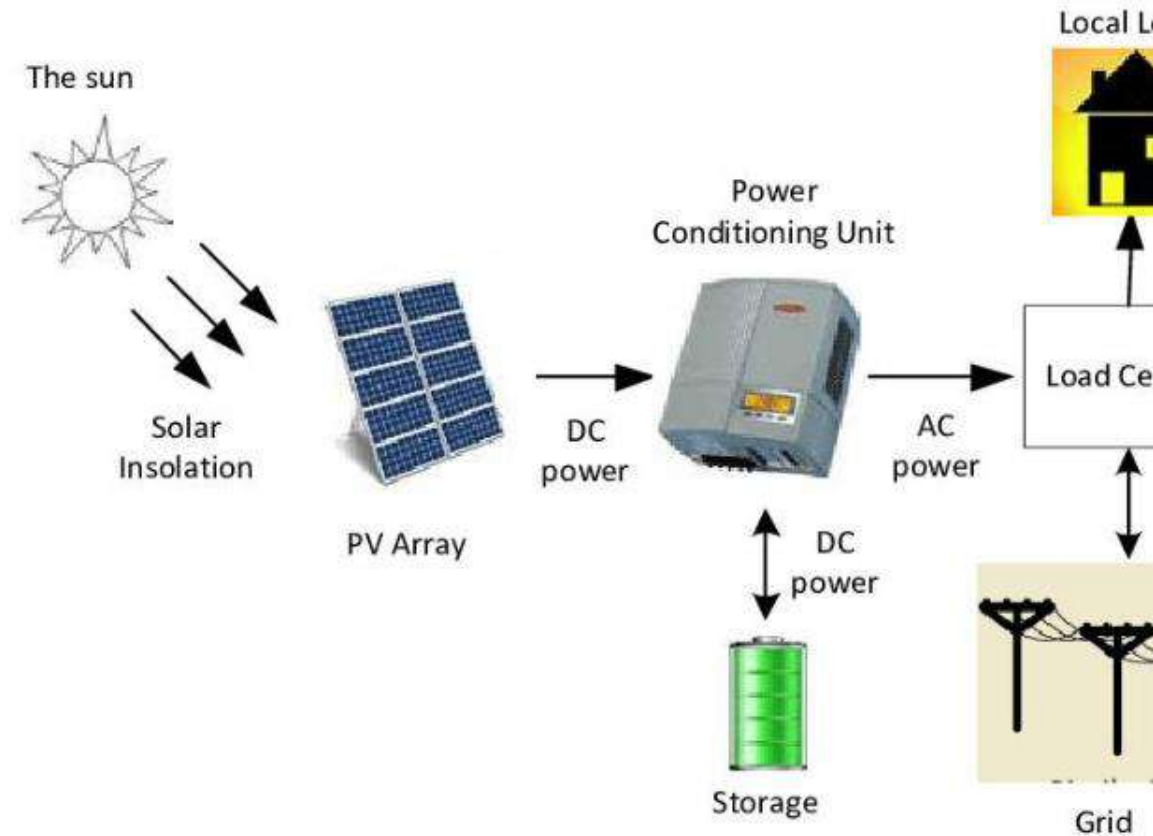
Solar energy

PV is a means of electricity generation by direct conversion of solar energy to electricity.

The solar cell is the core component for light-to-electricity conversion.

Currently, crystalline silicon solar cell is the dominant type in the market, and other types include amorphous silicon thin film solar cell and compound thin film PV cell.

A PV power system may operate independently or in parallel with the grid.



Wind energy

- Wind energy is a clean renewable energy.
- In wind energy, the kinetic energy is converted to mechanical energy by the rotor and then the mechanical energy is converted to electrical energy by generator.
- Wind power system also can be classified as independent and grid-connected type.
- Fig.3 shows the independent wind power system block diagram

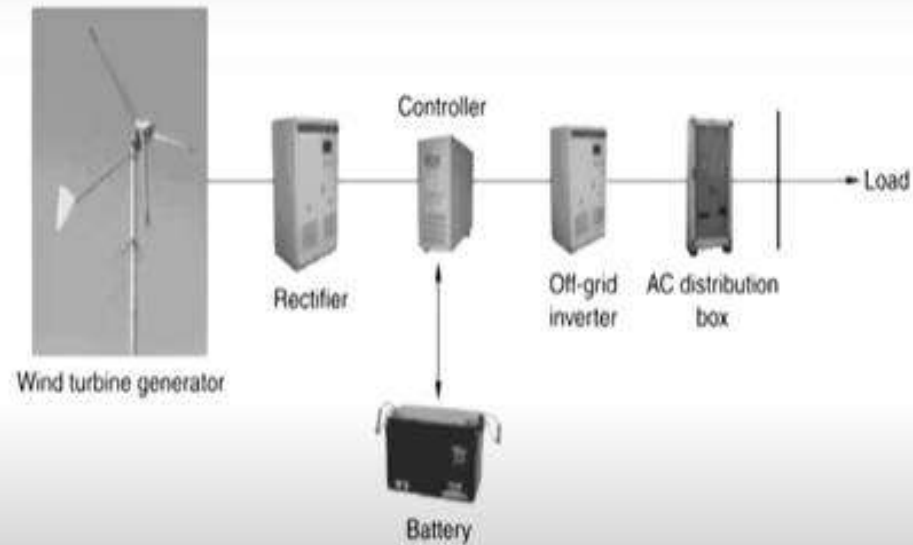
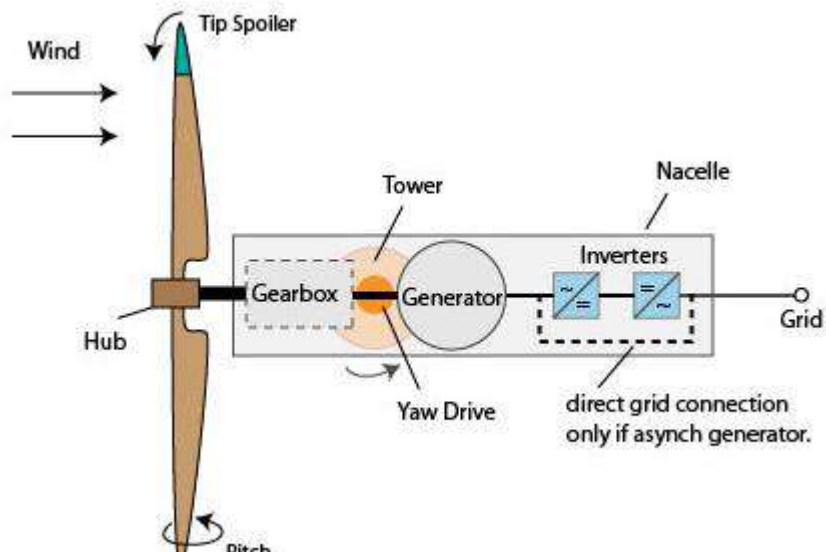
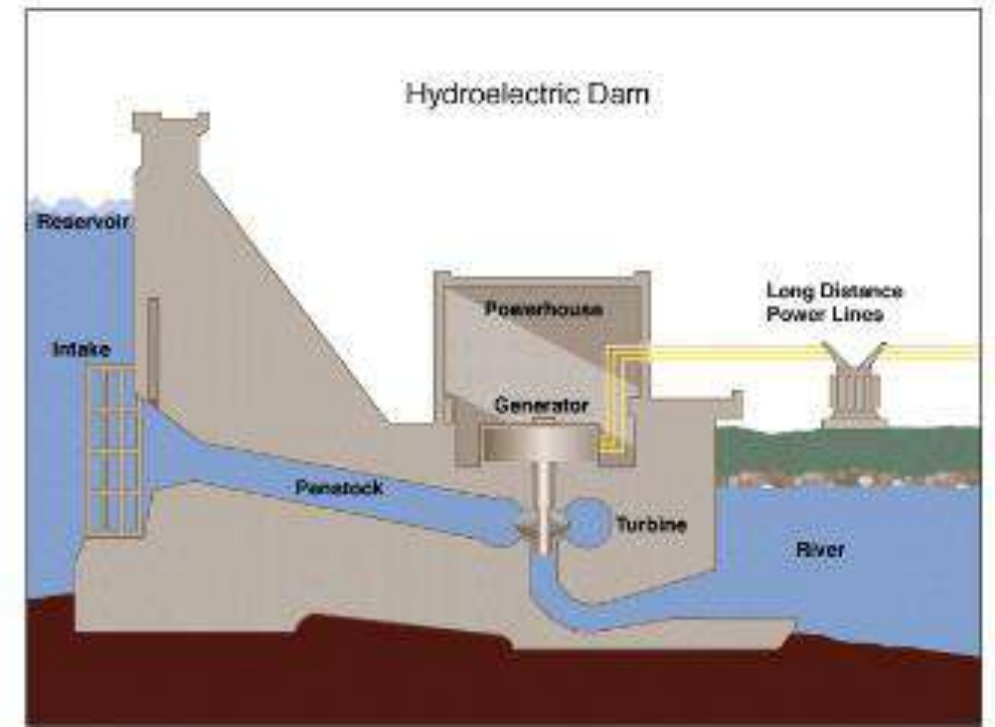
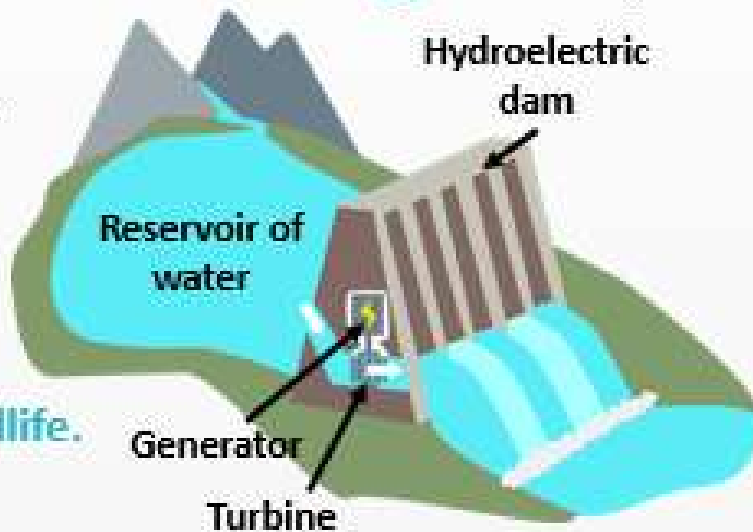


Fig.3: Structure of independent wind power system



Hydro energy

- **Hydroelectric power** harnesses the **kinetic energy of** running water.
- Water flows downwards with **gravity** to spin a **turbine**.
- More reliable than solar and wind power.
- Hydroelectric dams are very **expensive** and can **harm wildlife**.
- **1.5%** electricity from hydroelectric schemes in the UK (29% total)

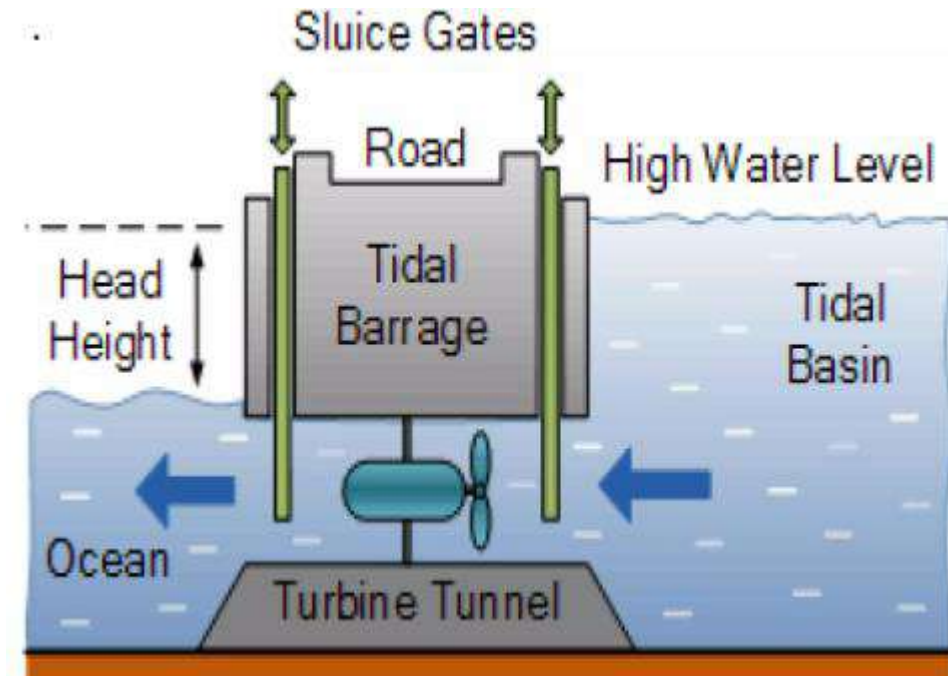


Ocean energy

- The oceans cover 75% of the world surface.
- It is the largest renewable energy source available to contribute to the security of energy supply reduce greenhouse gases emission.

→ THE OCEAN CONTAIN TWO TYPE OF ENERGY

- Ocean thermal energy conversion from the sun's heat.
- Mechanical energy from tides and waves.



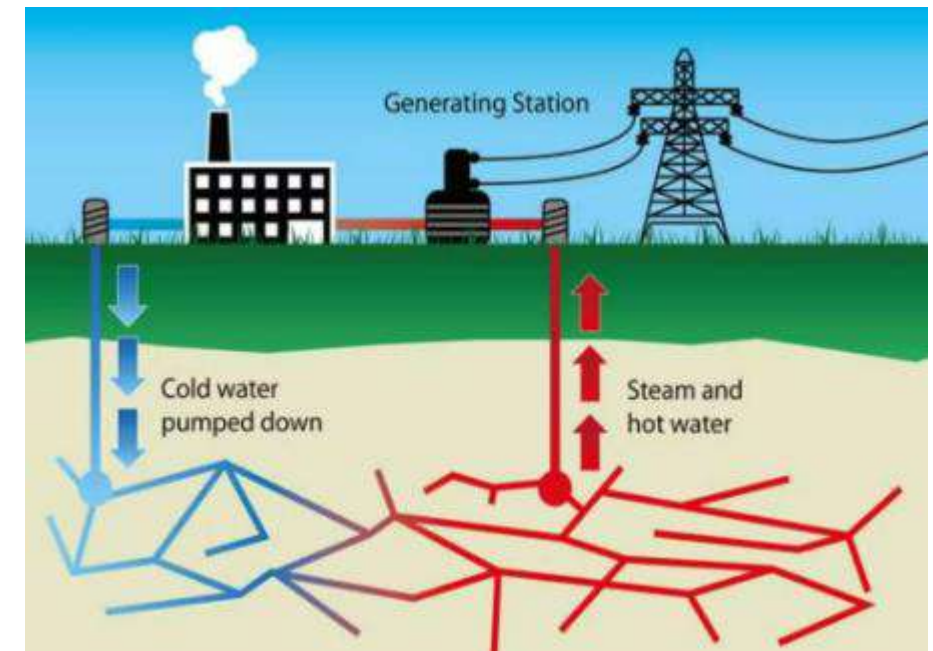
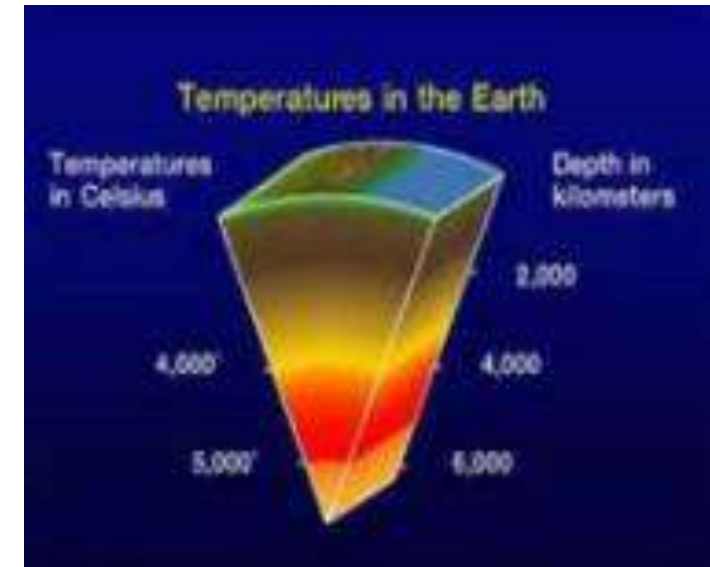
Geothermal energy

- **Geothermal energy** = heat energy from the Earth
- **Decay of radioactive elements** and **residual heat** from planetary formation 4.5 billion years ago
- Water is pumped down into hot rock where it is heated.
- Steam can then be used to heat buildings directly or to generate electricity by spinning a turbine.



Nesjavellir Geothermal Power Station, Iceland

- Geothermal energy is the heat from the Earth. It's clean and sustainable.
- Resources of geothermal energy range from the shallow ground to hot water and hot rock .
- It found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma.



Biomass energy

- Biomass is a **renewable** source of fuel to produce energy.
 - because: waste residues will always exist – in terms of scrap **wood**, mill residuals and forest resources; and.
 - properly managed forests will always have more trees, and we will always have crops and the residual biological matter from those crops.
-
- **Bioethanol** – used as fuel and as a petrol additive to increase octane and lower carbon emissions
 - **Biodiesel** – used as fuel and used to reduce levels of particulates and carbon monoxide in diesel powered vehicles



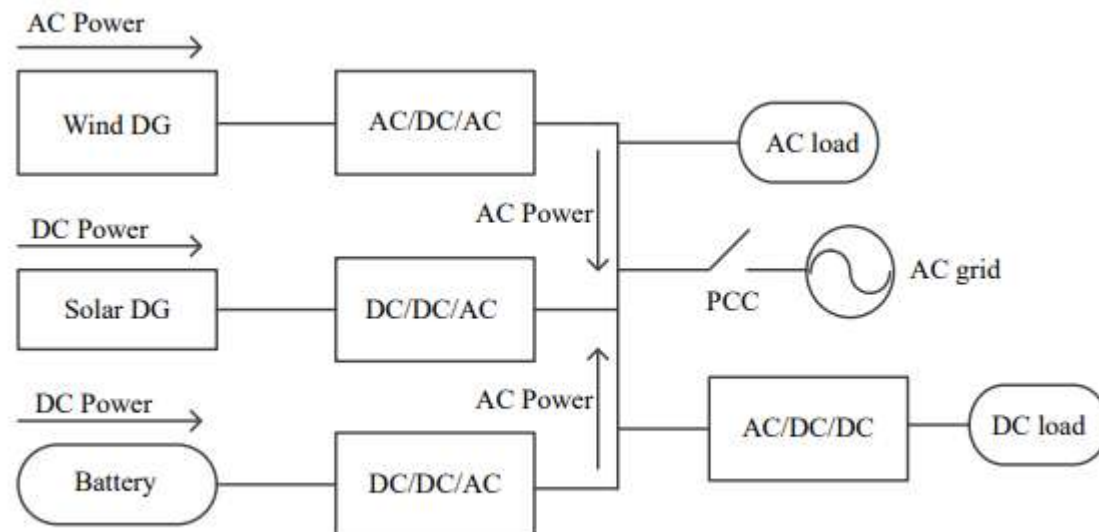
AC, DC, and Hybrid microgrid

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ACMG Structure

The main components of a micro-grid are - Distributive energy sources, Power storage system, fixed and flexible loads, controller which determine micro-grid interaction with grid, smart switches which put connection between load and source, protection and communication device and control and automation system.

For solar cell and battery a DC-DC-AC converter is used. where for wind sources a AC-DC-AC converter is used. AC load can be connected directly but to connect DC load a AC-DC-DC converter is needed.



ACMG Control

Centralized control: When the internal microgrid control is performed in a centralized way, a single entity is in charge of carrying out the decision-making processes.

- Centralized control is defined as a hierarchy decision-making structure where all decisions and processes are handled strictly by one single controller known as microgrid central controller (MGCC). Centralized control system relies on information data gathers in MGCC. The MGCC is responsible to accomplish calculation, determine the control actions for all DGs unit and send the information back to main systems .
- A microgrid central controller can be described as the controller that determines the setpoints of the loads, distributed generation and storage units.
- Centralized controller uses communication network for exchange the information between an MG and main grid. This control is suitable for small scale MGs. However, this type of control has a low reliability and redundancy. Other drawbacks of this control are severe communication problems, and requires shutdown the whole system in case of system maintenance.

ACMG Control (Centralized)

The control structure of a micro-grid is hierarchical and can be divided into primary, secondary and tertiary control. The main motto is to minimize cost and maximizing efficiency, reliability and controllability.

- Primary control is the localized control of converters to control local variables such as voltage and frequency. The local controller either does droop control or virtual impedance control to control the voltage frequency and power.
- The secondary control is mainly a centralized controller which compensates the steady state errors in voltage and frequency between different converters. It also controls the voltage profile of micro-grid bus to operate in different conditions. Mainly communication devices and wide area monitoring devices are used to control between different converters. The active and reactive power control between different converters is done here.
- By tertiary control the micro-grid operation is optimized and can interact with the power system by controlling the active and reactive power of different generators. Optimization is based on some economic criteria like the demand and energy supply balance. It estimates the change in load power, the generator power, the storage capability and specific demands of the grid to optimize economically the operation of micro-grid. Here the active and reactive power exchange between microgrid and main grid is controlled.

Primary Control: Local Control (LC)

- Objectives:**
- Parallel power sharing among multiple DG units
 - Bus voltages and system frequency stabilization

Droop Based Method

- Conventional Droop Control
- Adjustable Load Sharing Control
- VPD/FQB Droop Control
- Virtual Frame Transformation Method
- Virtual Output Impedance Method
- Adaptive Voltage Droop Control
- Signal Injection Method
- Non-linear Load Sharing

Non-Droop Based Method

- Centralized control
- Master-slave control
- Average load sharing control
- Circular chain control (3C)

Secondary Control: Microgrid EMS

- Objectives:**
- Microgrid Energy Management System (EMS)
 - Maintaining all electrical levels within acceptable range
 - Synchronization or restoration of microgrid with grid

Methods

- Genetic Algorithms (GA)
- Particle Swarm Optimization (PSO)
- Model Predictive Control (MPC)
- Ant Colony Optimization (ACO)
- Potential Function Based Control
- Voltage Unbalance Compensator Technique
- Multi-Agent (MAS) Concept
- Gossip-Based Technique
- Distributed Cooperative Control

Tertiary Control: Host Grid

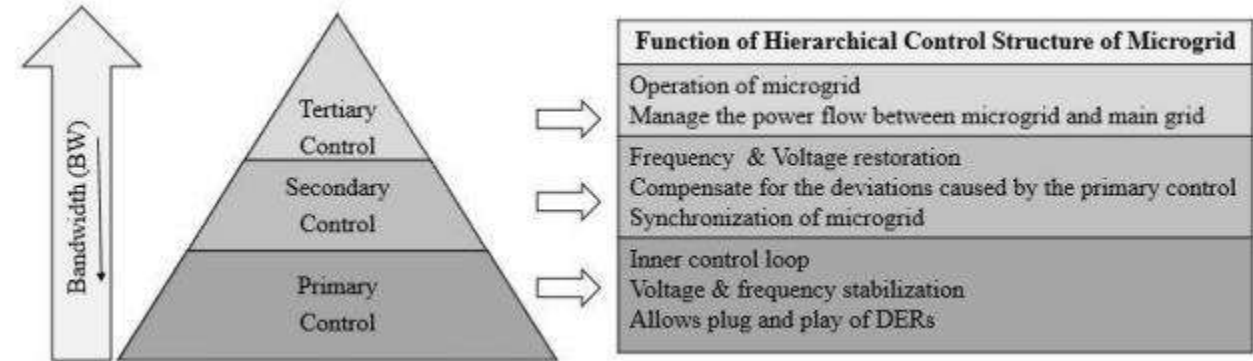
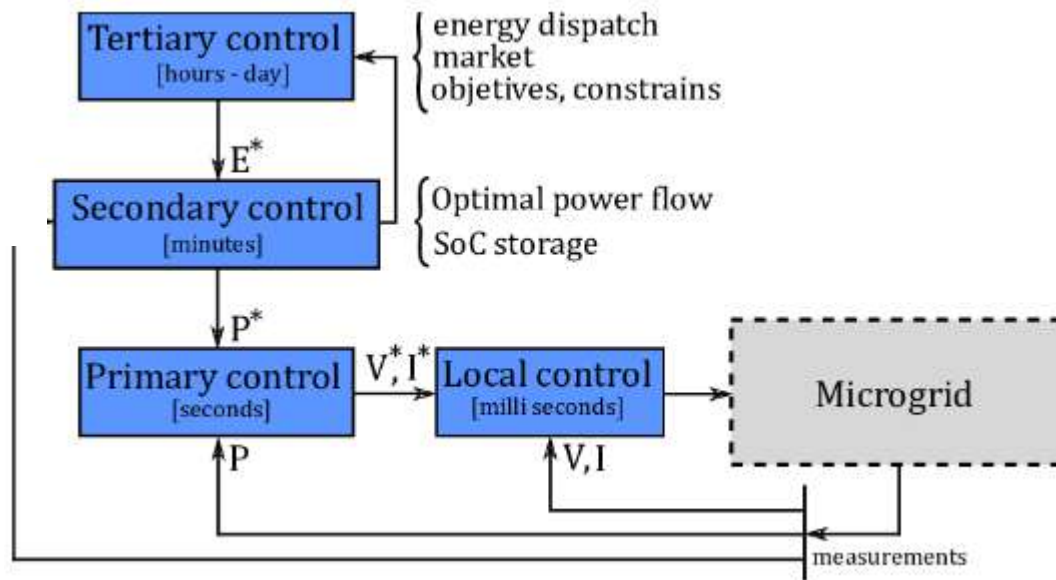
- Objectives:**
- Sets '*Optimal*' set points as per requirements of the host grid
 - Coordinates the operation of multiple microgrids
 - Import and export power to/from the grid

Methods

- Equal Marginal Cost Based Approach
- Gossiping Algorithm
- Game Theory Based Approach

ACMG Control (Centralized)

SoC



ACMG Control (decentralized)

Decentralized control: In a decentralized control scheme, the internal microgrid control takes place at each controllable element in the microgrid.

- Decentralized control can be defined as a systematic delegation of decision making where one MG has multiple controllers, where each of local controller has an access to different information. This type of control enables DG units and loads to act independently.
- In decentralized control, communication with other DG units is not necessary as this control enables plug and play capability.
- This kind of control allows a flexible system that can adapt to change system structures and situations. Hence, this control significantly reduces the computational need and releases the stress on the communication network. Despite its advantages, inability of local DGs in different areas to share information and complexity , are the main drawback for this control.

Control Structure	Centralized	Decentralized
Structure & Expansion Capacity	Suitable for small scale MG & Low scalability	Suitable for big scale of MG & Moderate
Decision making	Central controller DER depend on single central controller to send and receive information	Multiple controller for one MG
Communication network	Command & control Need high bandwidth of communication	Peer-to-peer Local controllers are connected with communication bus.
Reliability	Low	Medium
Cost	High	Moderate
Single point of failure	Yes	No

ACMG Protection Issues:

- The integration of DERs cause different problems in micro-grid like voltage rise, unwanted is-landing and violation of thermal limit of transmission line.
- Traditional power system over-current protection depends upon unidirectional radial system of power system. The addition of different DERs in the system change it to a complex bidirectional multi-source system where over-current protection does not work.
- Short circuit current magnitude changes with introduction of each DG to the grid. Majority of protection devices used this current magnitude in their protection scheme which cannot be used in micro-grid.
- In grid connected mode fault current has very higher value(10-50 times of full load current) so easily can be detected in over-current protection but in is-landing mode when a large number of DERs are connected then fault current magnitude become very lower (2-5 times of full load current). So over current protection does not work in is-landing mode.

ACMG Protection In Islanded mode:

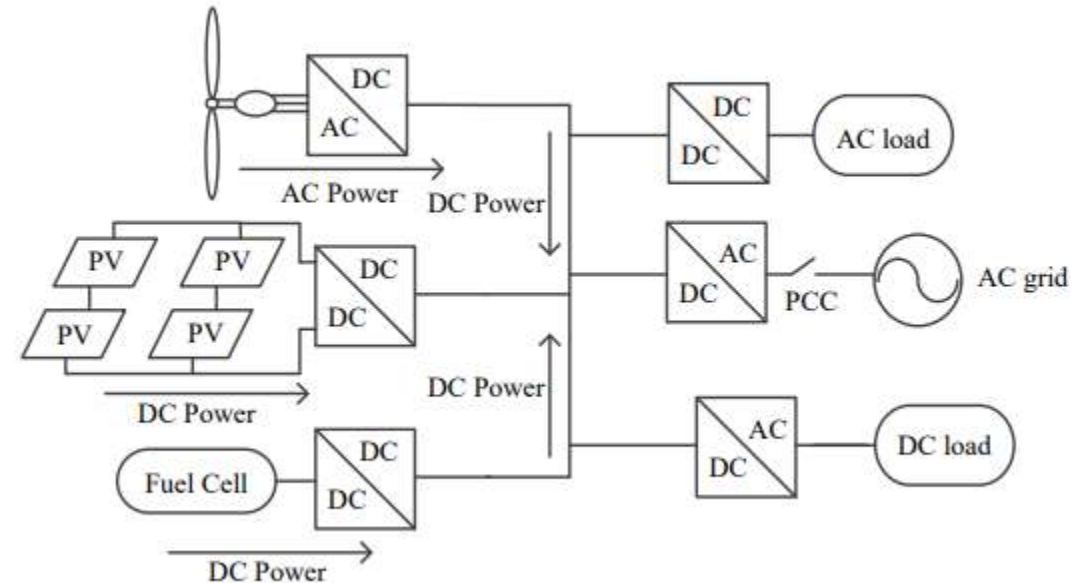
- Harmonic current based protection is for line-line-ground fault. The total harmonic distortion of converter output voltage is continuously measured by the protection relay. If some fault occurs the faulted phase has more amount of THD than sound phase. So if THD exceeds a certain value then the converter get a shut down by the relay. Comparison of THD between faulty phase and sound phase is used to detect the fault location.
- Voltage based protection scheme is for line to line and line to ground fault. Here the relay measures the output voltage of the converter and transforms the voltage into fixed or DC quantities by d-q frame of reference. Any kind of disturbances due to some fault is highly reflected into the DC quantities and immediately the converter and source got shut down.
- Symmetrical component and residual current based protection for line-line and line-ground fault. This scheme use residual current protection for upstream of the fault and zero sequence current for downstream of the LG fault. The negative sequence protection scheme is used for line-line fault.
- Some adaptive protection schemes (use of microprocessor) can be used by using intelligent electronic devise and the communication link.

DCMG Structure

A DC microgrid comprises of :

- ❖ DC Power Sources (PV Solar / Wind / Fuel Cell / Rectifier connected to a utility grid)
- ❖ DC Power Distribution Network(s) (Safe Class 2 wiring / Conduit / Wire)
- ❖ DC Devices / Loads (Lighting / Computers / Electronic Equipment / Controls / Motors / Fans)
- ❖ Controls / Monitoring (Wireless / Wired / Virtual / Cloud Based)

Here the solar and battery are connected by DC-DC converter to the bus where the wind source is connected through a AC-DC converter. The DC loads are connected through a DC-DC converter as voltage level of load may be different and an AC load is connected through a DC-AC converter. The main grid is also connected through a DC-AC converter.



DC microgrid advantages

- DC loads are increasing today and any AC loads can be converted to DC load by using a VFD. For DC loads in DC microgrid a DC-DC converter is used whereas for AC microgrid a AC-DC converter is used. The efficiency of DC-DC converter is higher than AC-DC converter.
- If we consider switching loss and conduction loss of converter and transmission line, loss in DC microgrid is less.
- In DC microgrid component takes less space and as efficiency is higher so lesser cooling requirement needed so less costly.
- To use an energy storage system DC microgrid is preferred as it has higher compatibility.
- Control of DC microgrid is easier as only one parameter needs to be control which is voltage whereas in AC microgrid voltage and frequency need to be controlled.
- No synchronization is needed in DC microgrid so generator can come back on line easier. The conversion from is-landed mode to grid connected mode taken less time and less control.
- In DC microgrid reactive power is eliminated so reliability and efficiency of power system increases.
- In DC microgrid distributed energy storing device can be used instead of a big storing device which is technically impossible for AC microgrid. Which reduce the transmission loss and rectification loss.
- Multiple DC renewable resources can easily integrated as there is no need for synchronization.
- DC microgrid system transmission line can be used for telecommunication system.

DC microgrid disadvantages

- As our traditional system is AC so very less research is done on DC devices.
- Funding and new construction of transmission system is another drawback.
- Existing plug in devices all are compatible to AC power system. So design of all plug in devices need to be changed if they are connected to DC microgrid.
- Presently there is no extra tax credit for using DC microgrid power. So many customer are not interested.
- DC microgrid has stability and protection issues.

DC microgrid applications

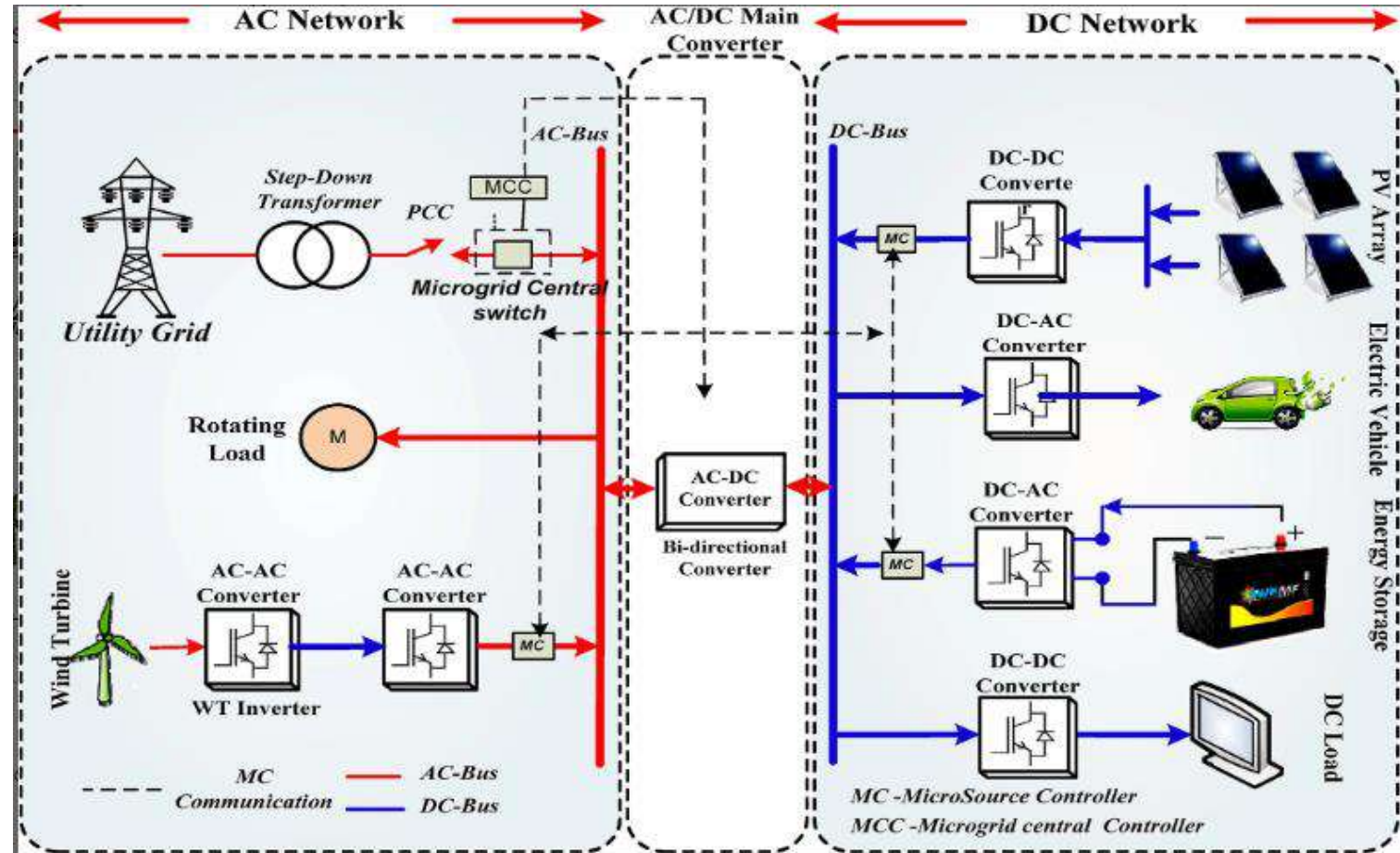
- **Data centers** have been the testing grounds for DC microgrids due to both their high energy demand and their almost entirely DC load profile. Currently, data centers are the areas that most commonly use DC power for things other than lighting. Data centers have consistently demonstrated savings of over 20% when compared with typical AC distribution architecture.
- In **traction systems** DC microgrid can be used.
- For **under water electric transportation** system, any AC current creates capacitance, so DC microgrid can be used.
- Direct current is also used to **tie together the various grid regions** in the US. This has to do with the fact that, for a grid to function, all of the generators need to sync up their frequency so that the peaks of the sine waves all hit at the same point. When you are trying to tie several regions together this becomes very difficult.
- **Lighting** is often thought of as an alternating current load, however in today's world more and more is actually DC. As the drive to increase efficiency moves forward we are turning to lighting sources such as fluorescent and LED (solid state) lighting to allow for this.

AC vs DC microgrid

Microgrid type	AC	DC
Conversion efficiency	Low: Multiple AC/DC and AC/DC conversions have to be used when interconnecting renewable sources and storages	High: AC/DC and DC/AC conversions between renewable sources and storages are reduced
Cost on converters	High: DC/AC converter has to be invested for each of the renewable sources and storages	Low: Reduced conversion stage means less converters are required
Transmission efficiency	Low: Additional loss due to reactive current	High: Loss associated with reactive current eliminated
Power supply reliability	Difficult-to-guarantee seamless transition after a utility fault	A guaranteed smooth transient DC power supply with limited voltage variation
Controllability	Difficult: Both voltage and frequency regulation needed; unbalance compensation needed in a three-phase system	Simple: No frequency, reactive power, or phase unbalance concern
Load availability	High: Available loads are dominantly designed with AC power supply	Low but with great potential: Digital and converter-based loads are highly compatible to DC
Protection	Mature arcing technique with cost-effective circuit breaker and well-developed protection system	High-cost circuit breaker with protection theory and equipment under development

Hybrid microgrid

- Reduces dc-ac-dc and ac-dc-ac conversions
- Consists of both AC and DC networks
 - Connected by multi-bidirectional converters
 - Sources and Loads are connected to their corresponding network types.
 - Energy Storage Systems can connect to either



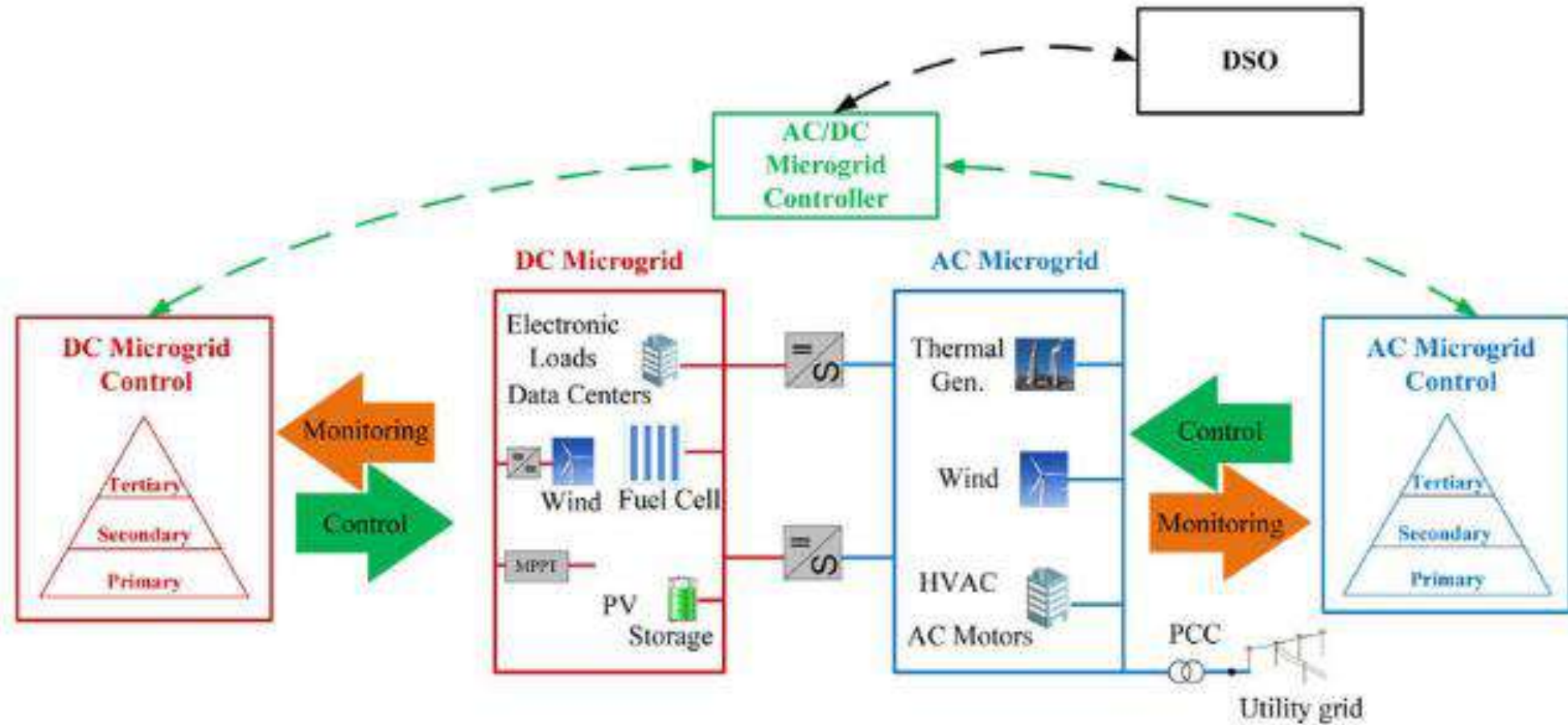
Hybrid microgrid advantages

- AC or DC based devices are directly connected to the network with the minimum number of interface elements, reducing the conversion stages and therefore the energy losses. This feature makes hybrid microgrids suitable for the integration of the increasing dc-based units—e.g. EV, photovoltaic generation, fuel cells, ESS, laptops, mobile phones, etc.—while maintaining the ac-based devices connected to the ac network.
- There is no need for synchronization of generation and storage units as they are directly connected either to the ac or dc network. Hence, the control strategy for these devices is simplified.
- The modification of voltage levels can be performed in a simple manner in the ac-side by the use of transformers. In the dc-side the conversion is performed by the use of dc-dc converters.
- A hybrid microgrid can be developed by the addition of a power converter to the current distribution grid and the communication network for the connected devices.

Hybrid microgrid disadvantages

- The operation of different energy sources and the control and interaction between them can become complicated.
- While the maintenance cost is low, the initial investment for a hybrid microgrid is higher as new converters need to be added.
- New construction is required which increases cost and complexity.
- Protection is a problem for DC parts.

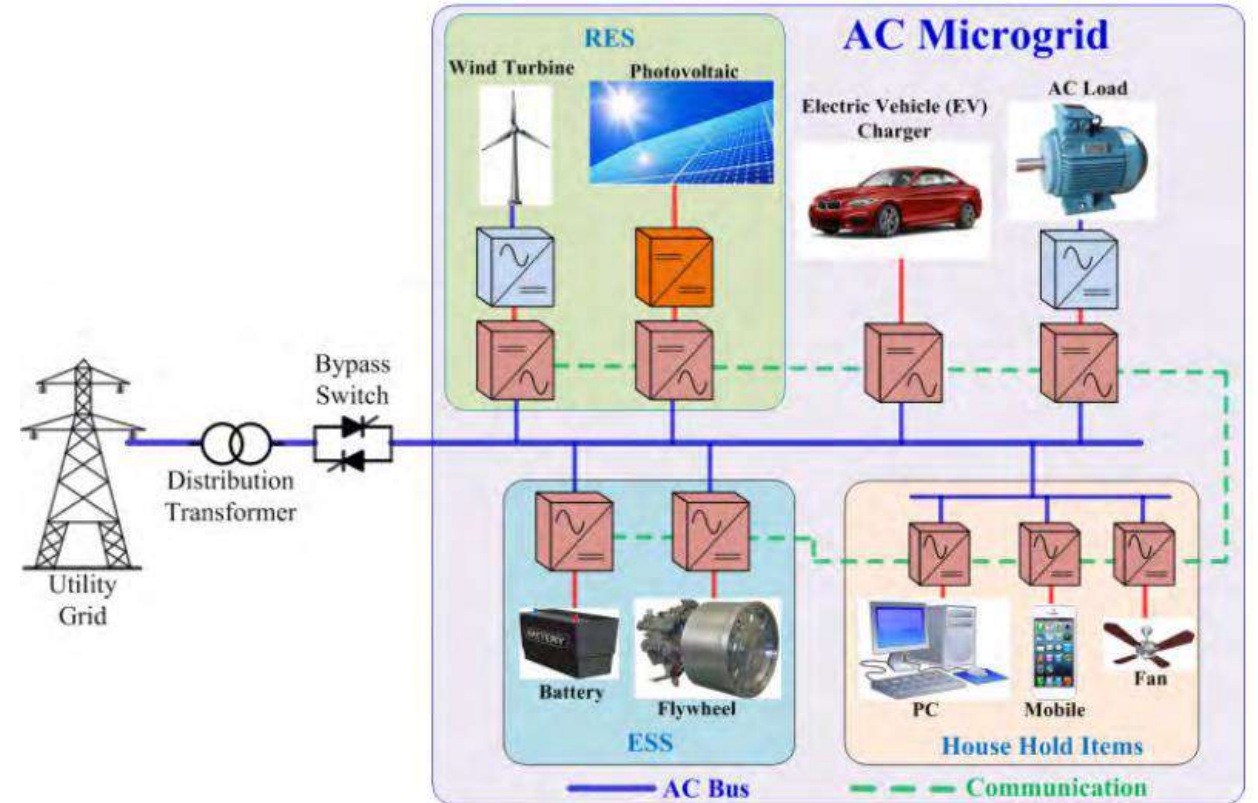
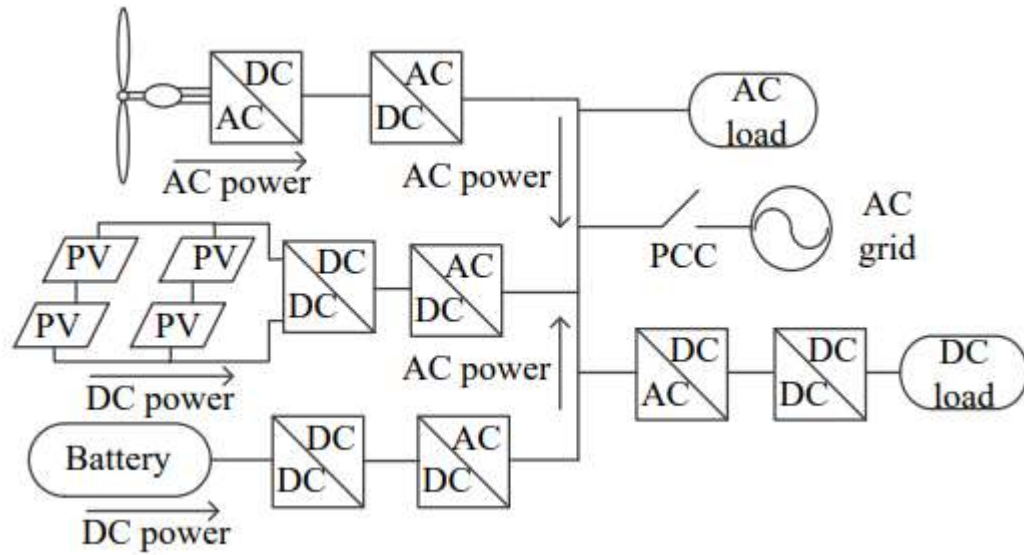
Hybrid microgrid Control



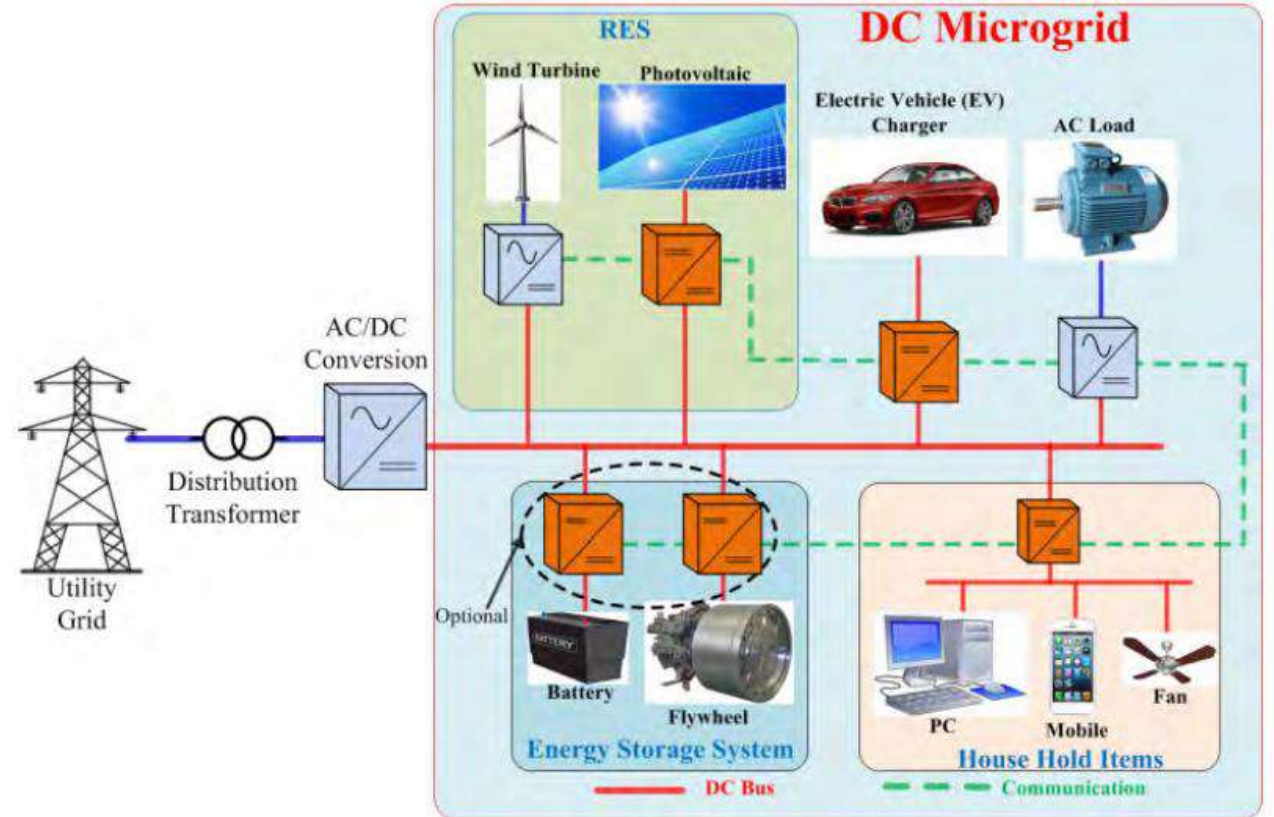
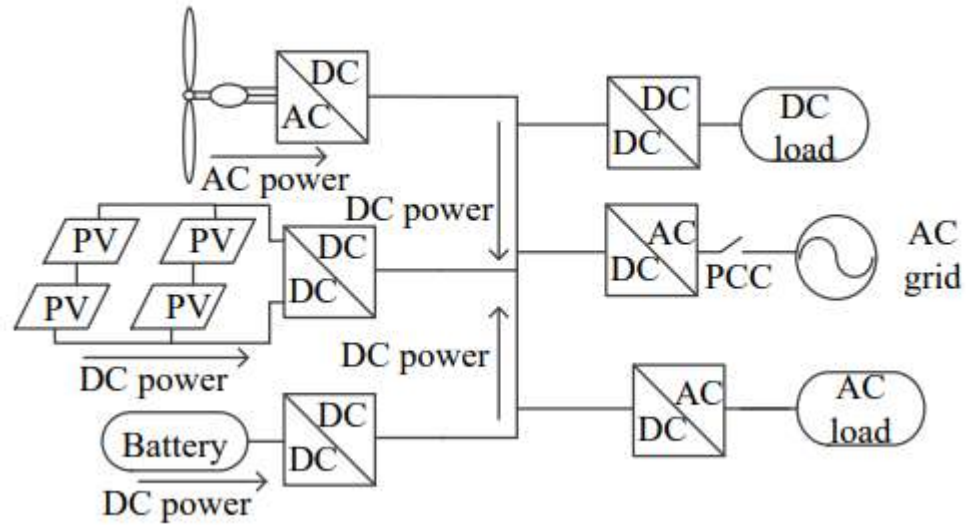
Architecture and converters of Microgrid

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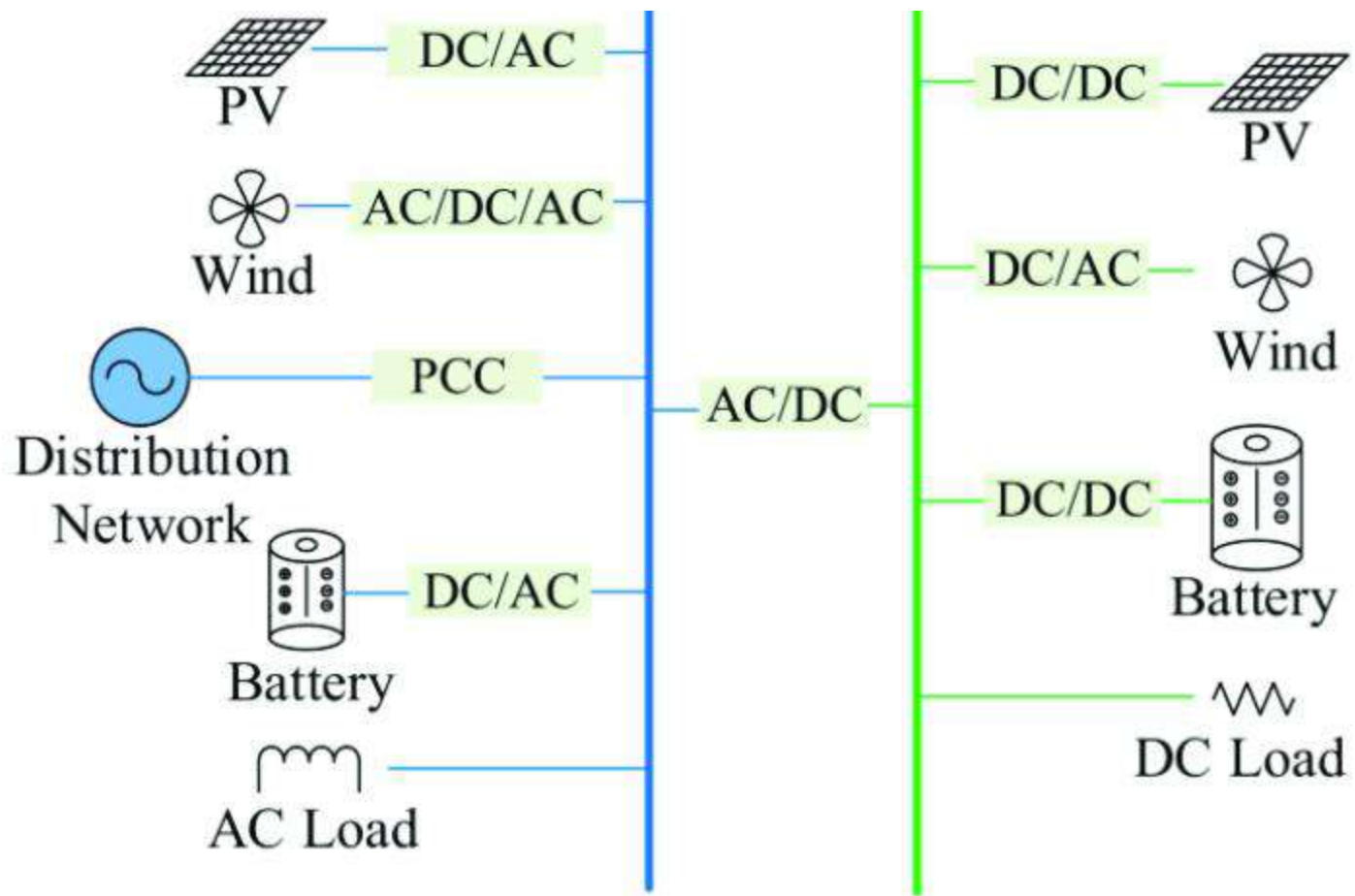
AC Microgrid



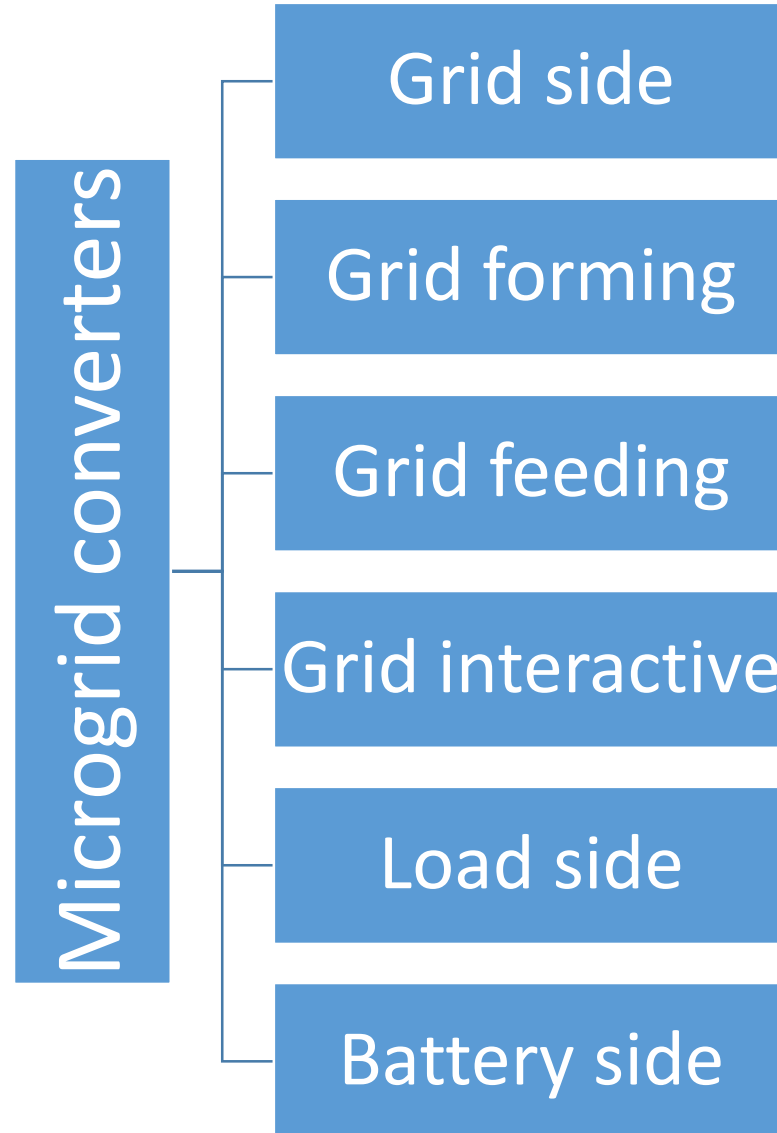
DC Microgrid

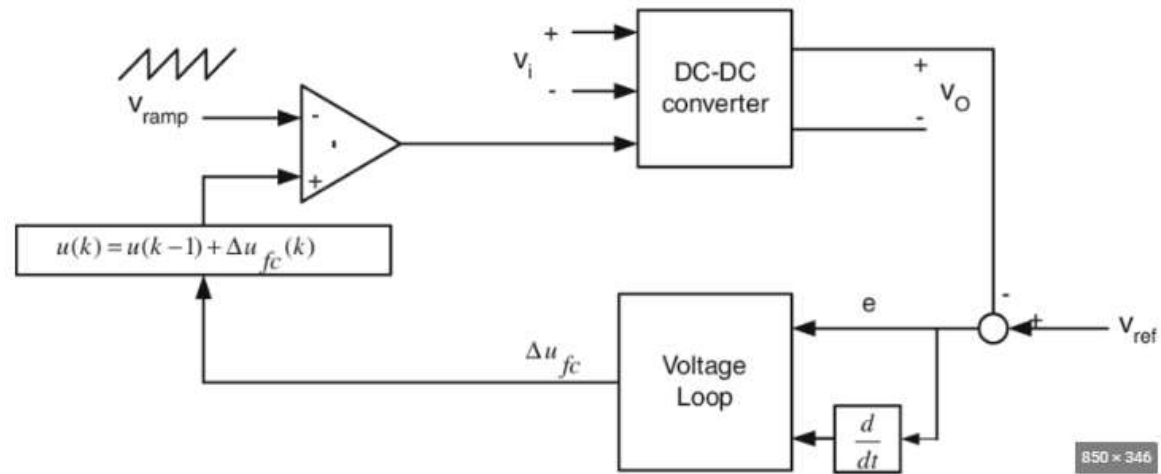


Hybrid Microgrid

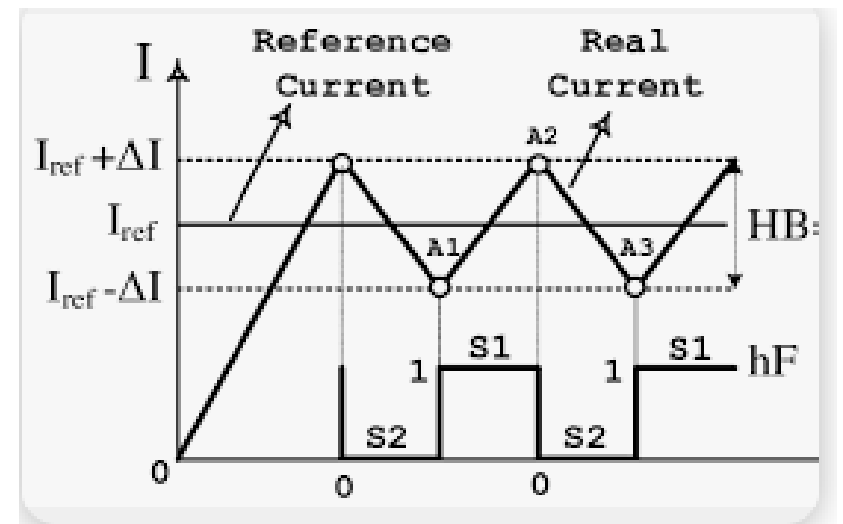
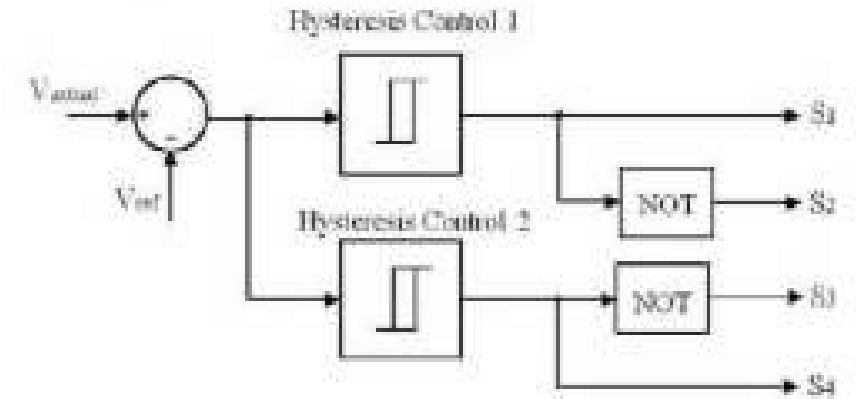


Converters

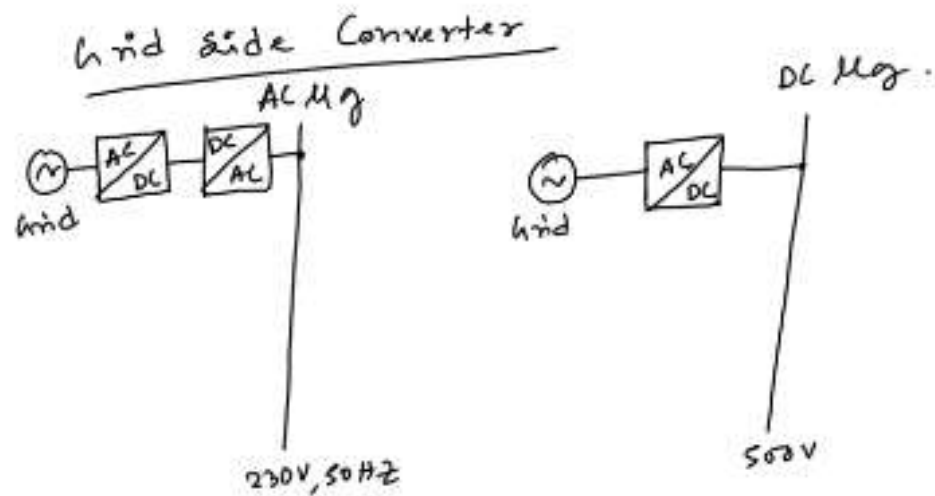
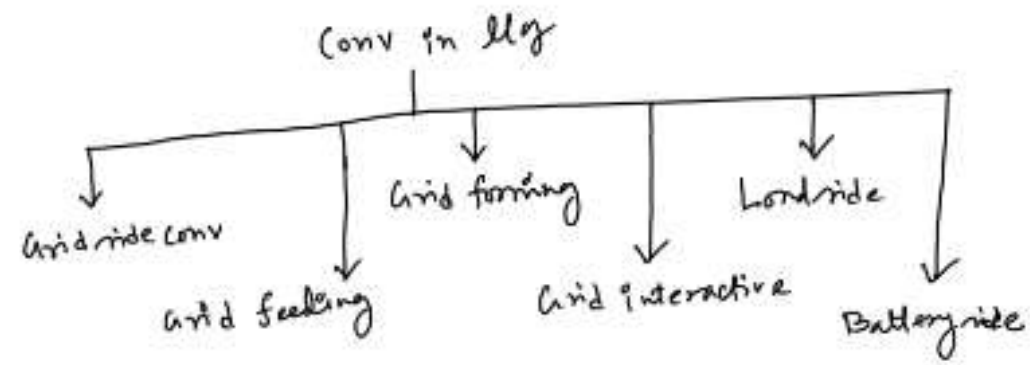




Voltage mode control

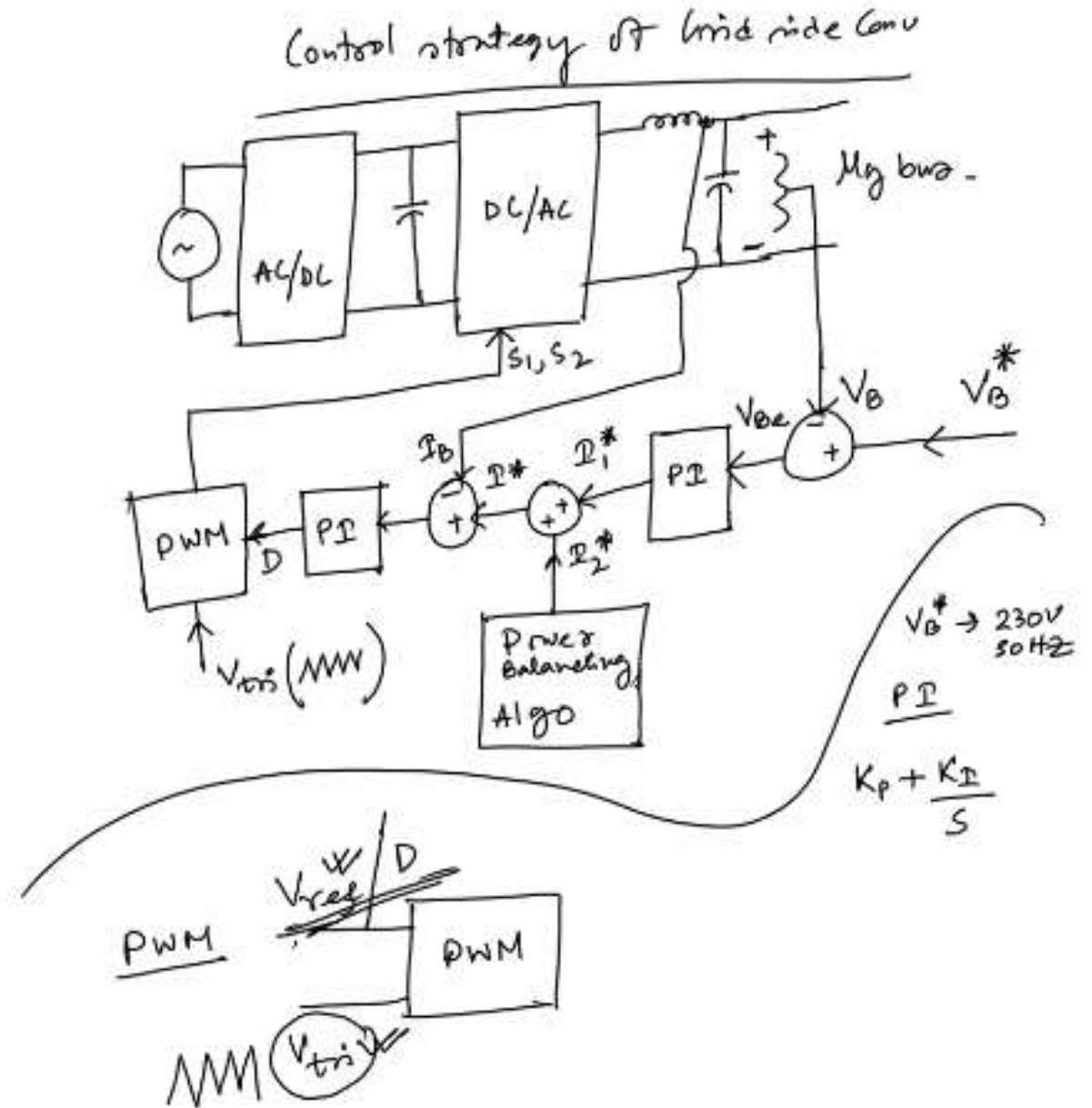


Hysteresis control

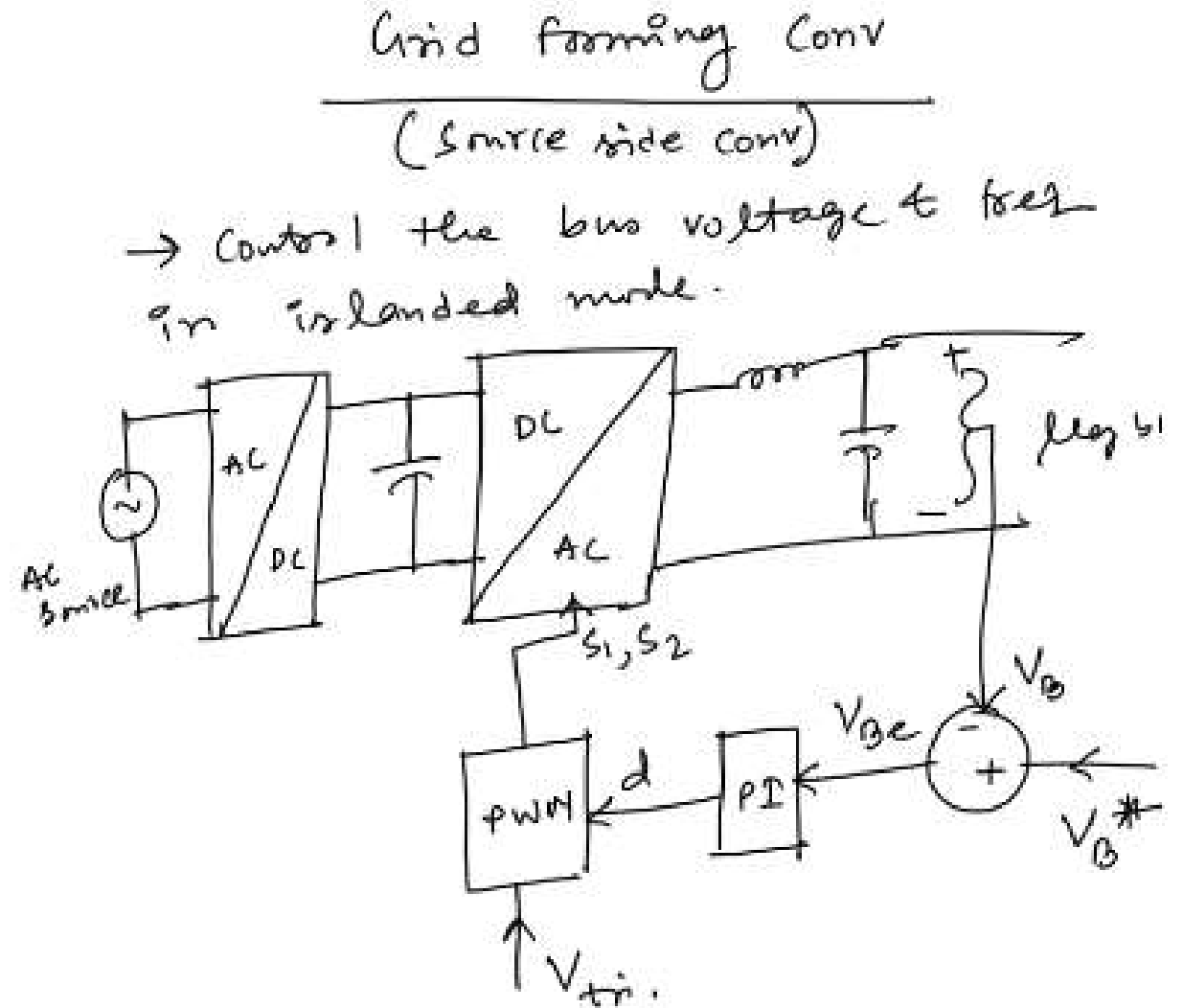


- It should balance the bus voltage & freq
- It should balance the power imbalance in Hg

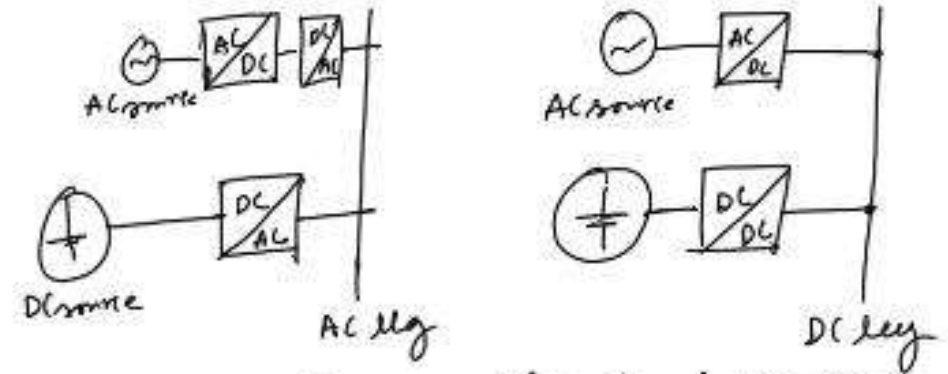
Grid-connected converters are power electronic devices that can interface renewable energy sources, energy storage systems, or flexible loads with the utility grid. They can provide various benefits, such as power quality improvement, voltage regulation, frequency support, and active filtering.



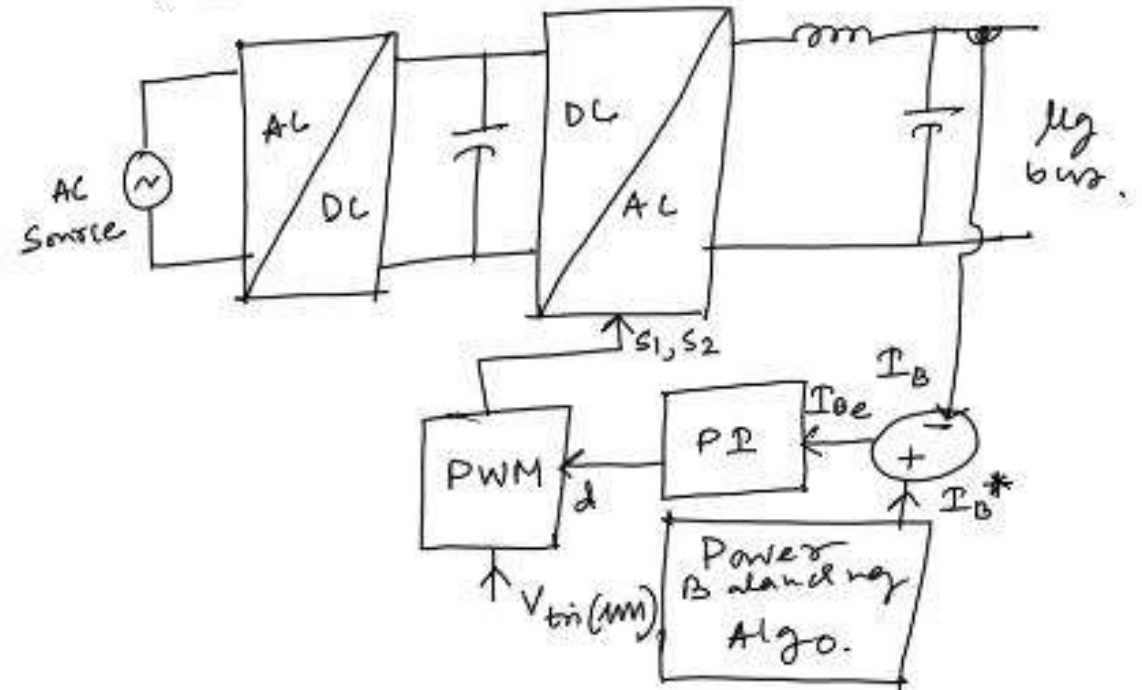
- The grid-forming converter is usually adopted in islanding operation of the MGs, to generate the desired voltage for the MG when the main grid voltage is absent.
- Therefore, the converter is controlled as an ideal voltage source with low output impedance. Such a grid-forming converter is said to be operating in voltage control mode (VCM). In an AC microgrid, VCM includes the voltage magnitude and frequency control, while for DC microgrid only the voltage magnitude control is necessary.
- In an islanded AC MG with multiple converters, at least one of these paralleled converters should operate as a grid-forming converter in VCM to supply a synchronous reference for the other converters. When there are more grid-forming converters in the AC MG, all of them have to be synchronized with each other.



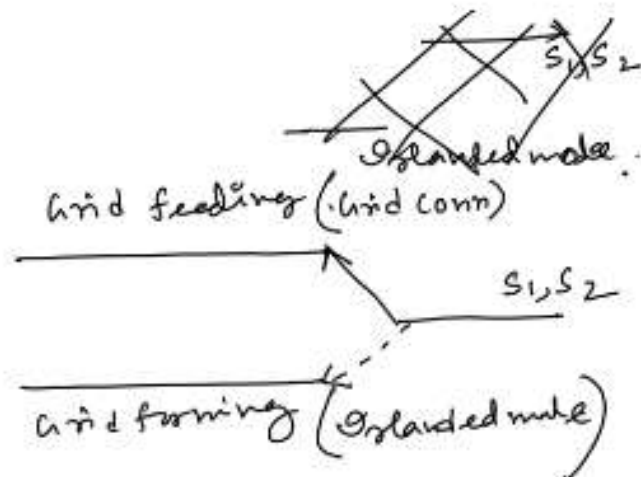
- Grid feeding Conv
(Source code Conv)



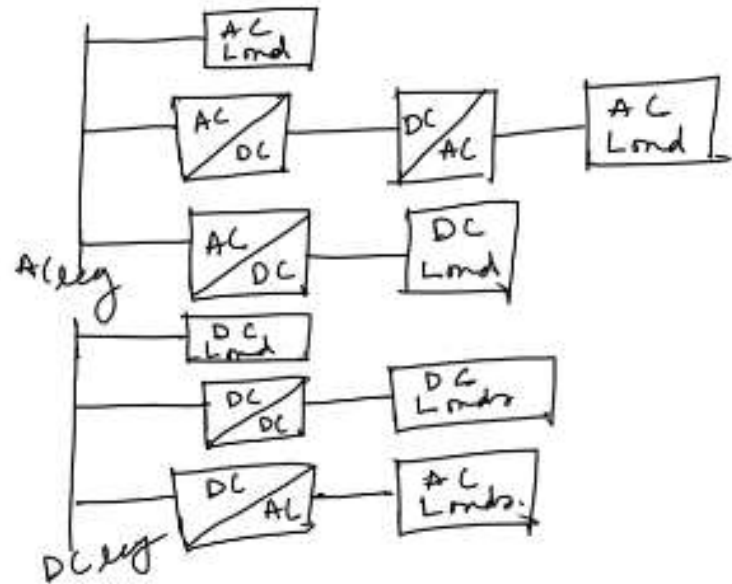
→ $g+$ balances the load power.



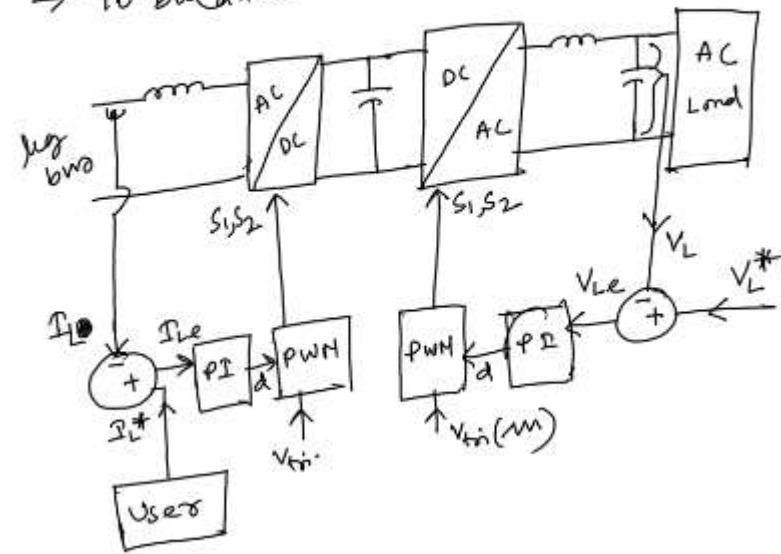
Grid Interactive Conv (Source side conv)



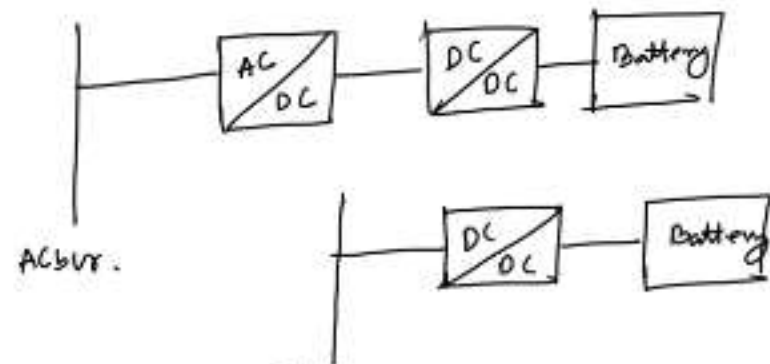
Load Side Conv



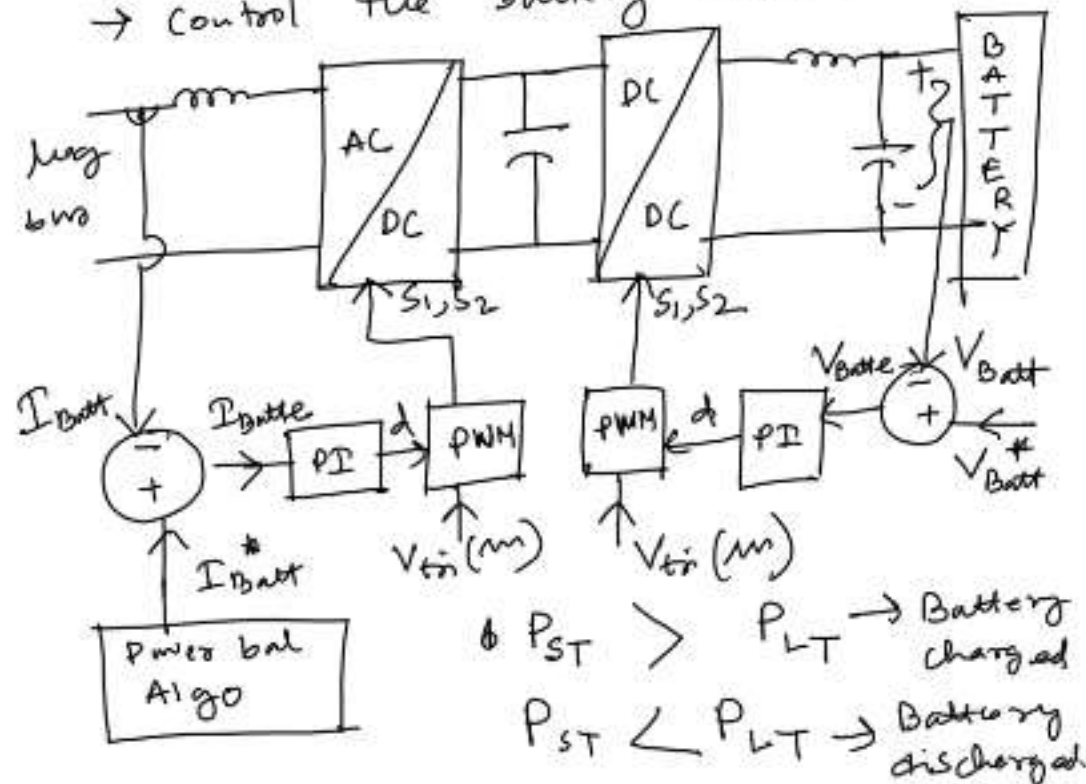
- To control the load power
- To balance the load voltage



Battery Side Converter



- Control the battery voltage
- Control the battery current



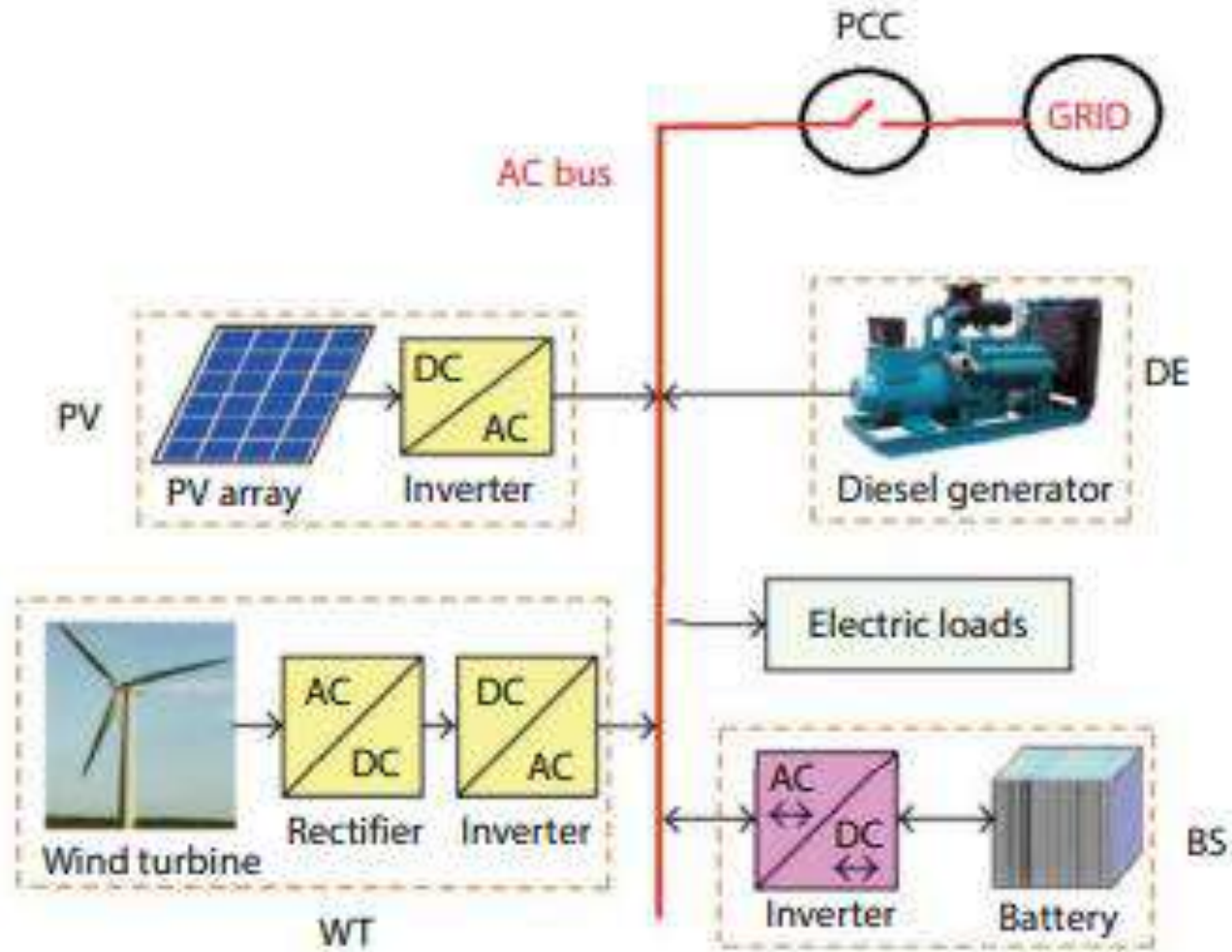
Microgrid in Grid connected mode

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Structure in Grid connected mode



Advantage for Grid connection

Interconnecting microgrids to the main grid have the following importance:

Availability: Highly available power grids may act as an additional source for micro-grids.

Operations/stability:

- ❖ Direct connection of ac microgrids to a large power grid facilitates stable operation but only if the power grid acts as a “stiff” source to the microgrid.
- ❖ When using renewable energy sources, a grid connection may allow reducing the need for energy storage in the microgrid.
- ❖ If not all loads in a microgrid are critical, a grid connection may allow to reduce the investment in local generation.

Economics:

- ❖ Microgrids are typically planned with extra capacity with respect to the local load. This extra power capacity can be injected back into the grid in order to obtain some economic benefit.
- ❖ Grid interconnection allows to reduce fuel operational costs by using the grid at night when electricity costs are low.

RE VIDEOS

Microgrid operation in grid connected mode

- In the grid-connected microgrid mode of operation, DG units generation is controlled to supply a pre-determined amount of active and/or reactive power required for the fulfillment of a pre-specified system requirement (e.g. peak shaving, exporting power to the main grid, etc.).
- Any difference between the microgrid total load and the active and reactive generation by the DG units is absorbed or supplied by the main grid.
- Thus the frequency and voltage regulation at the different system buses can be accomplished.
- Accordingly, similar to conventional distribution systems, the DG units in the grid-connected microgrid system can be controlled and modeled as PV or PQ buses.
- In the normal operation, the μ G is connected to a main medium voltage (MV) distribution grid being either partially supplied from it or injecting some amount of power into it.
- Depending on the demand request, in the grid-connected mode, the main grid and local DGs may send power to the loads.
- As the MV grid sets the root mean square (rms) voltage, all DGs inside the μ G can only generate currents but can be dispatched by the microgrid central control (μ GCC) in order to provide power references.
- The control system in the local controller of the DGs is known as "PQ inverter control" and the DG is said to be in "PQ mode."

Grid connection methods

➤ Interconnection methods:

- ❖ Directly through switchgear
- ❖ Power electronic interfaces
- ❖ Static switches

➤ Directly through circuit breakers:

- ❖ Relatively simple and inexpensive
- ❖ Slow (3 to 6 cycles to achieve a complete disconnection).
- ❖ Since electrical characteristics on both sides of the circuit breakers must be the same, then, electrical characteristics on the micro-grid side are dependent on the grid characteristics. For example, use of a circuit breaker implicitly limits the micro-grid to have, at least partially, an ac power distribution system in order to match the grid's electrical characteristics.
- ❖ Power flow through the PCC cannot be controlled

Use of Static switches

Use of static switches:

- ❖ Usually based on SCRs in antiparallel configuration to allow bidirectional power flow
- ❖ They are costlier and more complex than using circuit breakers.
- ❖ Usually, conventional circuit breakers are still used to provide a way to achieve full galvanic isolation. A Bypass switch is also added for maintenance reasons. They allow for many open/close operations
- ❖ They act much faster than conventional circuit breakers (in the order of half a cycle to a cycle). Sometimes IGBTs are used instead of SCR because IGBTs tend to be faster than SCRs and their current is inherently limited.
- ❖ Still power flow cannot be controlled. There are some conduction losses in the devices.

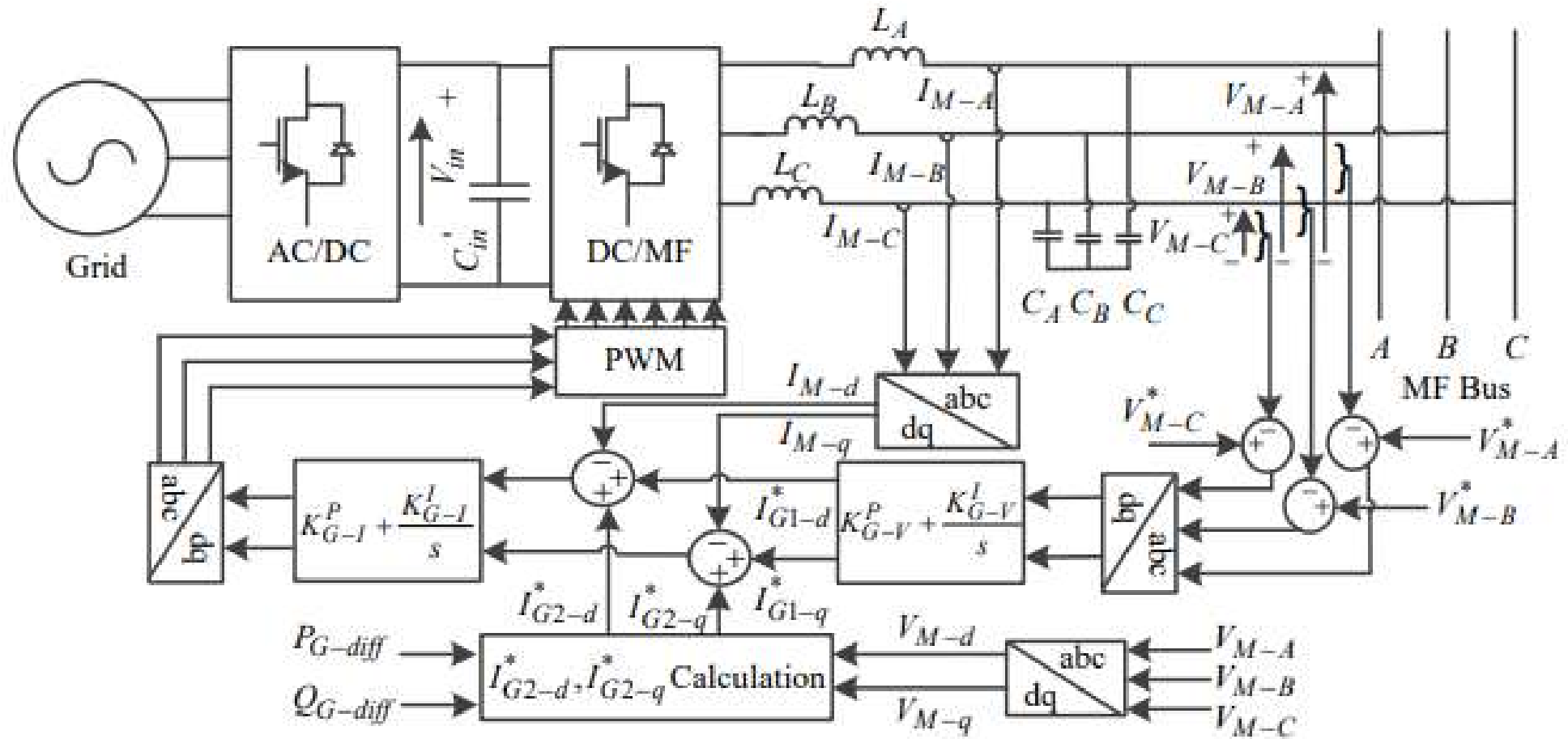
Use of power electronic interfaces

- ❖ It is the most costlier option however it is also the most flexible one.
- ❖ Allow for power distribution architecture characteristics on both sides of the PCC to be completely different. Both real and reactive power flow can be controlled.
- ❖ Reaction times to connection or disconnection commands are similar to those provided by static switches, although in the case of a power electronic circuit, its response also depends on its dynamic performance, given by its controller, topology, and internal energy storage components characteristics.
- ❖ Still, in many cases, a circuit breaker will still be required at the grid-side terminal of the power electronic interface with a local area power and energy system (LAPES) in order to provide a way to physically disconnect the micro-grid from the grid.
- ❖ The presence of a power electronic circuit also will lead to some power losses not found in the approach using mechanical interfaces.

Dynamic interaction of microgrid with main grid

- Since the capacity of Microgrid being sufficiently small, the stability of main grid is not affected when it is connected to the main grid.
- However, in future, when Microgrids will become more commonplace with higher penetration of DERs, the stability and security of the main grid will be influenced significantly.
- The dynamic interactions between Microgrid and the main grid will be a key issue in the operation and management of both the grids.
- The dynamic interactions between Microgrid and the main grid will be a key issue in the operation and management of both the grids.
- Microgrids need to be designed properly to take care of their dynamic impacts on main grid such that overall stability and reliability of the whole system is significantly improved.

Grid side converter control strategy

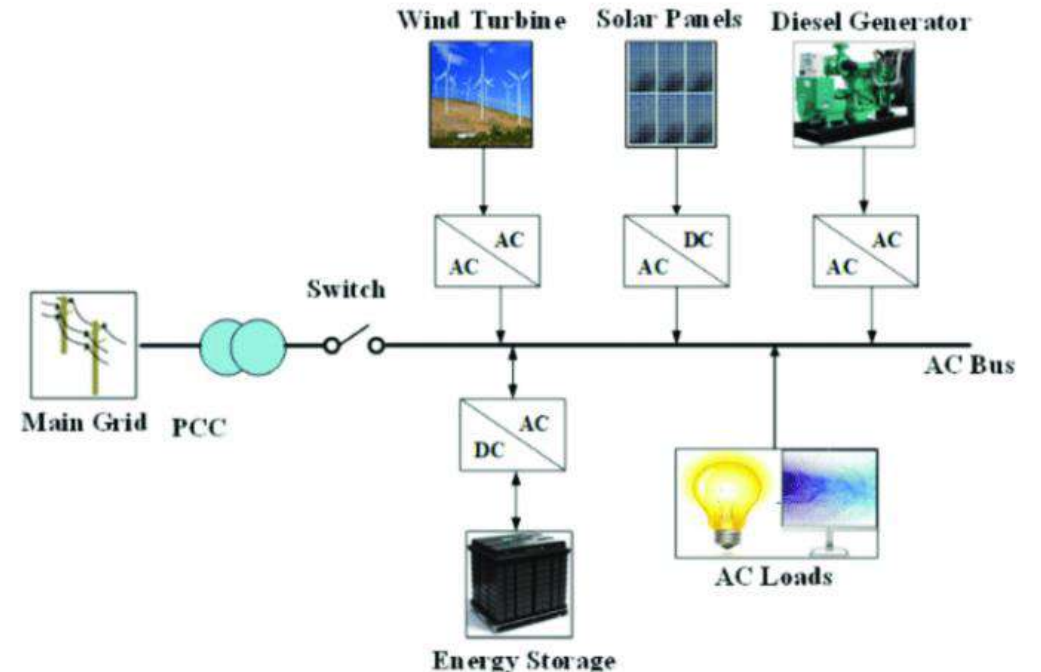


Microgrid in Islanded mode

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What is islanded mode

- A microgrid is said to be in islanded mode when it is disconnected from the main grid and it operates independently with micro sources and load.
- In the island mode, the microgrid is operated as an independent power island, controlling its own voltage and frequency.
- Islanding can be intentional or unintentional.
- Detecting the islanding condition and effectively disconnecting the microgrid within a specified time interval from the distribution network is a necessity.



Advantage and disadvantages of islanded mode

Advantages:

- power supply is not interrupted in the island even during the Grid disturbance so improves system reliability.
- Power quality is better.
- Allow for maintenance.

Disadvantages:

- Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered
- It may prevent automatic re-connection of devices.

Islanded mode operation

P-Q Control

- One grid forming converter must balance the bus voltage and frequency.
- All other converters behaves as grid feeding converter and balances power.

Droop Control

- All converters behaves as grid feeding converter and balances power.
- Bus voltage and frequency are not constant. They vary with change in load side active and reactive power.

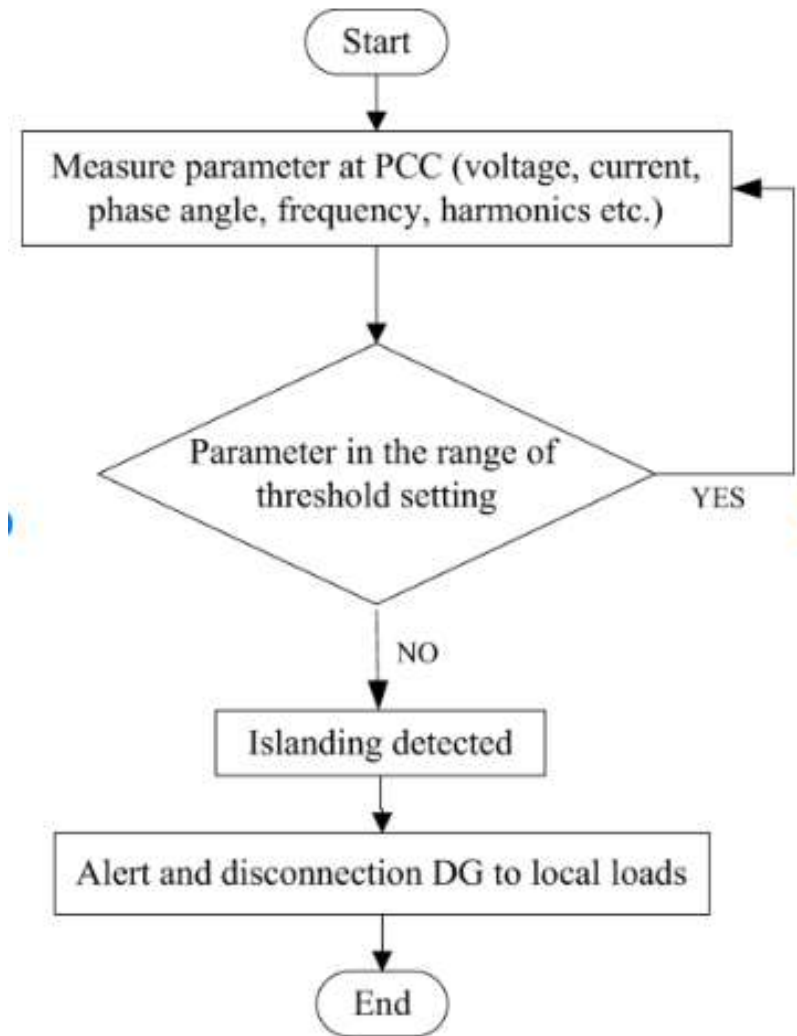
The **energy storage system** sometimes behave as source and sometimes behave as load.

Faulty condition

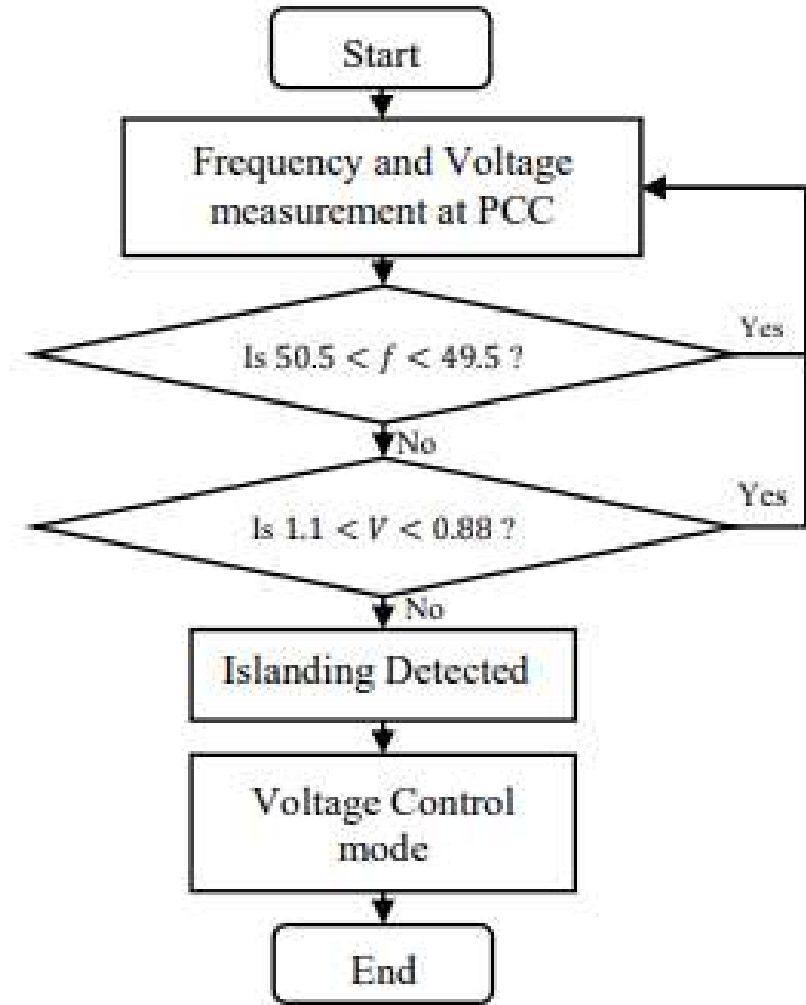
- The IEEE and IEC revise and modify the DG interconnection and islanding codes frequently to accommodate the fast growing renewable integration.
- **IEEE Std. 1547** defines islanding as a condition in which part of the power system becomes isolated from the rest of the network. The islanding condition should be detected and the microgrid disconnected from the main grid within 2 s.

Standards	Detection Time	Frequency Range	Voltage Range
IEEE-1547 [28]	$t < 2 \text{ s}$	$49.3 \text{ Hz} \leq f \leq 50.5 \text{ Hz}$	$0.88 \leq V \leq 1.1 \text{ pu}$
IEEE-929-2000 [29]	$t < 2 \text{ s}$	$49.3 \text{ Hz} \leq f \leq 50.5 \text{ Hz}$	$0.88 \leq V \leq 1.1 \text{ pu}$
IEC-62116 [30]	$t < 2 \text{ s}$	$48.5 \text{ Hz} \leq f \leq 51.5 \text{ Hz}$	$0.85 \leq V \leq 1.15 \text{ pu}$

Islanding detection flowchart

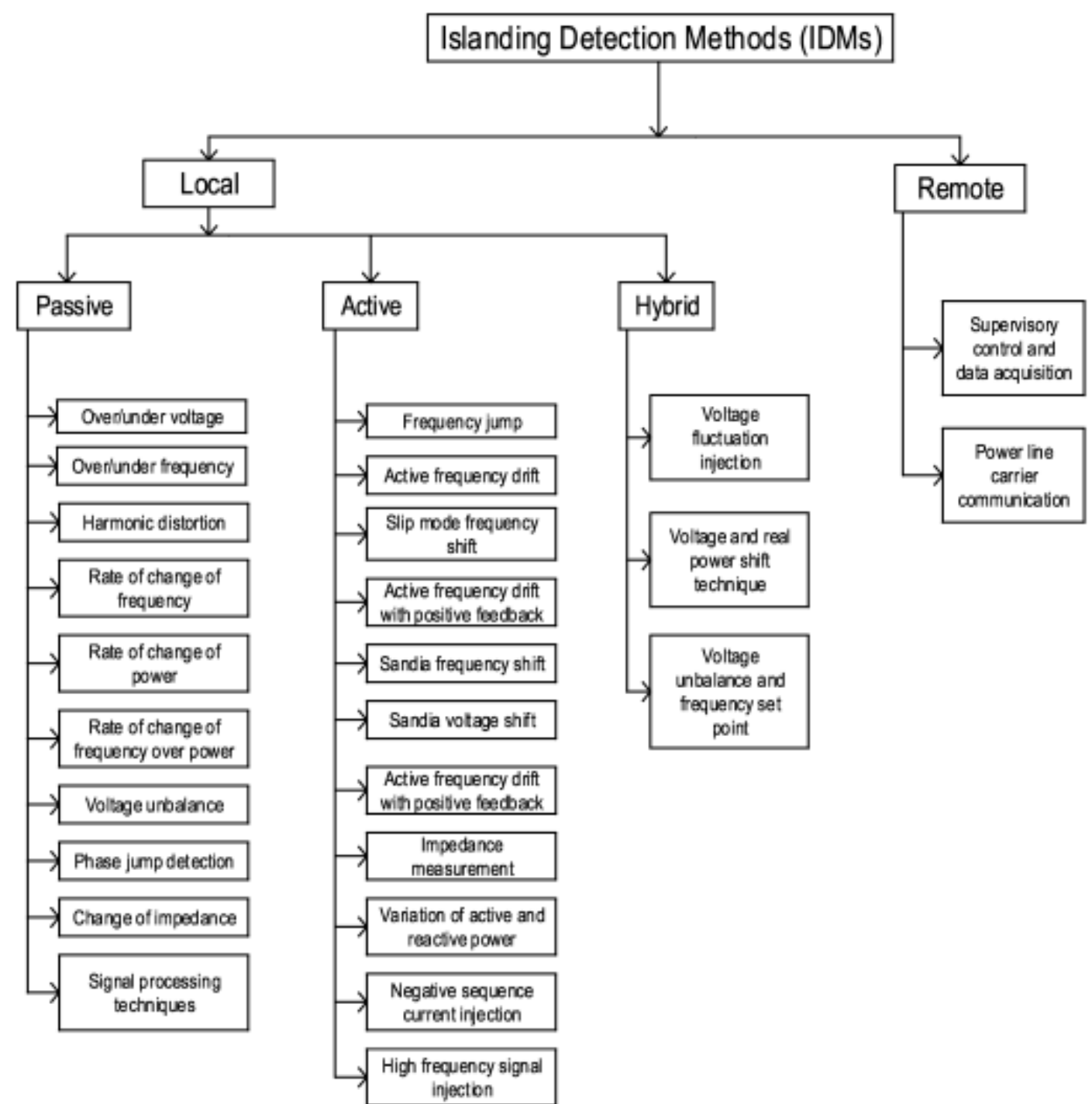


Flowchart for any islanding detection



Flowchart for OUV/OUF islanding detection method

Islanding detection techniques



Performance evaluation criteria of Islanding detection techniques

Non-Detection Zone: The NDZ represents a region of power imbalance between the power generated by the DG units and that dissipated by local loads where the islanding detection method fails.

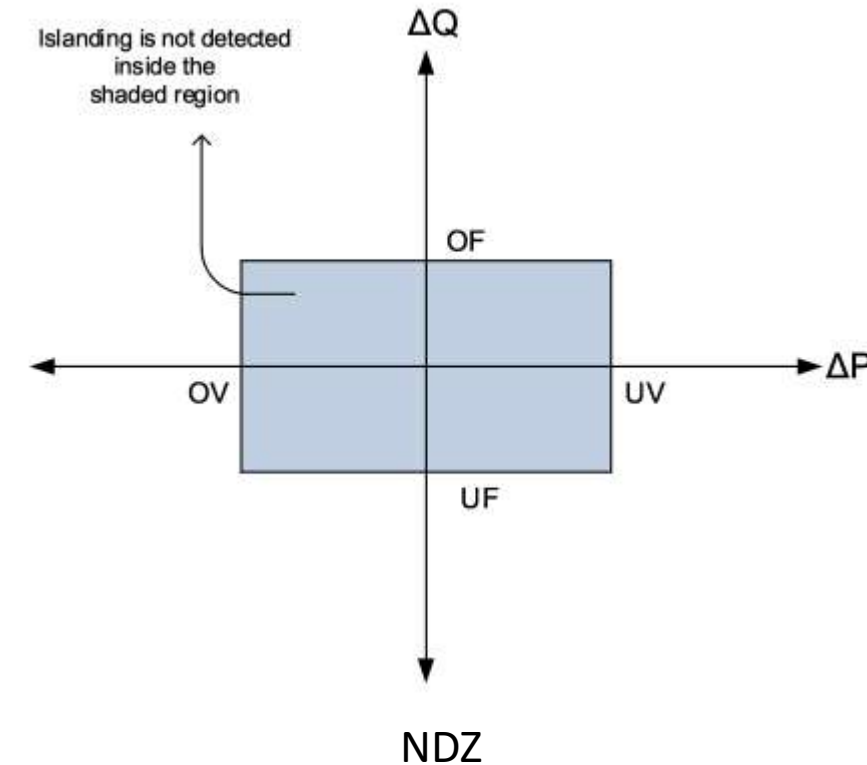
Detection Time: The detection time is defined as the time taken from the beginning of microgrid disconnection till the end of the IDM detecting islanding.

$$\Delta T = T_{IDM} - T_{trip}$$

Error detection ratio: Due to load switching, or other disturbances that affect measurement parameters to exceed normal limits, IDMs might detect false islanding, called error detection.

$$E = \frac{N_{error}}{N_{error} + N_{correct}}$$

Power Quality: Maintaining the power quality of the microgrid is an important index while selecting IDMs. IDMs that inject a disturbance to the system distort the power output and deteriorate the power quality.



Local and Remote Islanding detection techniques

Local Islanding detection techniques:

Local islanding detection techniques measure the system parameters at the DG site for islanding detection. The measured parameters include voltage, frequency, active power, reactive power phase angle, impedance and harmonic distortion.

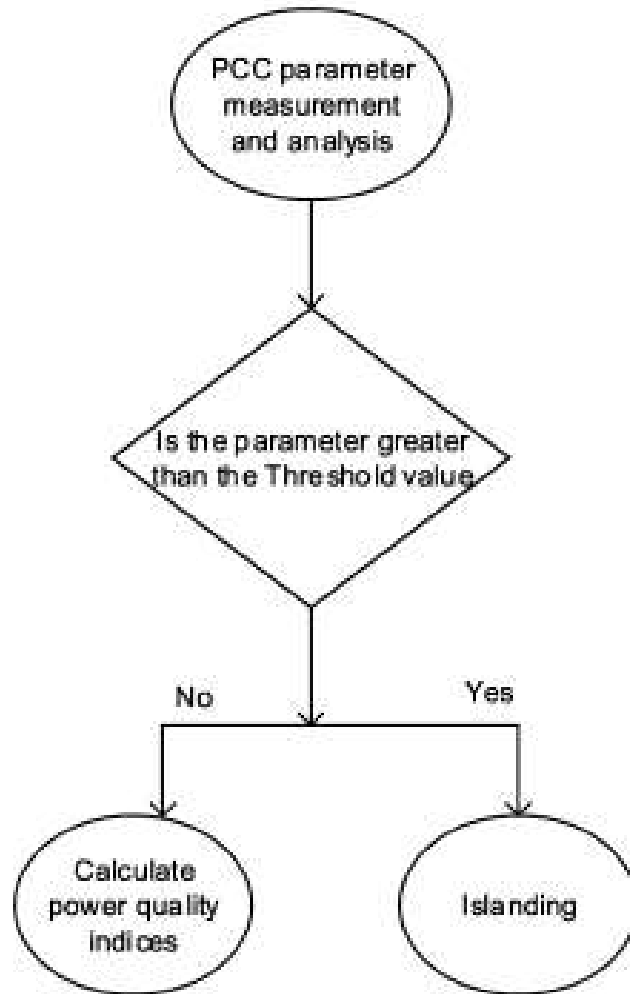
Adv: Cheap

Disadv: High error, Not applicable in large microgrids.

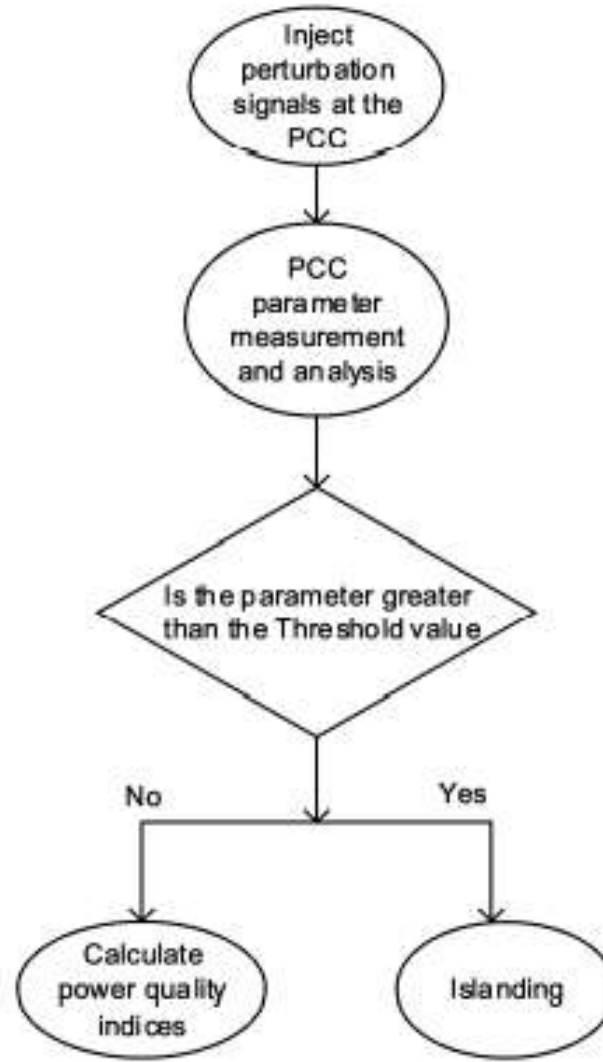
Remote Islanding detection techniques:

The remote methods utilize advanced signal processing and communication infrastructure for islanding detection. Remote methods do not have a non-detection zone (NDZ), error detection can be eliminated, and they do not affect the power quality; therefore, they are very sound approaches for islanding detection. Whereas remote methods tend to be expensive to implement for small microgrids, they are very beneficial for large microgrid applications.

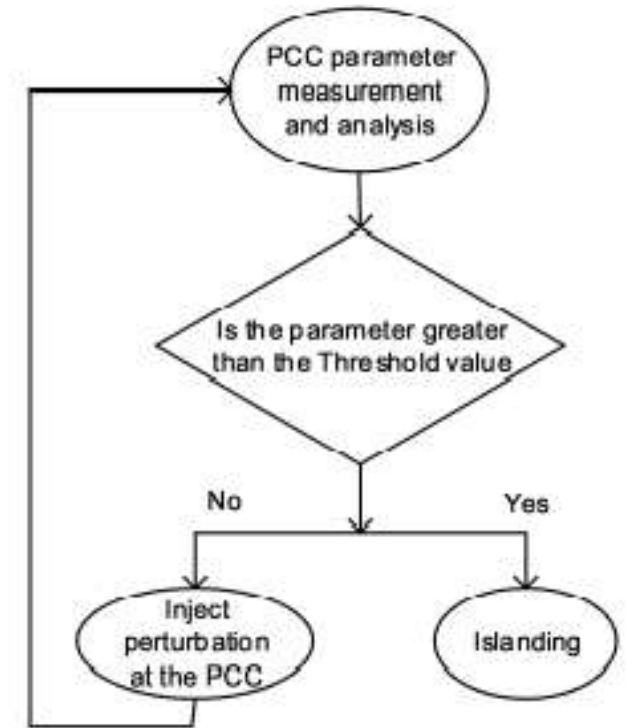
Passive, active and hybrid Islanding detection techniques



Passive technique



Active technique



Hybrid technique

Passive, active and hybrid Islanding detection techniques

- **Passive islanding detection techniques:** This method measures the system parameters and compares them with a predetermined threshold value for islanding detection.
- It is mostly used by power utilities as they are simple, low cost, do not degrade the power quality and have a fast detection speed within 2 s.
- However, these methods have a large NDZ, the error detection rate is high and setting the threshold requires special consideration.
- **Active islanding detection techniques :** The performance of active detection methods is based on the perturbation and observation concept. These methods perturb system parameters such as frequency, voltage, currents and harmonics. In the presence of a stiff grid, the amplitude of the variation at the PCC is negligible since the grid parameters are dominant. However, during the islanding phenomenon, injecting a disturbance at the PCC results in a significant variation in the DG parameters.
- It have a reduced NDZ and low error detection rate.
- Active techniques deteriorate the power quality, and additional power electronic circuits are required to inject the perturbations. To observe the effect of perturbation, additional detection time is required, which can affect the stability of the system.

Passive, active and hybrid Islanding detection techniques

- **Hybrid islanding detection techniques:** Hybrid islanding detection techniques are developed from the combination of passive and active detection techniques, and are implemented with two steps. The first step utilizes a passive technique, primarily to detect islanding. If islanding is not suspected in the first step, an active technique is employed to accurately detect the islanding.
- It has generally have a small NDZ, and the power quality degradation is low.
- However, the cost of the system is high, and the method is time consuming, which makes their real implementation infeasible.

Different Passive Islanding detection techniques

Over/under Voltage and over/under Frequency (OUV/OUF) :

This method works by comparing the PCC voltage and frequency with a predefined threshold voltage and frequency to detect islanding. The microgrid will be disconnected from the main grid if the measured voltage and frequency at the PCC exceed the thresholds.

Harmonic Distortion (HD):

The HD method is based on comparing the total harmonic distortion (THD) measured at the PCC and a predefined THD to detect islanding. When the microgrid is operated in grid-connected mode, the PCC voltage is a normal sine wave, and the harmonics generated by the load and the inverter are negligible. However, during islanding mode of operation, the harmonics produced by the inverter will distort the PCC voltage and, hence, islanding will be detected.

Rate of Change of Frequency (ROCOF) :

When the microgrid is disconnected from the main grid with a power mismatch, the frequency will change. The ROCOF method works by measuring df/dt for a few cycles and comparing it with a setting threshold. Islanding will be detected if the measured df/dt exceeds the predefined threshold.

Rate of Change of Frequency over Power (ROCOFOP) :

This method works by measuring $\partial f / \partial P_L$, where P_L is the load power, to detect whether or not islanding occurs.

Rate of Change of Power Output (ROCOP) :

This method measures the changes in the DG power output (dP/dt) over a few cycles and compares it with a setting threshold to detect islanding. Generally, a loss of the main grid produces load changes, and dP/dt measured after the microgrid is islanded is greater than dP/dt measured before the microgrid is islanded.

Phase Jump Detection (PJD) :

The working principle of PJD is to monitor the phase jump between the inverter’s terminal voltage and the current for islanding detection. During grid-connected mode, the inverter’s current will be synchronized with the voltage at the PCC using a phase locked loop (PLL) to detect the zero crossing of the voltage. In islanding operation, since PLL works only at the zero crossing of the voltage, the inverter output current remains unchanged. However, the voltage will have a sudden jump due to the load phase angle. Comparing the measured phase difference with a predefined threshold can detect islanding.

Voltage Unbalance (VU) :

A microgrid disconnected from the main grid changes the topology of the network that, in turn, causes a voltage unbalance at the DG output. This voltage unbalance can be used for islanding detection if it exceeds the setting threshold.

Method	NDZ	Detection Time	Impact on Power Quality	Error Detection Rate
Harmonic distortion	Large for high Q	45 ms	No	High
OUV/OUF	Large	4 ms to 2 s	No	Low
ROCOF	Small	24 ms	No	High
ROCOFOP	Smaller than ROCOF	100 ms	No	Low
ROCOP	Small	24–26 ms	No	High
Phase jump	Large	10–20 ms	No	Low
Voltage unbalance	Large	53 ms	No	Low

Active and reactive power control of microgrid

By Dr. Rajdip Dey

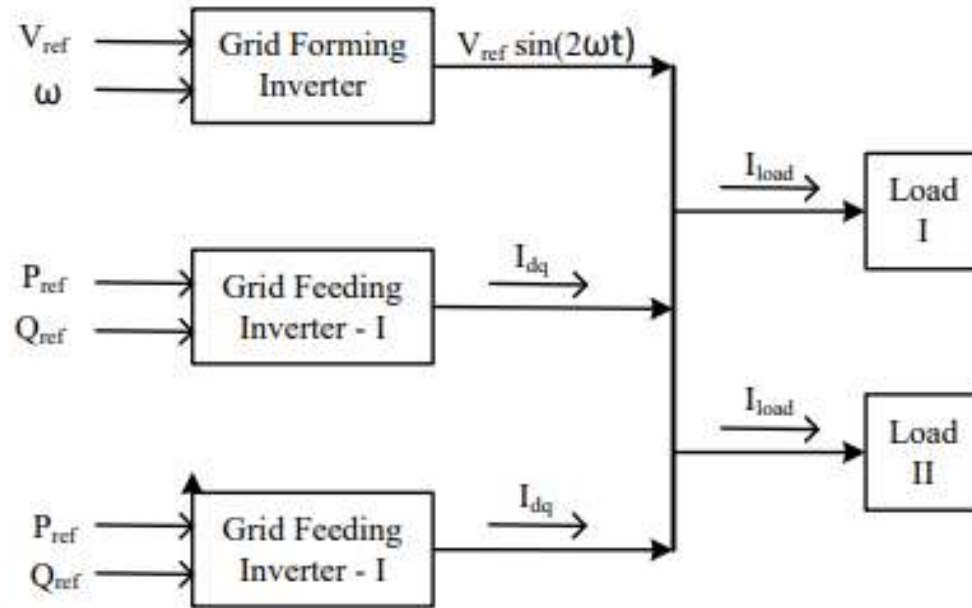
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A Microgrid is consist of several distributed generators forming grid through parallely connected inverters and interfaced with the load. Number of parallely connected inverters helps the Microgrid to achieve high degree of reliability and redundancy. At the same time number of parallely connected inverters demand precise control and load sharing to achieve reliable performance.

Communication based control (PQ control): In Communication Based control reference Power is communicated to inverters and other distributed generators through a communication network and maintained by the Microgrid Controllers following the control hierarchy. Traditional PQ Controller falls under this category. To ensure a stable and economical operation Proper control is essential for a Microgrid. Primary Control ensures voltage and frequency stability in islanding mode. Providing independent active and reactive power sharing control the issue of circulating currents can be minimized within the DERs. This primary control level includes fundamental control hardware for DERs. The Secondary Control is used to compensate the voltage and frequency deviations occurred due to the operation of the primary controls. Hence it helps proper Load Sharing and Synchronisation. The power flow between the microgrid and the main grid is controlled by the Tertiary Control, and it facilitates an economically optimal operation.

In this control inverters supplies to the load are communicated to them via a communication network. Two different types of inverters are used in this case. Firstly, the grid forming inverter maintains a steady microgrid voltage and frequency. In the process of doing so, grid forming inverter may act as a source or sink of excess power. On the other hand, the grid feeding inverters supply the required amount of power, communicated to them, to the load. It does so by calculating the reference currents guided by equations and adjusting the inverter switching pulse to achieve the desired current references. Thus, the grid feeding inverters basically act as current source inverters.



Non Communication based control (Droop control): As evident from the name no communication infrastructure is required for controlling of the Inverters. Inverters self adjusts the parameters (like frequency, voltage) essential for parallel operation and load sharing depending on the load demand. The Active and Reactive power transferred to the bus are,

$$P = \frac{U_1}{R^2 + X^2} [R(U_1 - U_2 \cos \delta) + XU_2 \sin \delta]$$

$$Q = \frac{U_1}{R^2 + X^2} [-RU_2 \sin \delta + X(U_1 - U_2 \cos(\delta))]$$

As the line inductance $X \gg R$. Hence neglecting R we get,

$$U_2 \sin \delta = \frac{XP - RQ}{U_1}$$

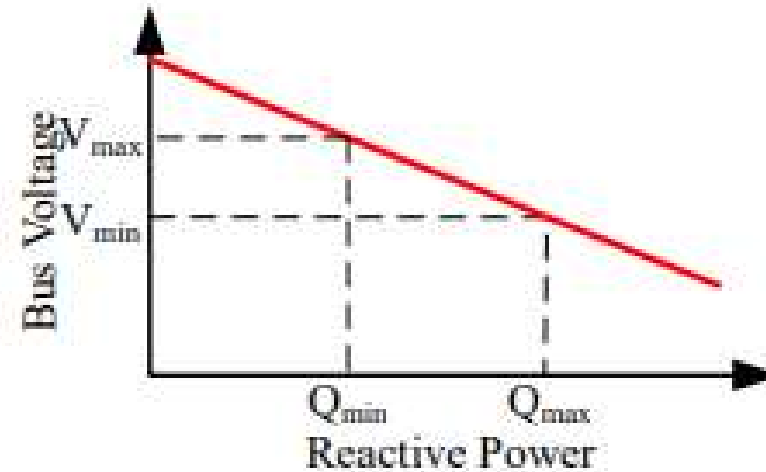
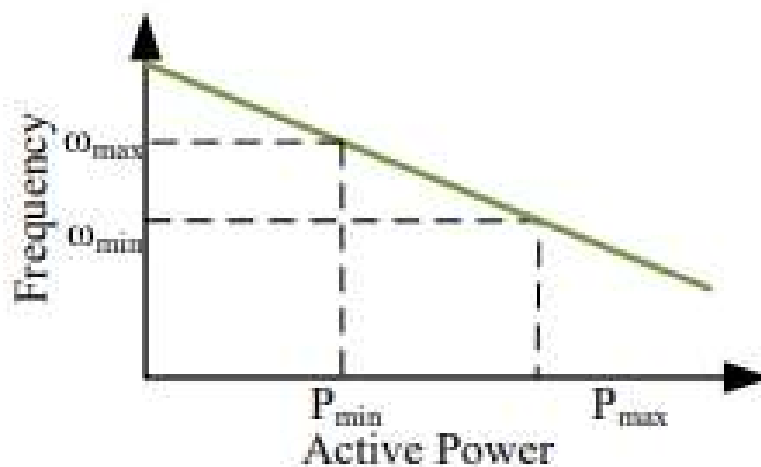
$$U_1 - U_2 \cos \delta = \frac{RP + XQ}{U_1}$$

If the power angle δ is small, then $\sin \delta \approx \delta$ and $\cos \delta \approx 1$,

$$\delta \approx \frac{XP}{U_1 U_2}$$

$$U_1 - U_2 \approx \frac{XQ}{U_1}$$

It is evident that the power angle δ depends pre-dominantly on Active Power P , and the voltage difference ($U_1 - U_2$) depends pre-dominantly on Reactive Power Q . Hence, it can be seen that real power flow can be controlled by changing the frequency, which results change in power angle. And, by controlling P and Q independently, frequency and amplitude of the grid voltage are adjusted. The above concludes the basis for the well-known frequency and voltage droop regulation through respectively active and reactive power.

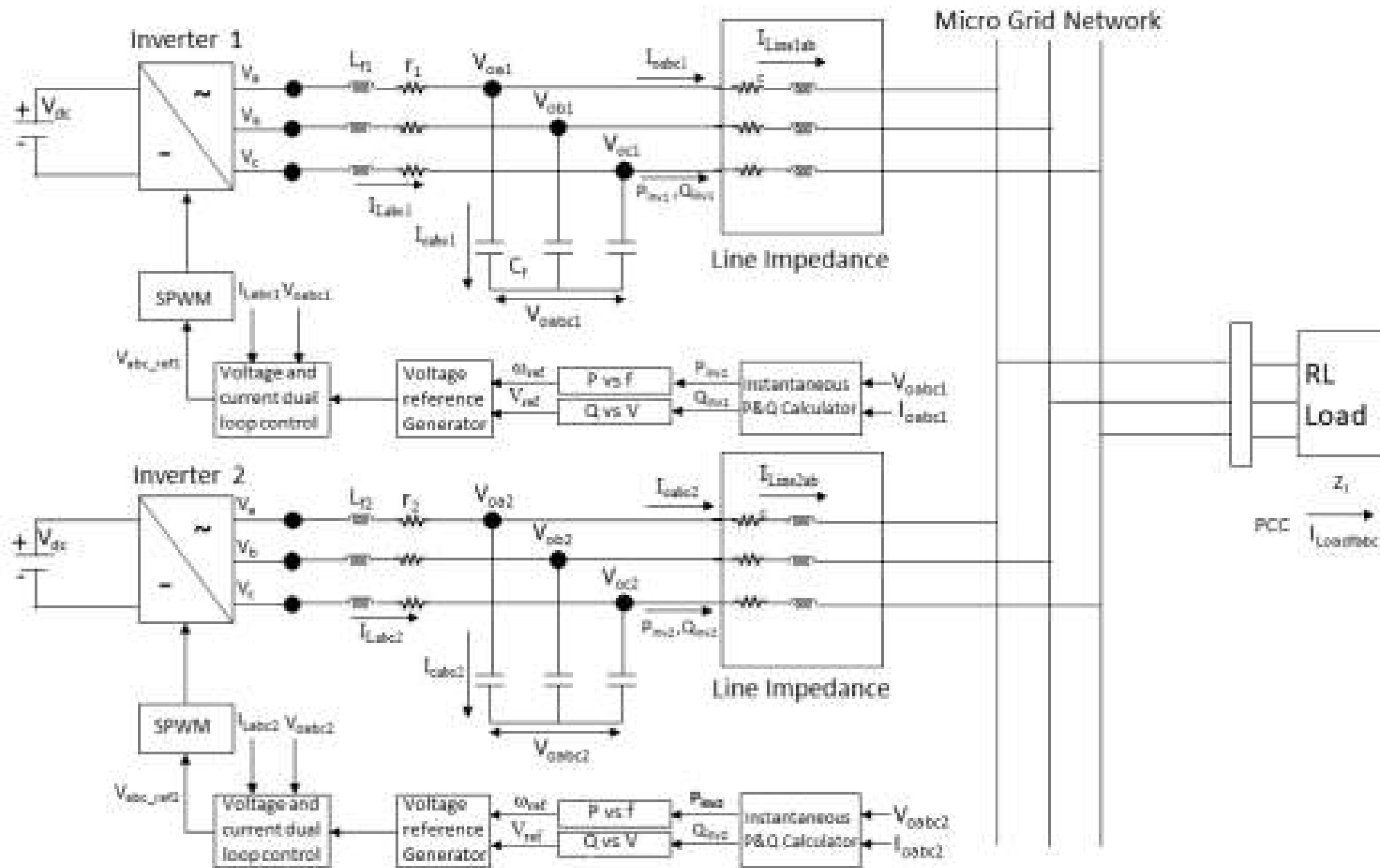


In droop control the active power is controlled by controlling the inverter output frequency which is guided by the active power-frequency droop equation, Where ω_{min} is the nominal frequency, P_{min} is the rated power and m is the droop constant.

$$\omega_{min} = \omega_{max} - m(P_{max} - P_{min})$$

The reactive power is controlled by controlling the inverter voltage output which is dictated by the reactive power-voltage droop equation, Where V_{min} is the nominal voltage, Q_{min} is the rated power, n is the droop constant.

$$V_{min} = V_{max} - n(Q_{max} - Q_{min})$$

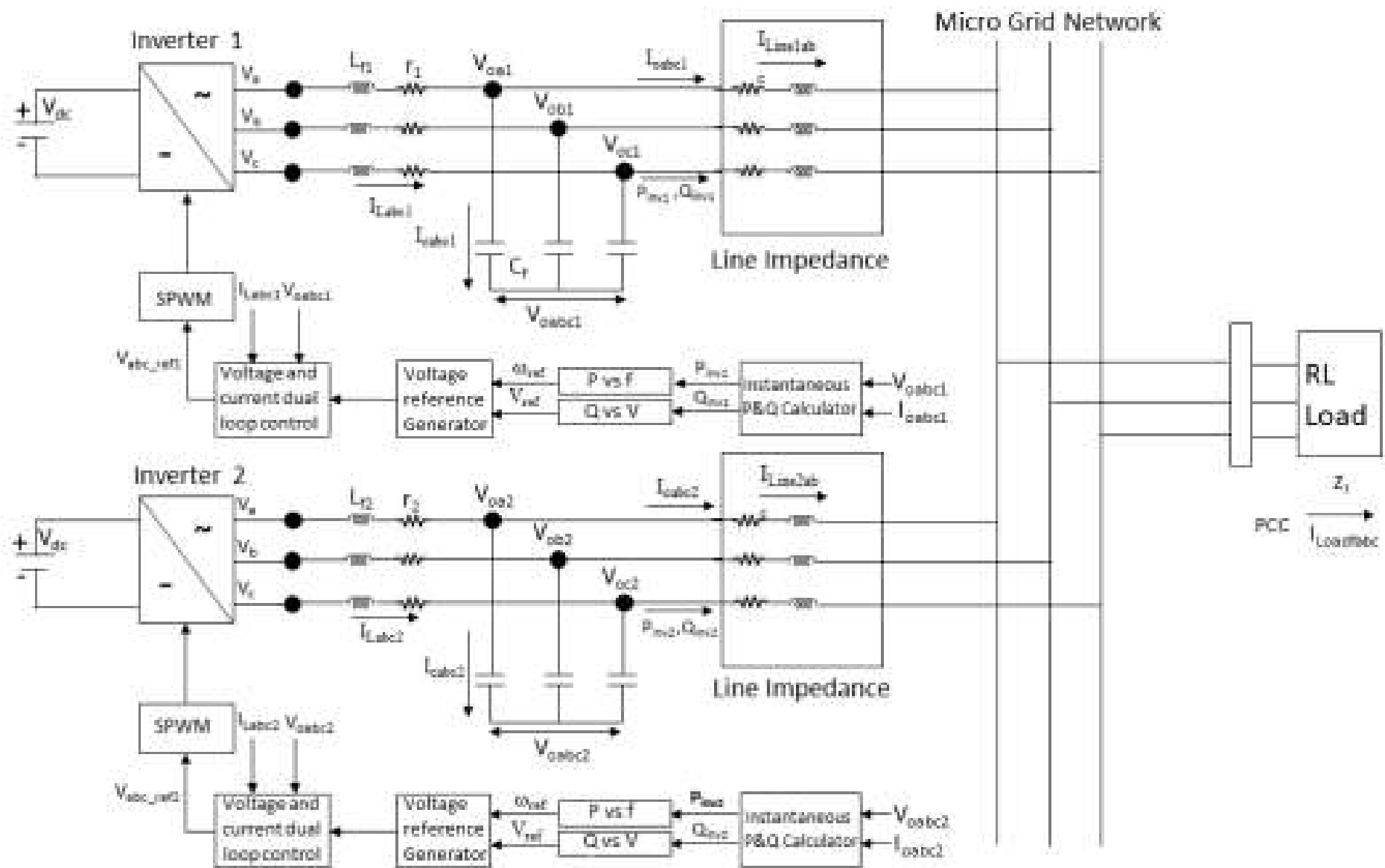


Comparison

Traditional PQ Control is a communication-based control. It requires separate communication infrastructure to convey the reference power to the grid feeding inverters. The droop control being a non-communication-based control does not require a separate communication infrastructure to control the active and reactive power. It automatically adjusts the voltage and frequency reference as per the active and reactive power demand according to the droop equations. The achieved voltage and frequency reference helps the inverter to deliver the required active and reactive power. Hence, it can be safely said that droop control **requires minimum infrastructure** and hence is **very cheap** as compared to Traditional PQ Control. In Traditional PQ control there is a high chance **of interference of communication network with noise signals**. This may interrupt the performance of the system and **reduce its reliability**. This problem is not present in droop control which is of good advantage.

Traditional PQ control being a communication-based control does not depend on the frequency and voltage variation to adjust the power output of the inverter. Hence frequency and voltage is fairly constant in Traditional PQ control irrespective of load power variation which **increases the stability** of the microgrid.

There is a chance of communication line failure in PQ control which **reduces the reliability** of microgrid.



Energy Storage System

By Dr. Rajdip Dey
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- The energy storage along with the renewable generators (PV and wind energy) is required to increase reliability and flexibility.
 - The intermittent nature of renewable sources like solar and wind needs storage to delivery the right amount of power at right quality.
 - Energy storage is used to enhance the stability and efficiency of microgrids by decoupling the generation source from the load.
 - The ESS stores excess renewable energy and supply load when renewable energy is low.
-
- Energy storage is needed for consistent operation of the renewable energy system and DC voltage regulation.
 - The load and renewable energy source power generation profiles are the main important factors for determining the kind of energy storage.
 - Several technologies for energy storage are available, among which batteries have been used extensively in microgrid-applications.

Advantages of ESS

- **Increase the reliability of the grid** by providing a back-up system: the battery storage system can be a reliable power source by reacting instantaneously in case of grid failure or downtime.
- **Lower dependency on fuel and minimize carbon footprint:** the storage system can allow solar systems to store excess energy during the daytime which can then be used during the night.
- **Increase solar penetration:** when the energy production is more than the load requirement, the excess energy can be stored.
- **Increase owners' net profits** by reducing their utility bills. BESS can be configured in such a way that they shift load during peak hours or provide energy during the high-demand hours.

Applications of ESS

BESS for grid-tied application

For grid-tied applications, where the micro-grid is connected to the main grid, BESS systems can help **owners to reduce their bills**. In developed countries, although the supply of electricity is ensured, there is a major difference between **prices during the off-hours and peak-hours**. Users can reduce their bills by shifting their load to micro-grids during peak hours.

Owners can avoid penalties by energy companies by reducing their load when their demand is above the maximum power purchase value. BESS systems can also be used to regulate power factor in order to avoid **cos-phi penalties**.

BESS for grid-tied applications in regions with expensive energy rates

In some countries, **buying energy from the national grid is in fact more expensive** than storing self-produced energy. For example, in Puerto Rico, the grid quality is average but the main aim of the users is to reduce the energy bought from the national grid. People prefer to **produce their own energy and store it**. The energy from the main grid has become a secondary choice or more of a back-up option.

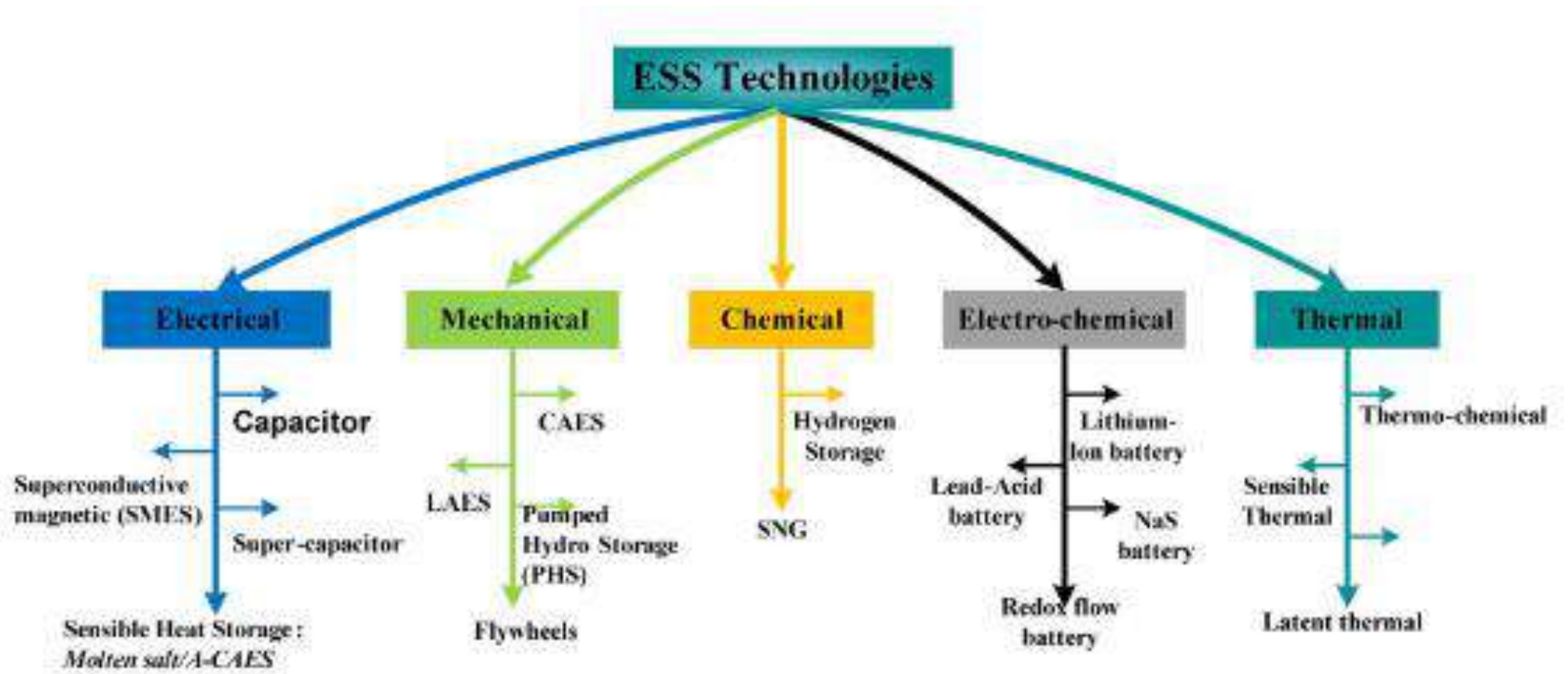
BESS for unreliable grid application

In countries like South Africa, where the national grid is not reliable at all and **frequent black-outs and load-shedding is a norm**, people tend to use micro-grids with the aim of becoming self-sufficient in terms of energy demand. BESS proves to be a source of reliable backup during hours of load-shedding.

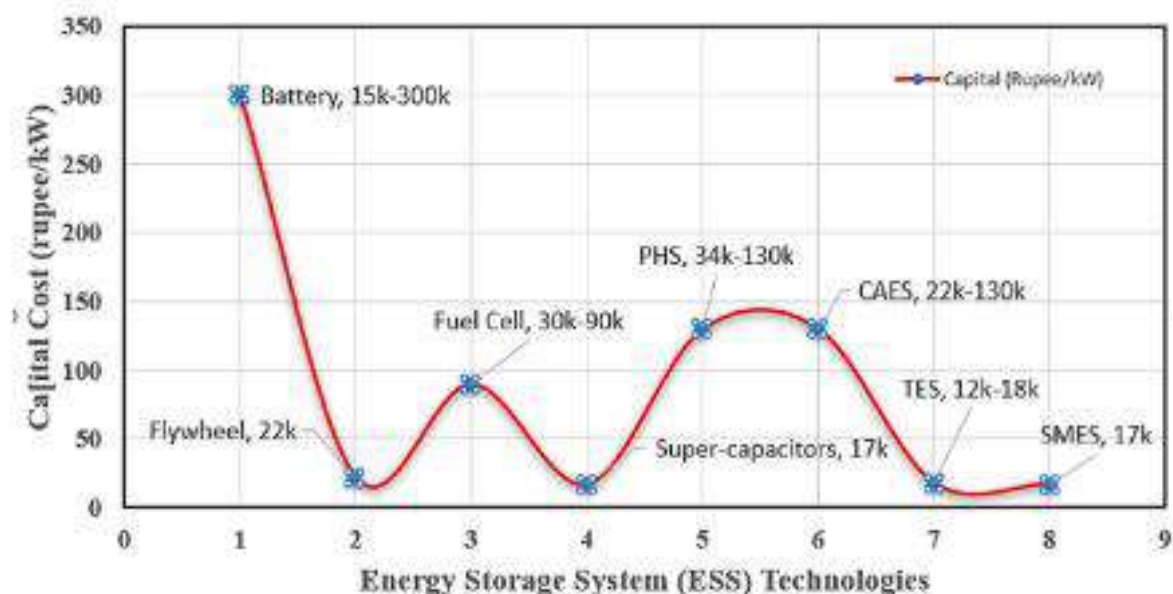
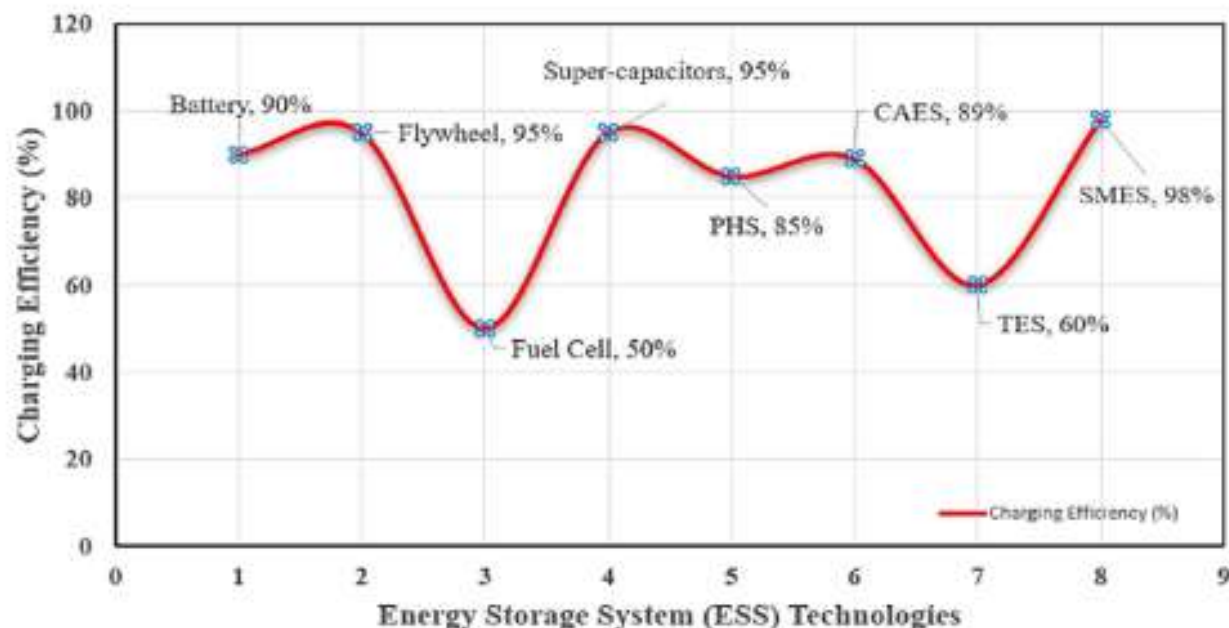
BESS for off-grid application

Lastly, off-grid micro-grids are established in **rural areas or isolated sites** where the cost of providing electricity is too high. Micro-grids are established in such areas **to avoid costly infrastructure** to connect the area with the national grid, for example rural areas of Africa or mountainous regions of China. Battery Energy Storage Systems are ideally suited for such applications where they are used to store energy and provide it according to the demand.

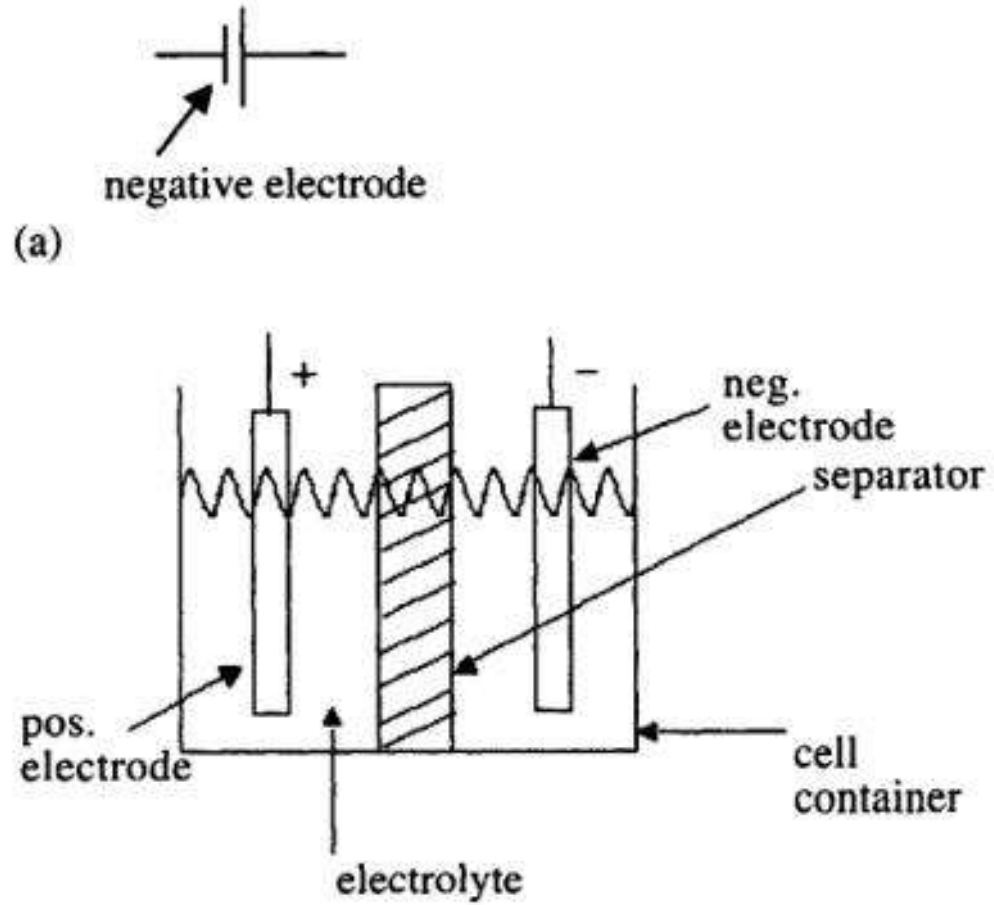
ESS technologies



Basic features]	ESS technologies							
	Battery	Flywheel	Fuel cell	Super-capacitors	PHS	CAES	TES	SMES
Charging efficiency (%)	50-90	90-95	20-50	90-95	70-85	50-89	30-60	95-98
Typical backup time	5-30 min	10-30 s	—	10-30 s	—	—	—	—
Power capacity (MW)	0-100	0-25	0-50	0-0.3	100-5000	3-400	0-300	0.1-10
Energy density (Wh/kg)	30-240	10-30	800-10 000	2.5-15	0.5-1.5	30-60	80-250	0.5-5
Capital (Rupee/kW)	15-300 k	22 k	30-90 k	17 k	34-130 k	22-130 k	12-18 k	17 k
Service lifetime (years)	5-15	20-35	5-15	10-35	40-60	20-60	5-40	>20
Maturity	Com./Dem.	Dem.	Dev.	Dev.	Mature	Dev.	Dev.	Dem.
Environmental impact	Negative	Almost	Small	Small	Negative	Negative	Small	Positive
Maintenance	1/y	1/5 y	—	—	—	—	—	—
Losses at Standby	Very low	Variable	—	High	—	—	—	—



Components of a battery cell



Lead-acid Battery

- Most popular choice of batteries.
- High-powered, inexpensive, safe and reliable.
- Recycling infrastructure available.
- First lead-acid battery produced as early as in 1859.
- Mature technology.

Advantages:

- Relatively low cost. Easy availability of raw materials (lead, sulfur). Ease of manufacture.

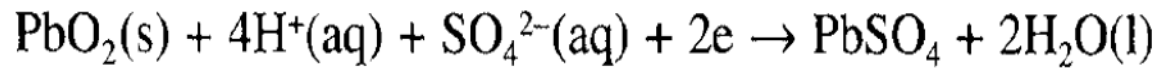
Disadvantages:

- Low specific energy. Poor cold temperature performance. Short calendar and cycle life

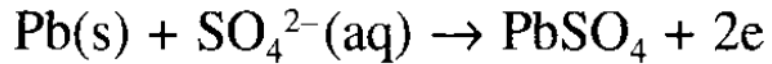
Cell Discharge operation

- Negative electrode (anode) made of spongy or porous lead (Pb). Positive electrode (cathode) consists of lead oxide (PbO₂). Electrolyte used is sulfuric acid (H₂SO₄).

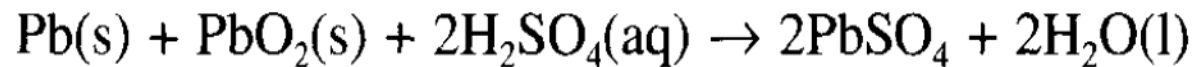
Positive electrode equation:



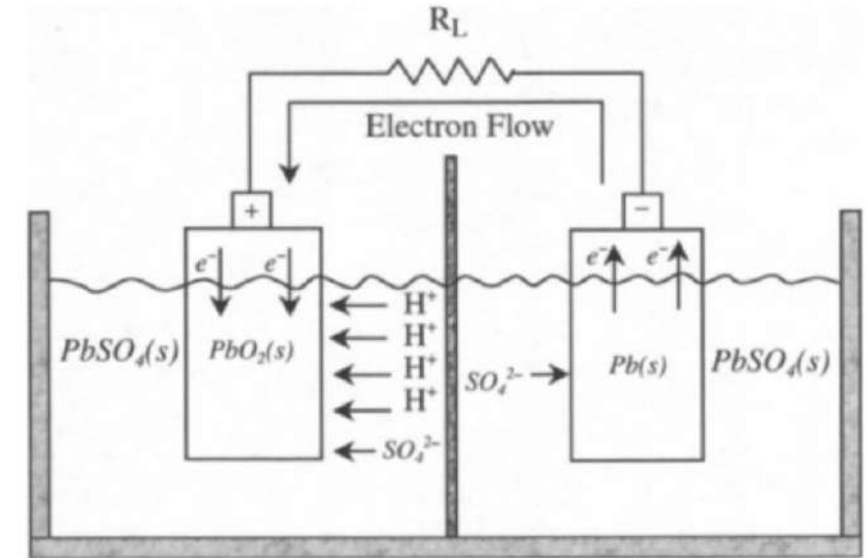
Negative electrode equation:



Overall cell discharge chemical reaction:



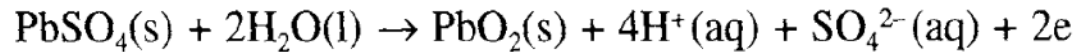
- Internal resistance of the cell rises **due to PbSO₄ formation**.
- Decreases the electrolyte conductivity as H₂SO₄ is consumed.
- PbSO₄ deposited on the electrodes in a dense, fine grain form can lead to sulfatation. This reduces cell capacity significantly.



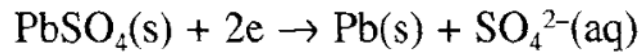
Cell Charge operation

- Reverse of the cell discharge operation.
- Lead sulphate converted back to the reactant states of lead and lead oxide.
- Current flows into the positive electrode from the external source, thus delivering electrical energy into the cell, where it gets converted into chemical energy.

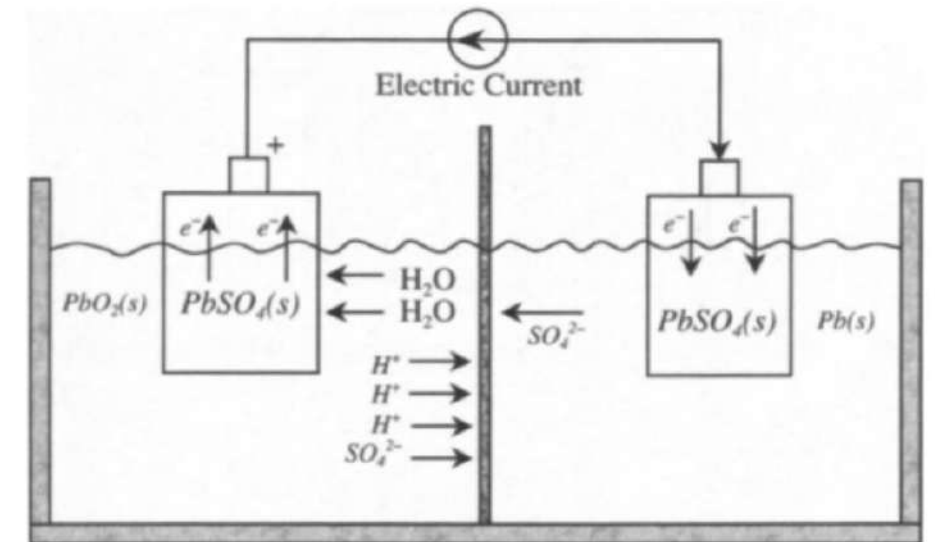
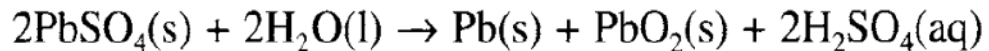
Positive electrode equation:



Negative electrode equation:



Overall cell discharge chemical reaction:



Nickel-Cadmium (NiCd) Battery

- Example of an alkaline battery.
- Electrical energy derived from the chemical reaction of a metal with oxygen in an alkaline electrolyte medium.
- Positive electrode: Nickel oxide.
- Negative electrode: Metallic Cadmium.
- Electrolyte: Potassium hydroxide (KOH).

Advantages: Superior low temperature performance compared to lead-acid batteries. Flat discharge voltage. Long life. Excellent reliability. Lower maintenance requirements.

Disadvantages: High cost. Toxicity contained in cadmium. Insufficient power delivered. Supplanted by the NiMH battery.

Lithium-Ion Battery

- Lithium metal is highly reactive with moisture, which limited their use earlier.
- Discovery in the late 1970s that lithium can be intercalated (absorbed) into the crystal lattice of cobalt or nickel to form LiCoO_2 or LiNiO_2 paved the way toward the development of Li-ion batteries.
- Negative electrode: Lithium intercalated (absorbed) carbons (Li_xC) in the form of graphite or coke.
- Positive electrode: Lithium metallic oxides (Cobalt oxide, manganese oxide)
- Electrolyte: Non-aqueous solutions, in which Lithium hexafluorophosphate (LiPF_6) salt dissolved in organic carbonates.

Advantages: High specific energy, High specific power, High energy efficiency, Good high-temperature performance, Low self-discharge, Recyclable.

Disadvantages: Contain flammable electrolytes.

Battery Parameters

Battery capacity: The amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode is called the battery capacity.

Discharge rate: The discharge rate is the current at which the battery is discharged. For a battery that has a capacity of Q_T Ah and that is discharge over Δt , the discharge rate is $Q_T / \Delta t$.

State of Charge: The state of charge of a battery describes the difference between a fully charged battery and the same battery in use. It is associated with the remaining quantity of electricity available in the cell. It is defined as the ratio of the remaining charge in the battery, divided by the maximum charge that can be delivered by the battery. $20\% < SOC < 80\%$ is preferable.

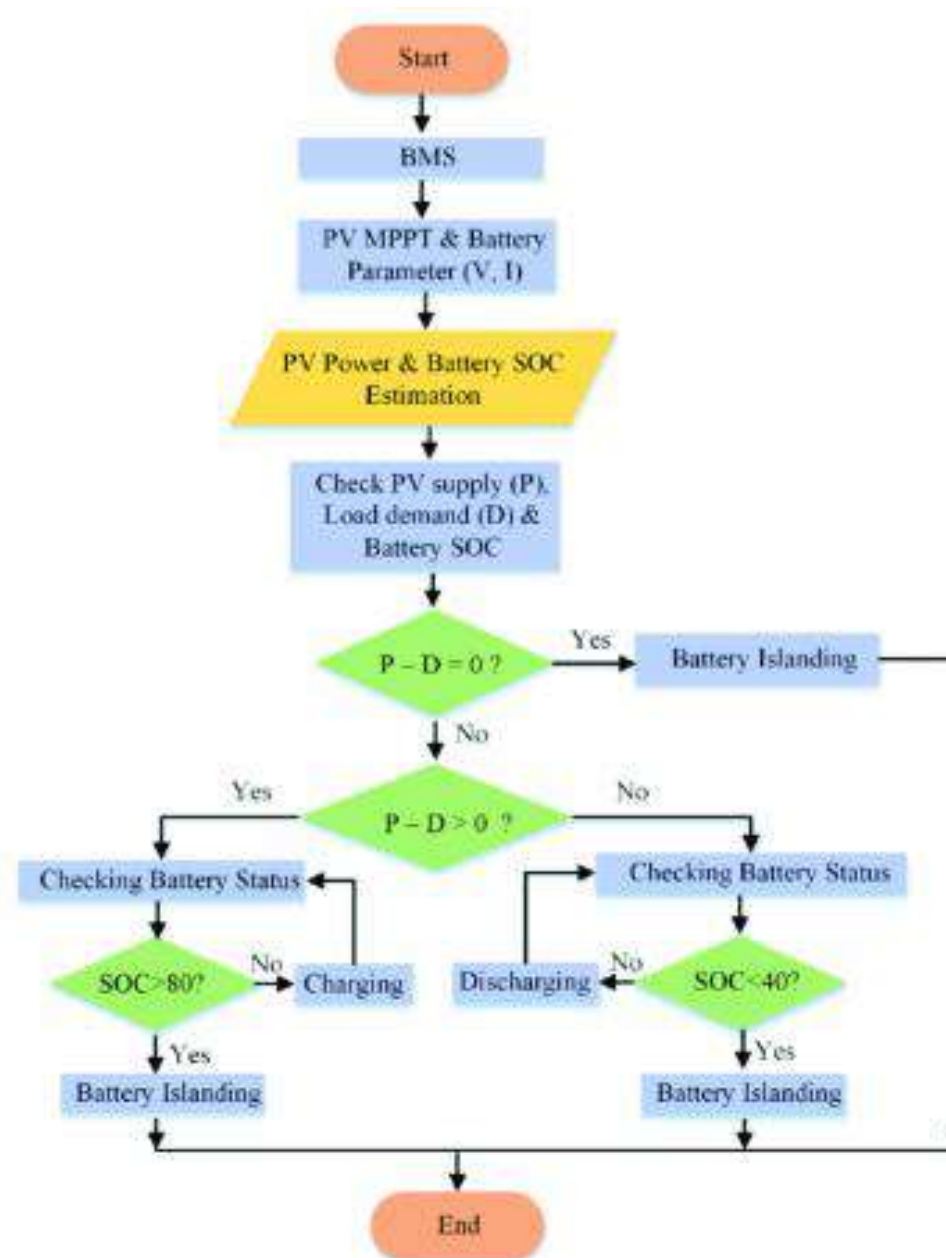
$$SOC = \frac{Q}{Q_{max}} * 100\%$$

$$DOD \text{ (Depth of discharge)} = 100\% - SOC$$

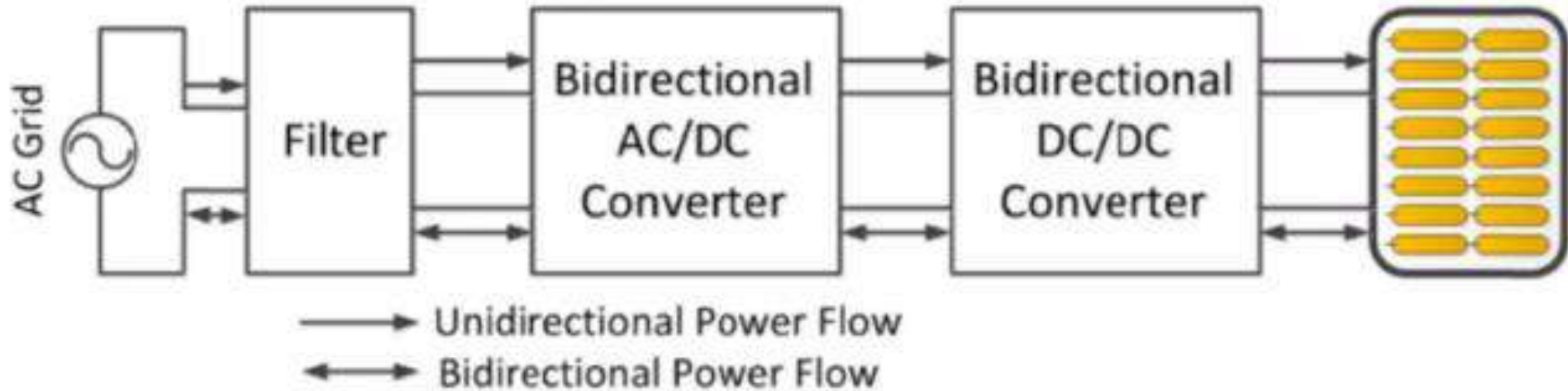
State of Health: The battery state of health is a measurement that indicates the level of degradation and remaining capacity of the battery. It is essentially the difference between the health of a new battery and the health of a used battery, and typically represented as a percentage of its initial capacity. If SOH is decreased then the capacity of charge storage also decreased.

$$SOH = \frac{Q_{max_{old}}}{Q_{max_{new}}} * 100\%$$

Battery charging and discharging Flowchart



Bidirectional converter of an EV

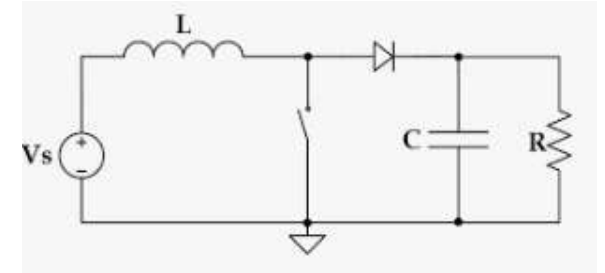


Bidirectional DC/DC converter

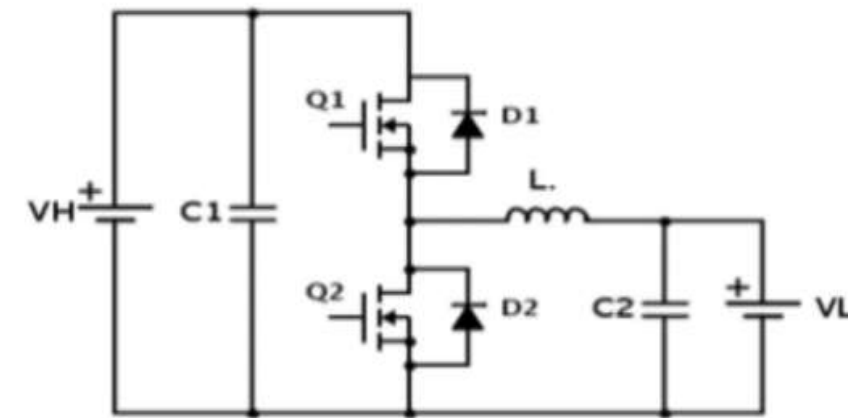
- When the Buck and the boost converters are connected in antiparallel across each other with the resulting circuit is primarily having the same structure as the basic Boost and Buck structure but with the combined feature of bidirectional power flow is called Bi directional dc-dc converter. It works in both directions.
- The switches Q1 or Q2 in sequence with the anti-parallel diodes D1 or D2 (acting as a freewheeling diode) respectively, which makes the circuit step up or step down the voltage connected across them.

Mode 1 (Boost Mode): In this mode switch Q2 and diode D1 begin into conduction depending on the duty cycle whereas the switch Q1 and diode D2 are off all the time. This mode can moreover be divided into two intervals depending on the conduction on the switch Q1 and diode D2.

Interval 1 (Q2-on): In this mode Q2 is on and hence can be examined to be short-circuited, hence the lower voltage battery charges the inductor and the inductor current goes on rising till not the gate pulse is separated from the Q2. Also since the diode D1 is reversed biased in this mode and the switch Q1 is off, no current flows into the switch Q1.

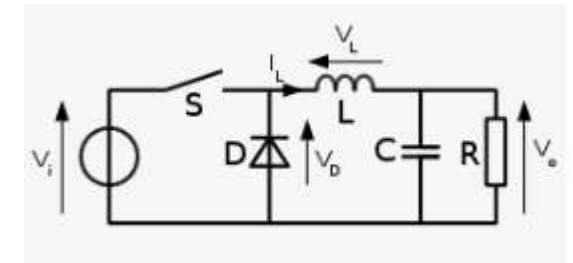


Boost converter



By directional DC/DC converter

Interval 2 (Q2-off): In this mode, Q2 and Q1 both are off and therefore can be considered to be opened circuited. Now since the current flowing into the inductor cannot change immediately, the polarity of the voltage across it reverses and hence it starts acting in series with the input voltage. Therefore the diode D1 is forward biased and so the inductor current charges the output capacitor C2 to a greater voltage. Therefore the output voltage boosts up.

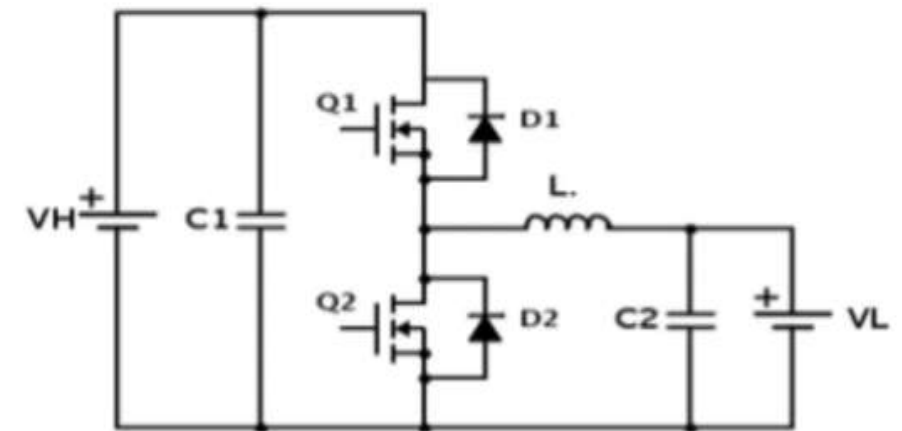


Buck converter

Mode 2 (Buck Mode): In this mode switch Q1 and diode D2 begin into conduction depending on the duty cycle whereas the switch Q2 and diode D1 are off all the time. This mode can moreover be divided into two intervals depending on the conduction on the switch Q2 and diode D1.

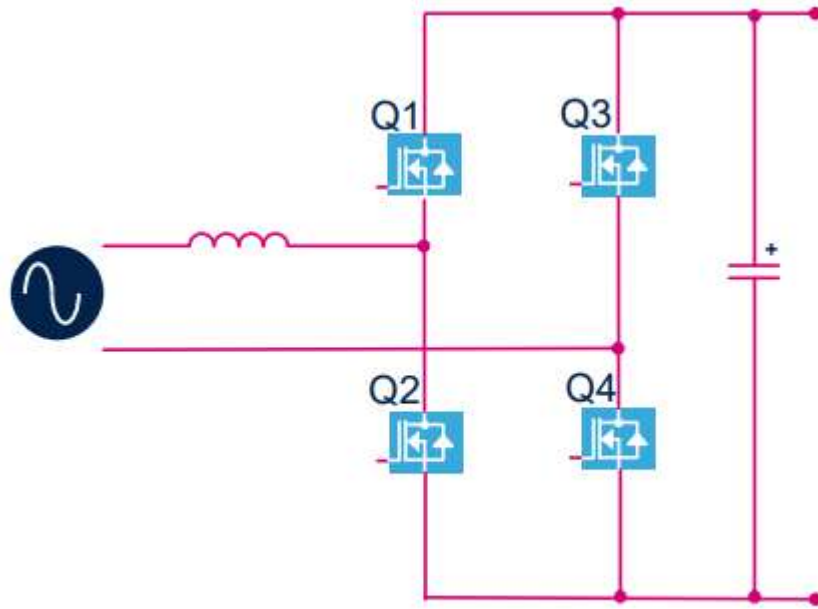
Interval 1 (Q1-on): In this mode, Q1 is on and Q2 is off. The greater voltage battery will charge the inductor and the o/p capacitor will get charged by battery.

Interval 2 (Q1-off): In this mode, Q2 and Q1 both are off. Again as the inductor current cannot change instantaneously, it gets discharged via the freewheeling diode D2. The voltage across the load is stepped down as correlated to the input voltage.

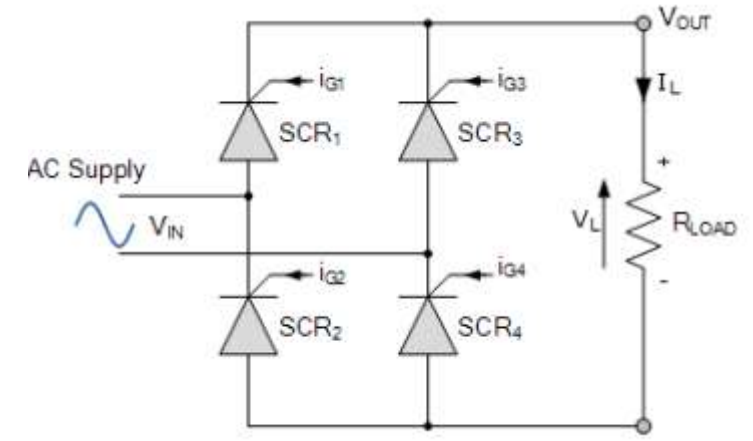


Bidirectional DC/DC converter

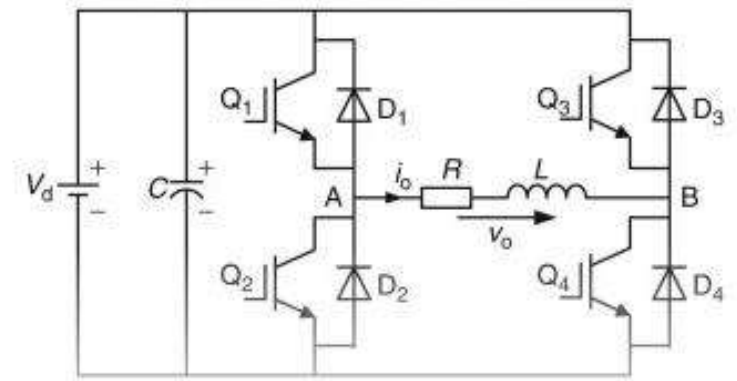
Bidirectional AC/DC converter



Bidirectional AC/DC converter



Unidirectional AC/DC converter



Unidirectional DC/AC converter

Microgrid Clusters

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A microgrid cluster, on the other hand, is a self-healing reconfiguring technique in which the distribution network is divided into smaller, controllable grids. It incorporates several geographically close microgrids into a single network of interconnected microgrids.

Microgrid clusters offer numerous economic benefits to both the utility grid and the microgrids. Microgrid clusters effectively coordinate power sharing among microgrids and the main grid, improving the stability, reliability and efficiency of the distribution network at the consumption premises.

Interconnecting several microgrids into a cluster requires a control and energy management architecture to allow safe and reliable operation of the entire cluster during the grid-connected and islanded modes of operation.

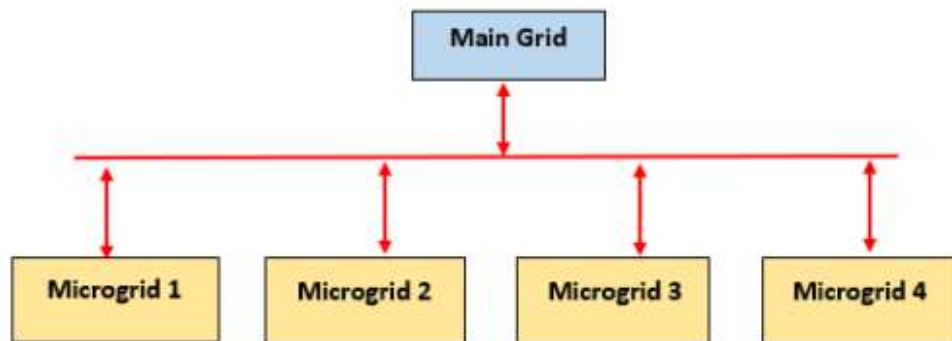


Advantages

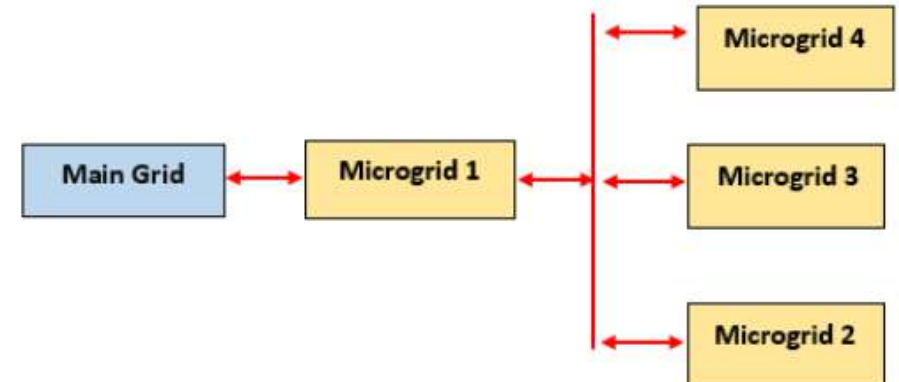
- During a failure of the main grid, the individual microgrids may fail to meet the demand continuously in the microgrid due to intermittency of renewable-energy-based distributed generation. Having interconnections among each other, the microgrids in the cluster overcome this barrier by mutually supporting each microgrid during islanded operation. So reliability increases.
- Each microgrid can sell power to each other so power cost decreases.
- As power is generated and consumed locally so efficiency increases.

Architecture of microgrid clusters

- **Parallel connected:** In the parallel-connected microgrid cluster architecture, all the microgrids are connected in parallel to the main grid, thus making a radial or star topology.
- In the star-connected topology, several microgrids are attached to the main grid through **a common bus**. If any microgrid has surplus power, it is transmitted to the adjacent microgrids in the cluster or to the main grid. On the other hand, if a microgrid experiences a deficit in generation, power is acquired through neighboring microgrids or the main grid. In the islanded mode of operation, the same common bus bar can be used for power sharing.
- In the radially connected topology, **large microgrids** can be connected directly to the main grid through **separate electrical connections**, with the separate point of common coupling and power sharing among the microgrids can only occur through the main grid. However, in islanded operation, all the microgrids should be self-sufficient, as there are no interconnections among microgrids.

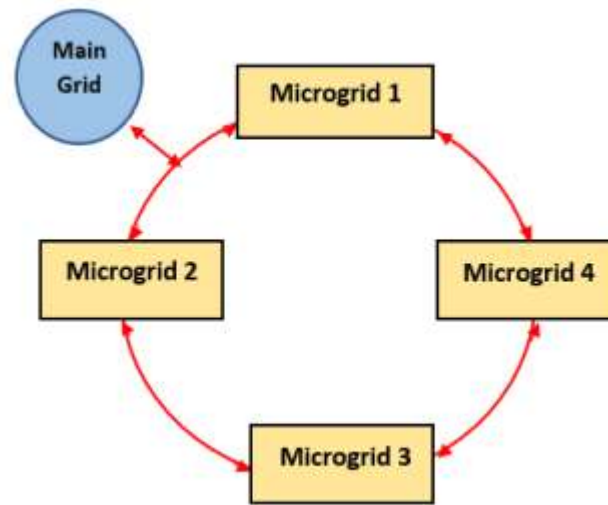


star-connected topology

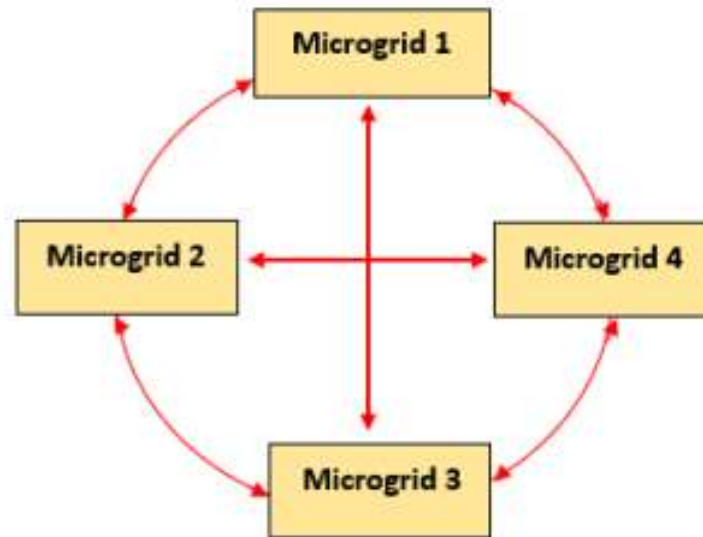


Radially-connected topology

Ring connected: The ring architecture considers a concept where each microgrid in the cluster is **connected to two adjacent microgrids** in the shape of a ring, and energy and information can be shared between them. Several microgrids can be connected to the main grid, with separate points of common coupling for each, where power exchanges directly with the main grid. Neighboring microgrids can communicate with each other to exchange power between them. The ring network has improved redundancy and stability compared to the radial structure. With secure fault isolation and improved reliability, the ring architecture becomes a suitable option for microgrid clustering. However, the network is comparatively complex, and the power exchange can occur between two adjacent microgrids and directly with the main grid. Therefore, controlling and protection of the system become complex.



Mesh connected: In the mesh structure, **microgrids are interconnected with each other**, making a complex network. Therefore, each microgrid is connected to all neighboring microgrids through a power transmission and communication network. Each microgrid can exchange power with the main grid and the neighboring microgrids. Having redundant connections, this configuration inherits improved operational performance with improved stability and reliability. However, control and protection of this type of complex network are challenging tasks. Dispatching and scheduling of distributed generation of each microgrid are affected by all the connected microgrids and its local demand and supply. As each microgrid is connected to others, power-sharing management is difficult. In grid-connected operation, the cluster can provide ancillary services to the main grid.



Performance comparison based on microgrid cluster layout architectures

Microgrid cluster architectures can be compared in terms of scalability, protection, reliability and stability to evaluate their performances.

Scalability: The term scalability considers the **capability of a microgrid cluster to accept new** DERs and microgrids. It accounts for the possibility of the growth of existing microgrids and connection of new microgrids to the cluster. With the growth of microgrids, power flow, as well as power generation and consumption, in each microgrid would change. This affects the power import and export requirements. When the growth of an individual microgrid is considered, it is more favorable if the microgrid is connected to other microgrids in the cluster at several points, as then it can facilitate more energy exchange. Hence, mesh architecture has better acceptance in terms of the growth of the microgrids in the cluster. In some parallel configurations, power exchange through the main grid or the dominant microgrid can make them saturate. Therefore, possible saturation can limit the advantage of simplicity in scalability. This drawback is avoided in the ring structure because each microgrid is connected to two adjacent microgrids, and its complexity is lower than that of the mesh structure.

Layout architecture	Microgrid cluster growing capacity	Individual microgrid growing capacity	Overall scaling capacity	Complexity
Parallel	Low	Medium	Low	Low
Ring	High	Medium	Medium	Medium
Mesh	High	High	High	High

Stability: Stability refers to the ability of the microgrid cluster to return to the steady state after a disturbance, and it refers to **voltage stability, frequency stability and rotor angle stability**. The microgrid cluster, while connected to the external grid, the grid provides enhanced network stability to the microgrids. However, when the microgrid cluster is islanded, the stability of a microgrid is supported by other microgrids in the cluster. In islanded operation, the stability of the cluster mainly depends on the power reserves, synchronous inertia, reactive power sources, etc. Therefore, unavailability of a single microgrid can be critical for the stability of the cluster, because it can disconnect the critical power flow balancing sources in the cluster. In the parallel architecture, a fault in the interconnection can completely isolate a microgrid, breaking the unique access to the rest of the microgrid and making the cluster less stable.

Layout architecture	Stability
Parallel	Medium
Ring	High
Mesh	High

Protection: The protection system should protect the microgrid cluster against electrical failures, isolating the fault area without affecting the rest of the system. Also, it should minimize the damage that can happen to the assets and facilities in the affected area. In the parallel connected architecture, there may be a unique path to the main grid or to another neighboring microgrid. In the event of a failure at the interconnection point, the protection system can effect the complete isolation of the microgrid, reducing the reliability. However, protection coordination is very **simple, guaranteeing good selectivity, discrimination, accurate sensitivity and fast protection actuation**. In ring and mesh architectures, the microgrids are operated in **closed-loop operation, having more interconnections**. Therefore, a robust protection system and a good communication system are required. Due to the high complexity, the cost will also increase.

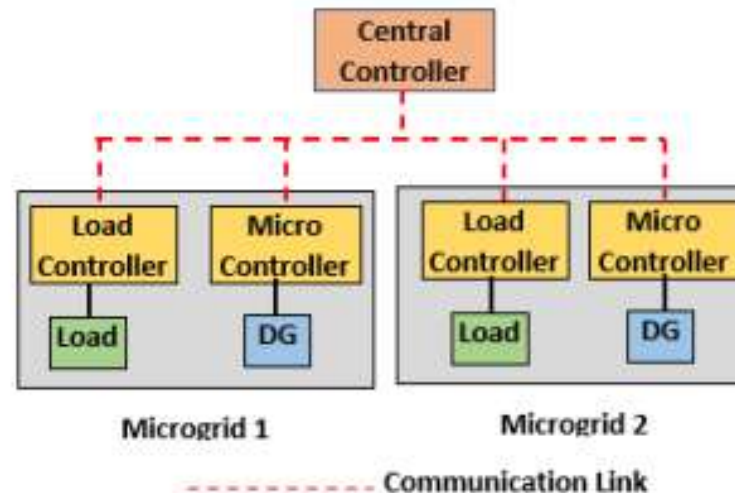
Layout architecture	Selectivity applicability	Coordination requirements	Overall protection difficulty
Radial	High	Low	Low
Ring	Medium	Medium	Medium
Mesh	Low	High	High

Reliability: The number of elements inside microgrids, how they are controlled and how the microgrids are connected can decide the reliability of the microgrid cluster. Once a contingency occurs, the affected area will be disconnected by the protection scheme, and a part of the power consumed or generated will be no longer associated with the microgrid cluster. Therefore, the **reliability of the cluster mainly depends on the connection parts and the redundancy of the system**. An architecture with **many interconnections** to the main grid will have the advantage in a contingency.

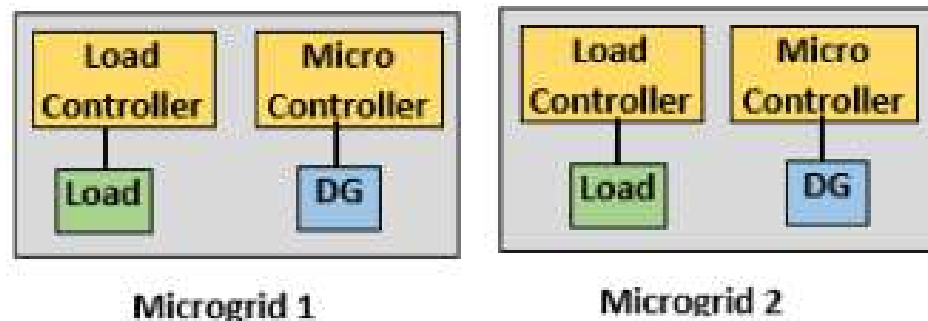
Layout architecture	Reliability
Parallel	Medium
Ring	High
Mesh	High

Control Strategy

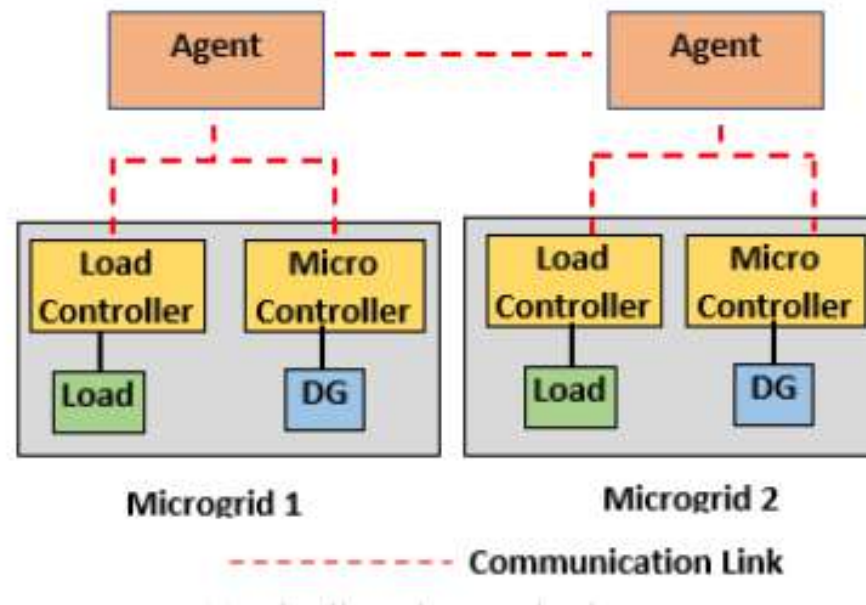
1. **Centralized control:** In the centralized control concept, all the micro-source controllers and load controllers are handled by a **central controller** using a bidirectional communication system. The central controller receives the local information, such as **current and voltage measurements and load and demand data**, from each microgrid in the cluster and then processes the data within it. Then, control actions are sent back to the microgrids, and they are executed by the local controllers. Therefore, the central controller manages the power flow among the microgrids and the load and demand balance in the system. Also, it participates in **economic aspects while keeping stability in the system**. Therefore, the **overall benefit of the system** is maximized. However, the central controller has a high computation burden, and with the increasing number of microgrids, with high renewable penetration, **the central controller can fail in some situations**. Failure in the central controller can lead to the total failure of the entire cluster.



2. **Decentralized control:** The decentralized control concept considers a concept where each microgrid in the cluster **determines its control actions independently**. The local controllers of each microgrid process the data provided by microcontrollers and load controllers, with a reduced burden compared to the central controller in the centralized approach, and send the control actions to local controllers. A microgrid can **operate autonomously**, and control actions can be generated for the optimal operation of each microgrid without relying on any communication among individual microgrids. Therefore, each local controller has the responsibility of collecting necessary information in order to optimize the microgrid operation. Therefore, decentralized control increases the stability of each microgrid in the cluster with a reduction in communication failures. Also, due to the autonomous operation capability, the cluster can scale in size. A failure in a microgrid does not affect the operation of the entire microgrid cluster. However, when it comes to the entire cluster, with the decentralized control, the **optimum operation cannot be guaranteed**, due to the absence of communication among microgrids. Each microgrid tries to work on the **individual objectives without knowing the information** of other neighboring microgrids, which increases the **competitiveness** across the cluster. Therefore, this structure is more suitable for a microgrid cluster with **different owners** for individual microgrids.



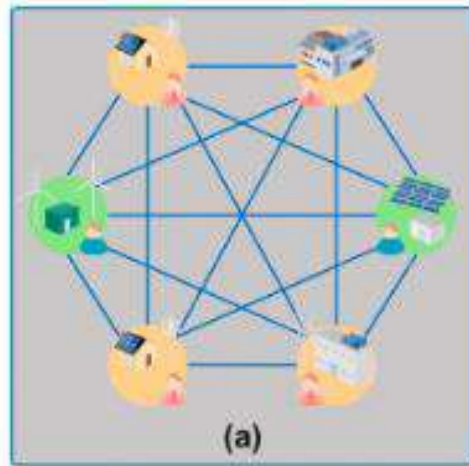
3. **Distributed control:** The distributed control concept considers a two-level operation to optimize the microgrid cluster. Central controllers, called central agents, and micro-controllers and local controllers of microgrids take part in the control concept via two-way communication. **Each agent is connected to the neighboring agents, making it possible to share the information** of each microgrid with other agents. Therefore, the operation of each microgrid in the cluster is controlled and coordinated by multiple dispersed central agents. This structure eliminates the competitiveness that exists in the decentralized structure, and the optimal operation can be achieved. However, since the data of each microgrid are being shared among the agents, **security is compromised**.



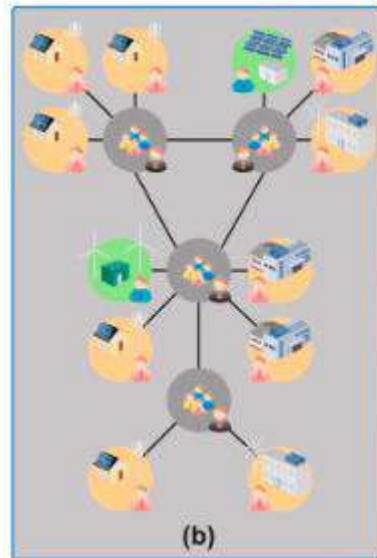
	Advantages	Disadvantages
Centralized [32,33]	- Offers a simple control architecture with a single central controller - Low operation costs	- Unable to expand to larger and more complex networks - Requires communication links between central controller and local controllers
Decentralized [32,33]	- Suitable for the coordination of multiple autonomous systems - Provides autonomy to each individual system with no communication among systems	- Complicated control tasks due to the lack of a central controller - Decrease in aggregate performance due to competitiveness among individual systems
Distributed [33,34]	- Impacts to the aggregate performance are considered and control tasks shared by each individual system - Provides cooperation among individual systems	- Data is shared among individual systems compromising security - Requires communication links between the neighbouring systems

Energy market design

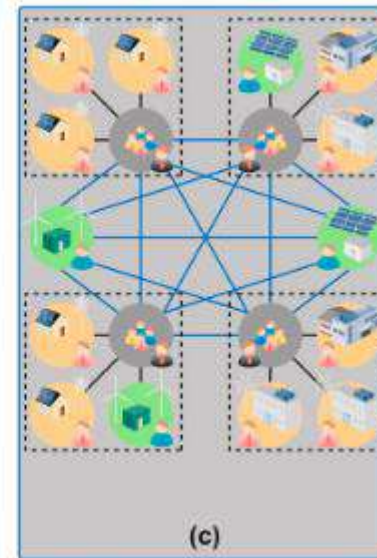
A **P2P** energy market is a **fully decentralized** model which allows all the participating peers (i.e. prosumers and producers) to trade energy with each other directly, providing an autonomous and flexible internal market. A **P2G** energy market is a structured model which relies on a community manager controlling all the energy trades inside the community as well as any interactions with other community managers in the grid (e.g. communities of prosumers connected to an MG). The **P2P and the P2G models can be combined in a hybrid market** model. This hybrid model consists of prosumer groups which rely on a central entity such as a community manager controlling the energy trades, but these groups and other peers can trade energy with each other in a P2P manner.



P2P



P2G



Hybrid

Solar Energy system

By Dr. Rajdip Dey
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Solar energy systems

- More energy from the sun falls on the earth in one hour than is used by everyone in the world in one year. A variety of technologies convert sunlight to usable energy for buildings. The most commonly used solar technologies for homes and businesses are solar photovoltaics for electricity, passive solar design for space heating and cooling, and solar water heating.
- Photovoltaics (often shortened as PV) gets its name from the process of converting light (photons) to electricity (voltage), which is called the *photovoltaic effect*. This phenomenon was first exploited in 1954 by scientists at Bell Laboratories who created a working solar cell made from silicon that generated an electric current when exposed to sunlight. Solar cells were soon being used to power space satellites and smaller items such as calculators and watches. Today, electricity from solar cells has become cost competitive in many regions and photovoltaic systems are being deployed at large scales to help power the electric grid.
 - PV is a means of electricity generation by direct conversion of solar energy to electricity.
 - The solar cell is the core component for light-to-electricity conversion.
 - Currently, crystalline silicon solar cell is the dominant type in the market, and other types include amorphous silicon thin film solar cell and compound thin film PV cell.
 - A PV power system may operate independently or in parallel with the grid.

Advantage and disadvantage of Solar energy systems

Advantages of Solar Energy

Lowers your Electricity Bills

Environmentally Friendly

Moves us Closer Towards Energy Independence

Sustainable

Low Maintenance

Benefits the Electricity Grid

Disadvantages of Solar Energy

Expensive Initial Investment

It Won't Work at Night

Limited Energy Storage

Space Constraints

Isn't 100% Pollution-Free

Depends on Location

Different solar cells

Crystalline Silicon Cells

Around 90% of solar cells are made from crystalline silicon (c-Si) wafers. Single crystals are used to create monocrystalline solar panels and cells (mono-Si), while multiple crystals are used for polycrystalline panels and cells. Monocrystalline cells are cut into shape, which can be wasteful, but do provide the highest levels of efficiency. Polycrystalline cells do not need to be cut to shape as the silicon is melted and poured into square moulds.

Thin Film Solar Cells

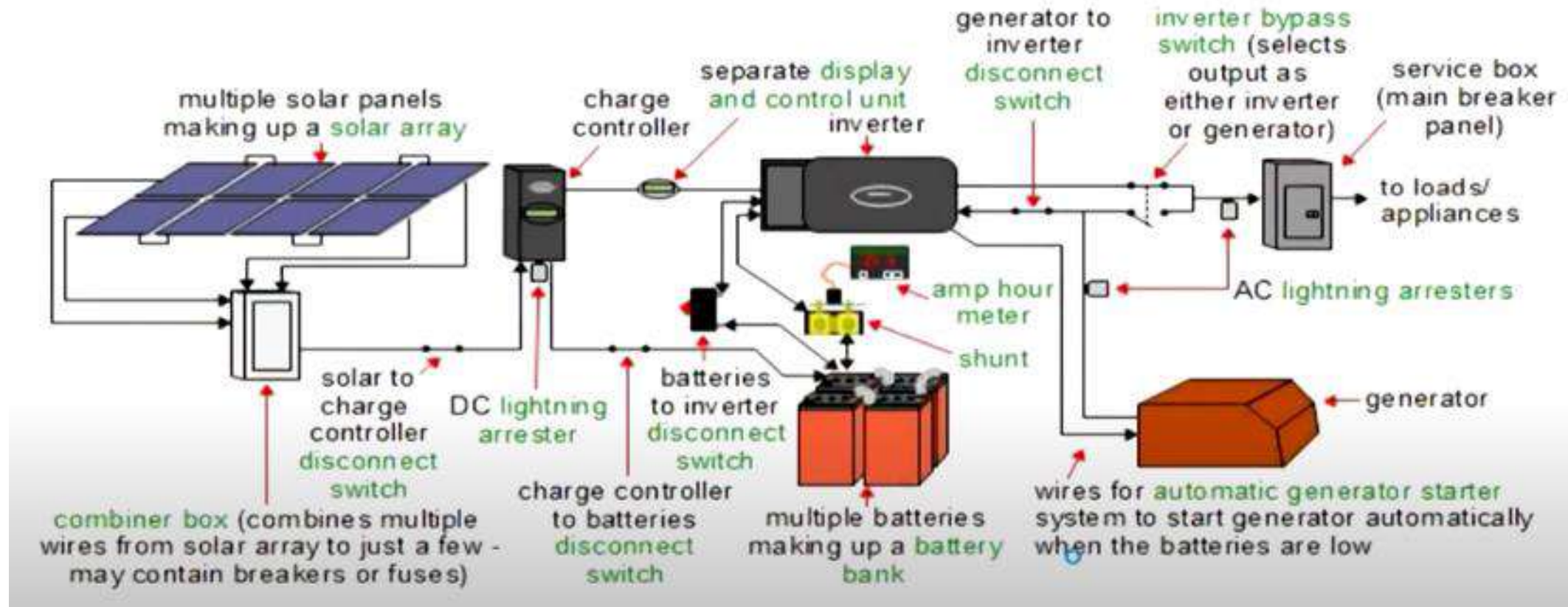
Thin-film solar cells, also called thin-film photovoltaics are around 100 times thinner than Crystalline silicon cells. These thin film solar panels and cells are made from amorphous silicon (a-Si), in which the atoms are randomly arranged rather than in an ordered crystalline structure. These cells are produced by layering photovoltaics to create a module and are the cheapest option for producing solar panels. The cells can be laminated onto windows, skylights, roofing tiles and other substrates, including glass, metals and polymers.

Third Generation Solar Cells

The latest solar cell technologies combine the best features of crystalline silicon and thin-film solar cells to provide high efficiency and improved practicality for use. They tend to be made from amorphous silicon, organic polymers or perovskite crystals, and feature multiple junctions made up from layers of different semiconducting materials.

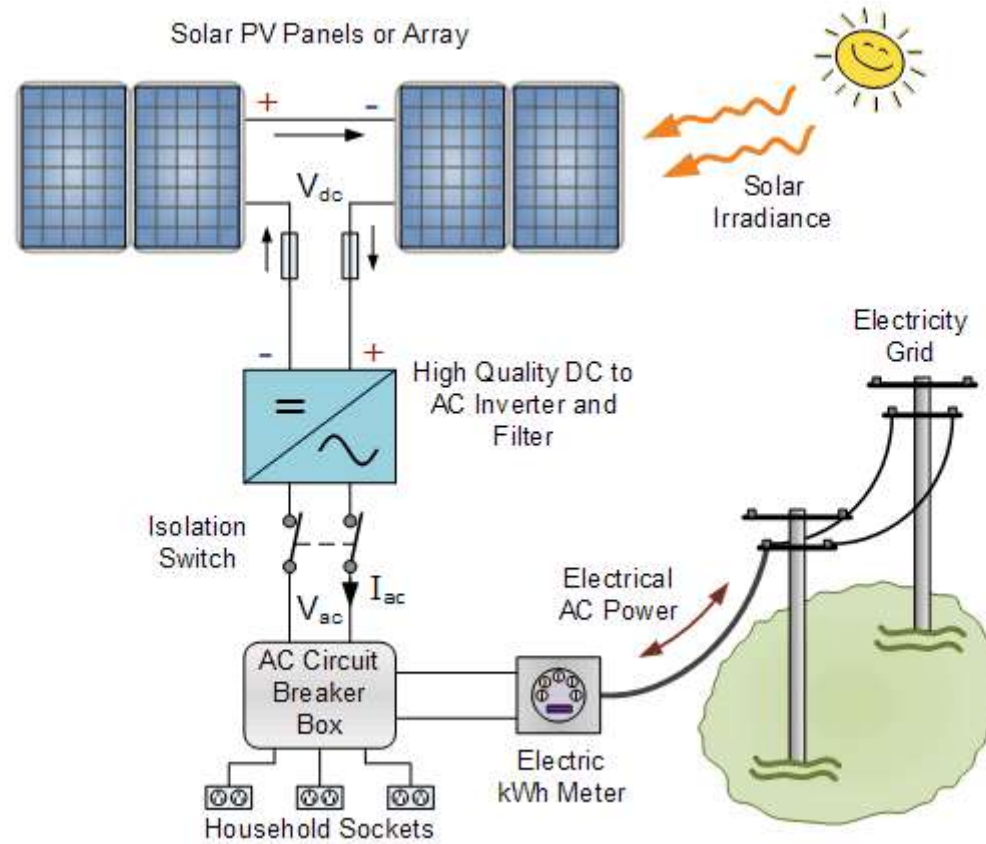
Solar Cell Type	Efficiency Rate	Advantages	Disadvantages
Monocrystalline Solar Panels (Mono-Si)	~20%	High efficiency rate; optimised for commercial use; high life-time value	Expensive
Polycrystalline Solar Panels (p-Si)	~15%	Lower price	Sensitive to high temperatures; lower lifespan & slightly less space efficiency
Thin-Film: Amorphous Silicon Solar Panels (A-Si)	~7-10%	Relatively low costs; easy to produce & flexible	shorter warranties & lifespan
Concentrated PV Cell (CVP)	~41%	Very high performance & efficiency rate	Solar tracker & cooling system needed (to reach high efficiency rate)

Different solar energy system structures



Structure of independent solar system

Different solar energy system structures

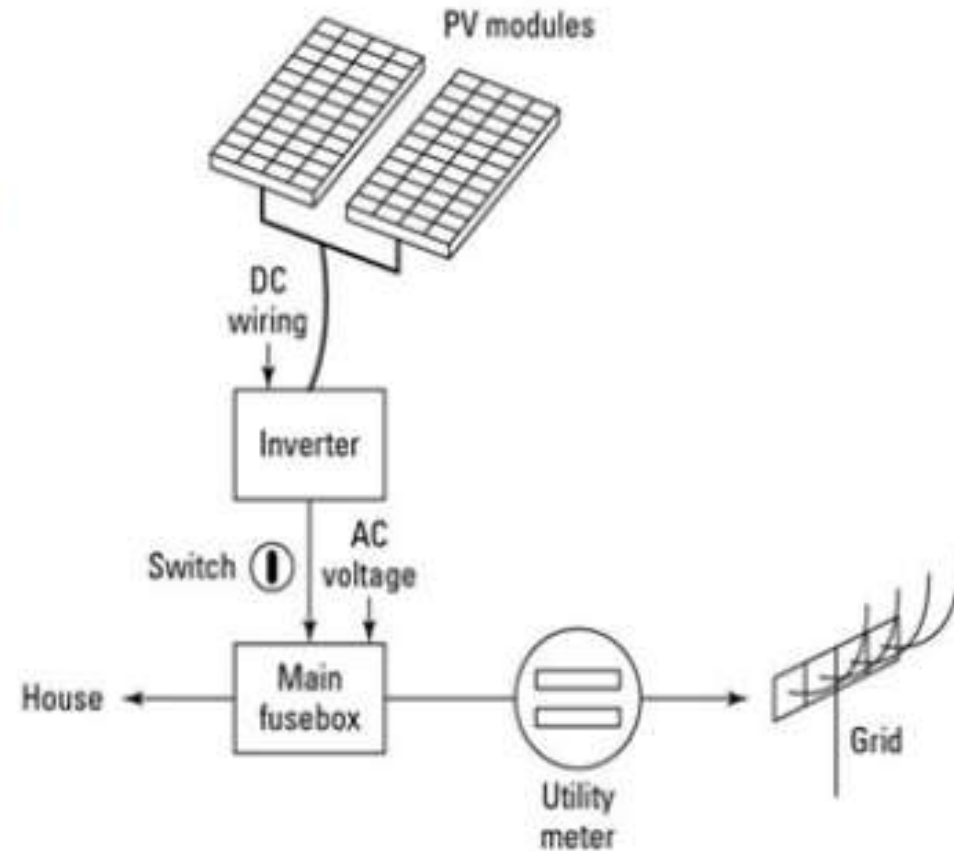


Structure of grid connected solar system

Basic components of solar cell

The basic components of a solar power system includes:

1. PV Module
2. Inverter
3. Main Fuse Box
4. Utility Meter
5. Grid



1. PV Module :

A PV module is nothing but a panel consisting of large number of solar cells or photovoltaic cells that stores the solar energy and convert into electricity for further usage.



1. Inverter : Inverter is a small set-up that has a simple working principle of converting Direct Current (D.C.) into Alternating Current (A.C.).

2. Main Fuse Box :

It is a distributor box that supplies the power to different appliances according to the requirement of individual appliance.



4. A utility meter is defined according to its usage. The utility can be in the form of electricity, Gas, Water, Heat, etc.



5. **Grid** : The Grid is a connection of Photovoltaic or PV modules used to generate more & more electricity using solar energy. It consists of a

Solar energy system working

SUNLIGHT ACTIVATES THE PANELS: Each individual panel is constructed of a layer of silicon cells, a metal frame, a glass casing surrounded by a special film, and wiring. For maximum effect, the panels are grouped together into “arrays” (an ordered series) and placed on rooftops or in large outdoor spaces. The solar cells, which are also referred to as *photovoltaic cells*, absorb sunlight during daylight hours.

THE CELLS PRODUCE ELECTRICAL CURRENT: Within each solar cell is a thin semiconductor wafer made from two layers of silicon. One layer is positively charged, and the other negatively charged, forming an electric field. When light energy from the sun strikes a photovoltaic solar cell, it energizes the cell and causes electrons to ‘come loose’ from atoms within the semiconductor wafer. Those loose electrons are set into motion by the electric field surrounding the wafer, and this motion creates an electrical current.

THE ELECTRICAL ENERGY IS CONVERTED: the electricity generated is called direct current (or DC) electricity, which is not the type of electricity that powers most homes, which is alternating current (or AC) electricity. Fortunately, DC electricity can easily be changed into AC electricity by a gadget called an inverter. In modern solar systems, these inverters can be configured as one inverter for the entire system or as individual microinverters attached behind the panels.

THE CONVERTED ELECTRICITY POWERS YOUR HOME: Once the solar energy has been converted from DC to AC electricity, it runs through your electrical panel and is distributed within the home to power your appliances. It works exactly the same way as the electrical power generated through the grid by your electric utility company, so nothing within the home needs to change. Since you still remain connected to your traditional power company, you can automatically draw additional electricity to supplement any solar shortages from the grid.

A NET METER MEASURES USAGE: On cloudy days and overnight, solar panels may not be able to capture enough sunlight to use for energy; conversely, in the middle of the day when nobody is home, they may collect surplus energy more than you need to operate your home. That’s why a meter is used to measure the electricity flowing in both directions to and from your home. Your utility company will often provide credits for any surplus power you send back to the grid. This is known as *net metering*.

Use of Solar energy

SOLAR ELECTRICITY : As [solar panel costs](#) decline and more people become aware of [solar energy's financial and environmental benefits](#), solar electricity is becoming increasingly accessible. While it's still a tiny percentage of the electricity generated in the U.S. ([2.8% as of 2021](#)), solar electricity is growing rapidly. Technicians usually install a distributed solar PV system on [the rooftops of homes](#) or [businesses](#). These solar power systems generate electricity to offset the property owner's usage and [send any excess production to the electric grid](#).

SOLAR BATTERIES AND GENERATORS: A solar battery can connect to your solar power system. This setup lets you use solar after sundown and provides [backup battery power for homes](#) during emergencies. Some homeowners may choose to go completely off-grid with a [solar power and battery system or a solar power and generator system](#).

SOLAR WATER HEATING : Homeowners can also use solar energy to power their water heaters. [Two types of solar water heating systems](#) exist:

Active solar water heater systems : Active solar water heaters use **mechanical circulating pumps** to move fluids between your rooftop solar panels and storage tank. In turn, these heaters have two different types:

In **direct circulation systems**, a pump moves regular water into your house through solar collectors. Because the water can freeze, direct circulation systems work best in climates that rarely see freezing temperatures.

Indirect circulation systems circulate nonfreezing liquids through solar collectors to a heat exchanger. From there, the energy transfers to water that circulates into your house. Climates with freezing temperatures can rely on indirect circulation systems.

Passive solar water heater systems: Unlike active solar water heater systems, passive systems lack mechanical pumps. Instead, they have simple physics to thank because heat naturally rises. Unsurprisingly, this makes them much cheaper (albeit less efficient) than their active counterparts.

SOLAR LIGHTING:

1. SOLAR LANDSCAPE LIGHTING
2. SOLAR HOME LIGHTING
3. SOLAR STREET LIGHTS

SOLAR APPLIANCES:

1. SOLAR OVENS
2. SOLAR HEATERS
3. SOLAR COOLER
4. SOLAR ROOF

SOLAR WEARABLES:

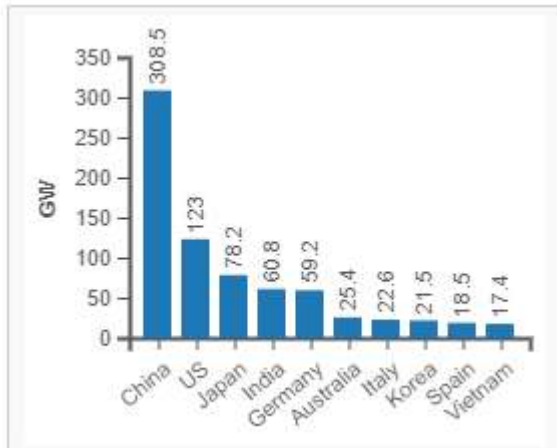
1. SOLAR WATCHES
2. SOLAR BACKPACKS
3. SOLAR BLUETOOTH HEADPHONES, EARBUDS AND HEADSET

SOLAR TRANSPORTATION:

1. CARS
2. SOLAR CHARGING STATIONS
3. BOATS

Solar energy in INDIA

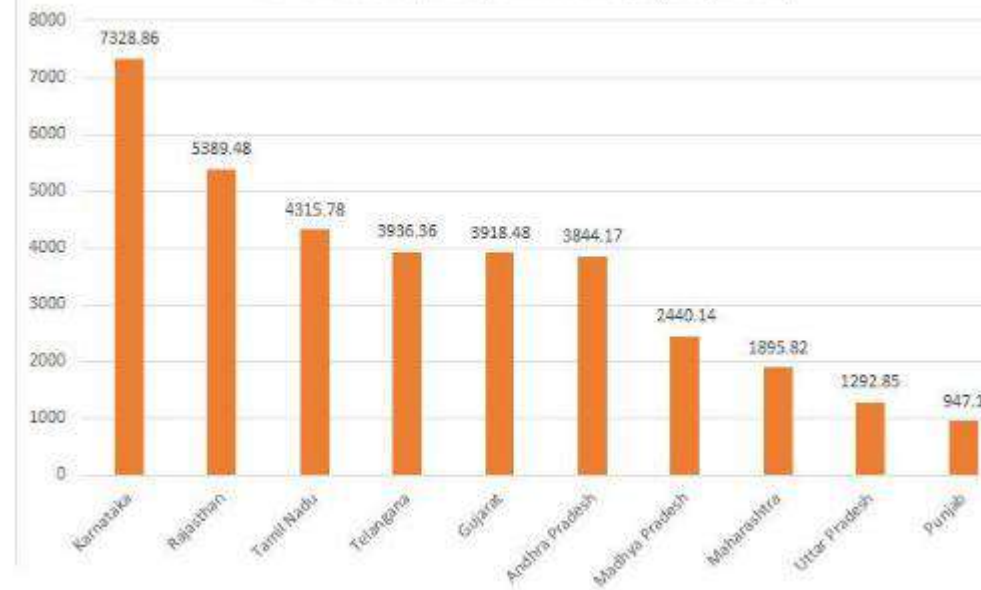
Recently, India stands 4th in solar PV deployment across the globe as on end of 2021. Solar power installed capacity has reached around 61.97 GW as on 30th November, 2022. Presently, solar tariff in India is very competitive and has achieved grid parity.



Year Cumulative Capacity (in MW)

2010	161
2011	461
2012	1,205
2013	2,319
2014	2,632
2015	3,744
2016	6,763
2017	12,289
2018	21,651
2019	28,181
2020	34,627
2021	40,085
2022	56,951

Cumulative Capacity in MW till (31/12/2020)



Solar energy in INDIA

Monthly solar power generation in India, April 2019 – March 2020

Month ↕	Regional solar power generation (GWh) ^[82]					Total (GWh) ↕
	North ↕	West ↕	South ↕	East ↕	North East ↕	
April 2019	839.92	903.75	2,358.89	64.69	1.41	4,168.67
May 2019	942.89	926.49	2,402.74	53.94	1.37	4,327.42
June 2019	932.40	787.48	2,136.10	61.13	1.02	3,918.13
July 2019	785.69	702.83	1,889.87	48.44	1.23	3,428.06
August 2019	796.67	630.70	2,111.37	36.03	0.97	3,575.73
September 2019	885.50	585.18	2,054.69	38.84	0.93	3,565.14
October 2019	988.51	763.85	2,074.86	54.23	0.97	3,882.41
November 2019	807.47	776.97	2,305.09	46.22	1.07	3,936.82
December 2019	851.38	803.72	2,228.86	43.31	1.13	3,928.39
January 2020	945.68	904.87	2,712.82	48.35	1.00	4,612.72
February 2020	1,151.87	979.12	2,906.16	51.97	1.54	5,090.66
March 2020	1,218.18	1,091.06	3,253.81	68.66	1.59	5,633.30
Total (GWh)	11,146.16	9,856.02	28,498.91	615.81	14.2	50,131.10

Photovoltaic (PV) installed capacity by application (MW_{AC})^[83]

Application	31 January 2023
Ground mounted including floating and hybrid.	53,387.30
Rooftop	8,218.00
Off-grid	2,288.00
TOTAL	63,893.30

Solar energy in INDIA

Major photovoltaic (PV) power plants

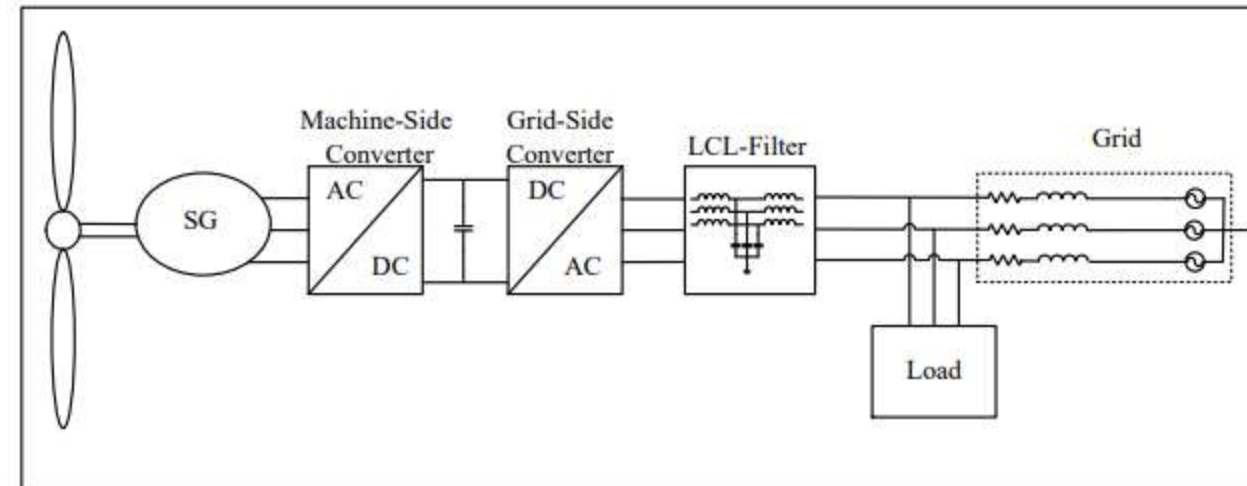
Plant	State	Coordinates	DC peak power (MW)	Commissioned	Notes
Bhadla Solar Park	Rajasthan	 27°32'22.81"N 71°54'54.91"E	2,245	2020	World's biggest solar park in terms of generation and second largest in terms of area as of March 2020
Pavagada Solar Park	Karnataka	 14°15'7"N 77°26'51"E	2,050	2019	Second biggest solar park in the world and world's largest in terms of area as in March 2020
Kurnool Ultra Mega Solar Park	Andhra Pradesh	 15.681522°N 78.283749°E	1,000	2017	
NP Kunta	Andhra Pradesh	 14°01'N 78°26'E	978	2021	In Nambulapulakunta Mandal. Total planned capacity 1500 MW
Rewa Ultra Mega Solar	Madhya Pradesh	 24°28'49"N 81°34'28"E	750	2018	
Charanka Solar Park	Gujarat	 23°54'N 71°12'E	690	2012	Situated at Charanka village in Patan district . Capacity expected to go up to 790 MW in 2019.
Kamuthi Solar Power Project	Tamil Nadu	 9.347568°N 78.392162°E	648	2017	With a generating capacity of 648 MW _p at a single location, it is the world's 12th largest solar park based on capacity.
Gujarat solar park 1	Gujarat	 23°54'N 71°12'E	221	2012	
Ananthapuramu – II	Andhra Pradesh	 14°58'49"N 78°02'45"E	400	2019	Located at Talaricheruvu village in Tadipatri mandal of Anantapur district . Planned capacity 500 MW
Galiveedu solar park	Andhra Pradesh	 14°6'21"N 78°27'57"E	400	2020	Located at Marrikommadinne village in Galiveedu mandal of kadapa district .
Mandsaur Solar Farm	Madhya Pradesh	 24°5'17"N 75°47'59"E	250	2017	

Wind Energy Conversion System

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Basics of WECS

- Wind energy conversion systems are the most dominant technology as wind is safe, economical and clean renewable source. Wind energy harvesting has been a very long tradition. Some historians suggest that wind mills were used over 3000 years ago. Until the early twentieth century wind power was used to provide mechanical power to water pump, boats, ships and grinding mills.
- Generally there are two type of wind energy conversion system (WECS). Variable speed WECS are mainly used topology as they have several advantages over fixed speed WECS like higher efficiency and good power quality.
- In variable speed WECS, different types of electric generators are used such as synchronous generator with external field excitation, squired-cage induction generator, doubly fed induction generator and permanent magnet synchronous generator.
- The system model includes a wind turbine, a generator, PWM rectifier in generator side converter, intermediate DC link capacitor and PWM inverter in grid side converter. Accordingly, it allows fully decoupled control between the grid side converter and the generator side converter.
- When using wind rotors to extract wind power, it is not 100% efficient. In 1919, a German physicist Albert Betz found limit of power conversion factor $16/27$ th of the kinetic energy into mechanical power. This conversion factor is known as constant or Betz limit



Modelling of Wind turbine

A wind turbine can't capture full wind energy because of various aerodynamic losses depending upon rotor construction so actual energy extracted by a wind turbine is given as

$$P_m = 0.5C_p(\lambda, \beta)\rho Av^3$$

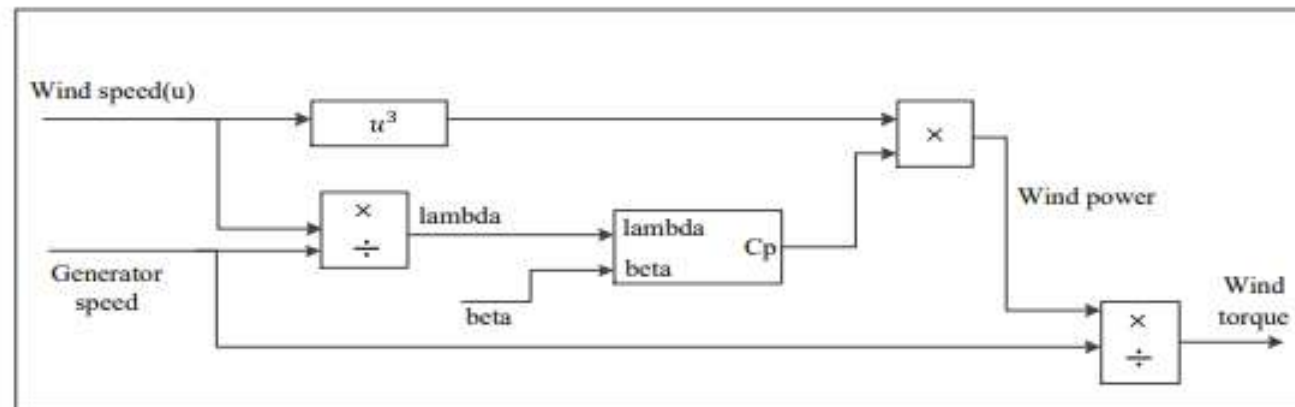
Where 'A' is the swept area of wind turbine blades and is the power coefficient depending upon two parameters, tip speed ratio (λ) and pitch angle (β). Where the tip speed ratio (λ) is given by

$$\lambda = \frac{\omega_m R}{v}$$

Where 'R' is the blade length of wind turbine, is the wind turbine rotor speed and 'v' is the wind speed. The wind turbine torque output is given by

$$T_m = 0.5\rho AC_p(\lambda, \beta)v^3 \frac{1}{\omega_m}$$

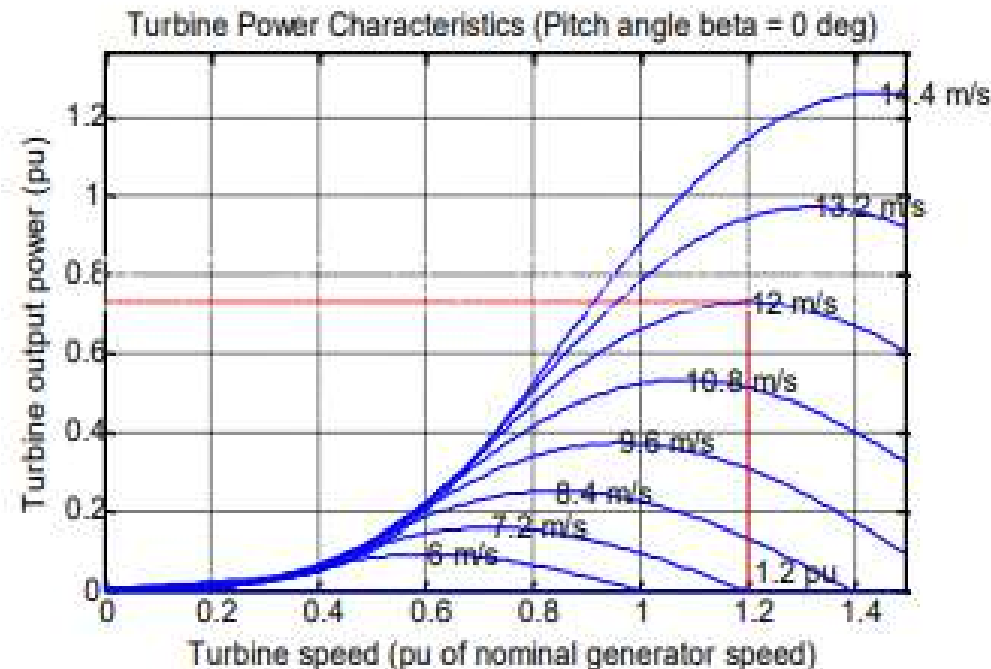
Input to the wind turbine is generator speed, wind speed and pitch angle and output of wind turbine is mechanical torque.



MPPT Tracking

Power coefficient (C_p) depend upon the tip speed ratio (λ). Fig(2.7) shows the power coefficient vs. tip speed ratio graph where there is only one point where is maximum. To get the maximum power wind turbine should operate at this point.

$$W_{opt} = \frac{\lambda_{opt} v}{R}$$



Horizontal Axis Wind Turbine

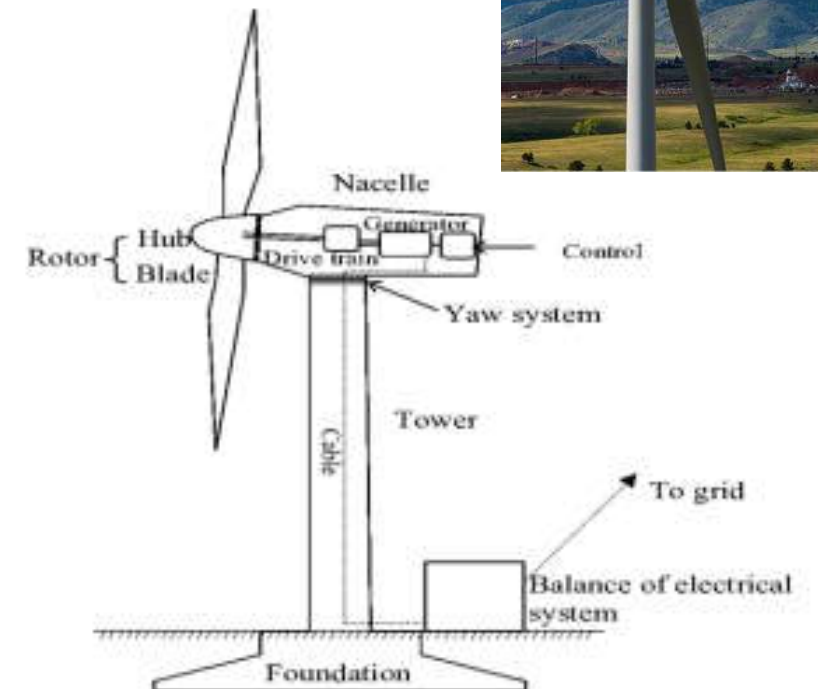
Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbine are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind.

Advantages:

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

Disadvantages:

- **Massive tower construction** is required to support the heavy blades, gearbox, and generator.
- Components of horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) **being lifted into position**.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- Download variants suffer from fatigue and **structural failure** caused by turbulence when a blade passes through the tower's wind shadow.



Vertical Axis Wind Turbine

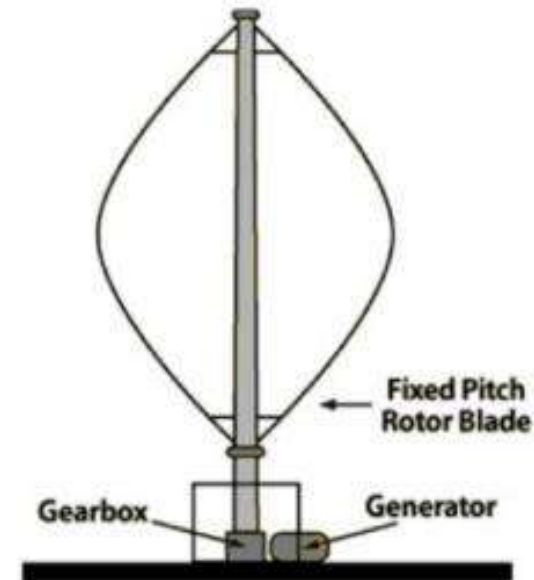
Vertical wind turbines (VAWTs), have the main rotor shaft arranged vertically .

Advantages:

- The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This makes them suitable in places where the **wind direction is highly variable** or has turbulent winds.
- With a vertical axis, the generator and other primary components can be **placed near the ground**, so the tower does not need to support it, also makes maintenance easier.
- May be built at locations where **taller structures are prohibited**.

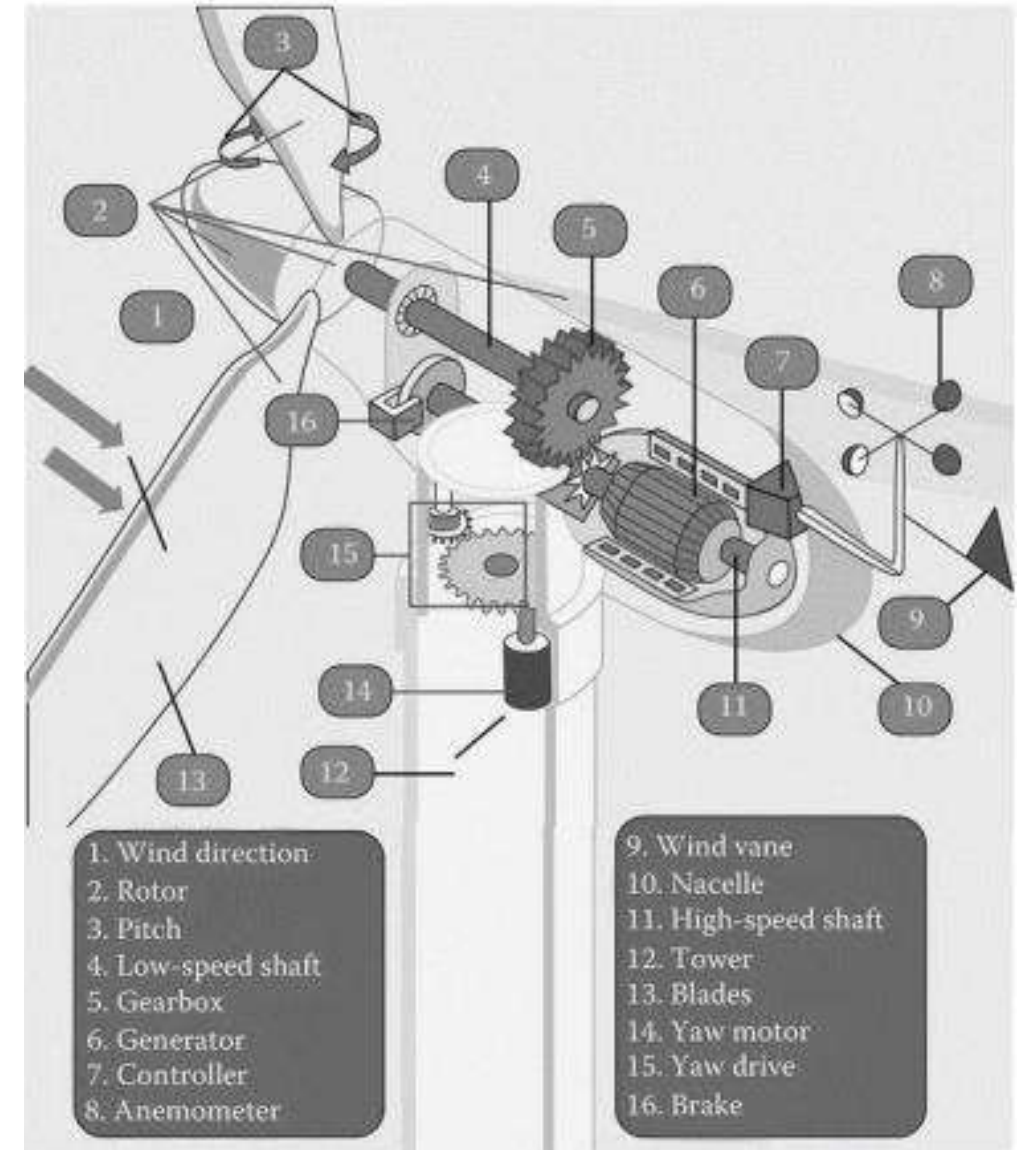
Disadvantages:

- The main drawback of a VAWT is that, it generally **creates drag** when rotating into the wind.
- The wind speed is slower at a lower altitude, **so less wind energy** is available for a given size turbine.
- Air flow near the ground and other objects can create **turbulent flow**, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life.



Components of Wind Turbine

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



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

Working strategy of Wind Turbine

- Wind (moving air that contains kinetic energy) blows toward the turbine's rotor blades.
- The rotors spin around, capturing some of the kinetic energy from the wind, and turning the central drive shaft that supports them. Although the outer edges of the rotor blades move very fast, the central axle (drive shaft) turns quite slowly.
- In most large modern turbines, the rotor blades can swivel on the hub at the front so they meet the wind at the best angle (or "pitch") for harvesting energy. This is called the pitch control mechanism. On big turbines, small electric motors or hydraulic rams swivel the blades back and forth under precise electronic control. On smaller turbines, the pitch control is often completely mechanical. However, many turbines have fixed rotors and no pitch control at all.
- Inside the nacelle (the main body of the turbine sitting on top of the tower and behind the blades), the gearbox converts the low-speed rotation of the drive shaft (perhaps, 16 revolutions per minute, rpm) into high-speed (perhaps, 1600 rpm) rotation fast enough to drive the generator efficiently.
- The generator, immediately behind the gearbox, takes kinetic energy from the spinning drive shaft and turns it into electrical energy. Running at maximum capacity, a typical 2MW turbine generator will produce 2 million watts of power at about 700 volts.
- Anemometers (automatic speed measuring devices) and wind vanes on the back of the nacelle provide measurements of the wind speed and direction.
- Using these measurements, the entire top part of the turbine (the rotors and nacelle) can be rotated by a yaw motor, mounted between the nacelle and the tower, so it faces directly into the oncoming wind and captures the maximum amount of energy. If it is too windy or turbulent, brakes are applied to stop the rotors from turning (for safety reasons). The brakes are also applied during routine maintenance.

- The electric current produced by the generator flows through a cable running down through the inside of the turbine tower.
- A step-up transformer converts the electricity to about 50 times higher voltage so it can be transmitted efficiently to the power grid (or to nearby buildings or communities). If the electricity is flowing to the grid, it is converted to an even higher voltage by a substation nearby.
- The consumer enjoy clean, green energy: the turbine has produced no greenhouse gas emissions or pollution as it operates.

Siting of Wind Turbine

High annual average wind speed: The speed generated by the wind mill depends on cubic values of velocity of wind, the small increases in velocity markedly affect the power in the wind. For example, Doubling the velocity, increases power by a factor of 8. It is obviously desirable to select a site for WECS with high wind velocity. Thus a high average wind velocity is the principle fundamental parameter of concern in initially appraising WECS site. For more detailed estimate value, one would like to have the average of the velocity cubed.

Availability of anemometry data: It is another improvement sitting factor. The anemometry data should be available over some time period at the precise spot where any proposed WECS is to be built and that this should be accomplished before a sitting decision is made.

Availability of wind $V(t)$ Curve at the proposed site: This important curve determines the maximum energy in the wind and hence is the principle initially controlling factor in predicting the electrical output and hence revenue return of the WECS machines. It is desirable to have average wind speed such that $V \geq 12-16$ km/hr (3.5 – 4.5 m/sec) which is about the lower limit at which present large scale WECS generators start turning. The $V(t)$ Curve also determines the reliability of the delivered WECS generator power, for if the $V(t)$ curve goes to zero there be no generated power during that time. If there are long periods of calm the WECS reliability will be lower than if the calm periods are short. In making such reliability estimates it is desirable to have measured $V(t)$ Curve over about a 5 year period for the highest confidence level in the reliability estimate.

Wind structure at the proposed site: The ideal case for the WECS would be a site such that the $V(t)$ Curve was flat, i.e., a smooth steady wind that blows all the time; but a typical site is always less than ideal. Wind specially near the ground is turbulent and gusty, and changes rapidly in direction and in velocity. This departure from homogeneous flow is collectively referred to as the structure of the wind.

Altitude of the proposed site: It affects the air density and thus the power in the wind and hence the useful WECS electric power output. Also, as is well known, the wind tends to have higher velocities at higher altitudes.

Terrain and its aerodynamic: One should know about terrain of the site to be chosen. If the WECS is to be placed near the top but not on the top of a not too blunt hill facing the prevailing wind, then it may be possible to obtain a speed-up of the wind velocity over what it would otherwise be. Also the wind here may not flow horizontally making it necessary to tip the axis of the rotor so that the aeroturbine is always perpendicular to the actual wind flow. It may be possible to make use of hills or mountains which channel the prevailing wind into a pass region, thereby obtaining higher wind power.

Local Ecology: If the surface is bare rock it may mean lower hub height hence lower structure cost. If trees or grass or vegetation are present, all of which tend to destructure the wind, the higher hub heights will be needed resulting in larger system costs than the bare ground case.

Distance to road or railways: This is another factor the system engineer must consider for heavy machinery, structure, materials, blades and other apparatus will have to be moved into any chosen WECS site.

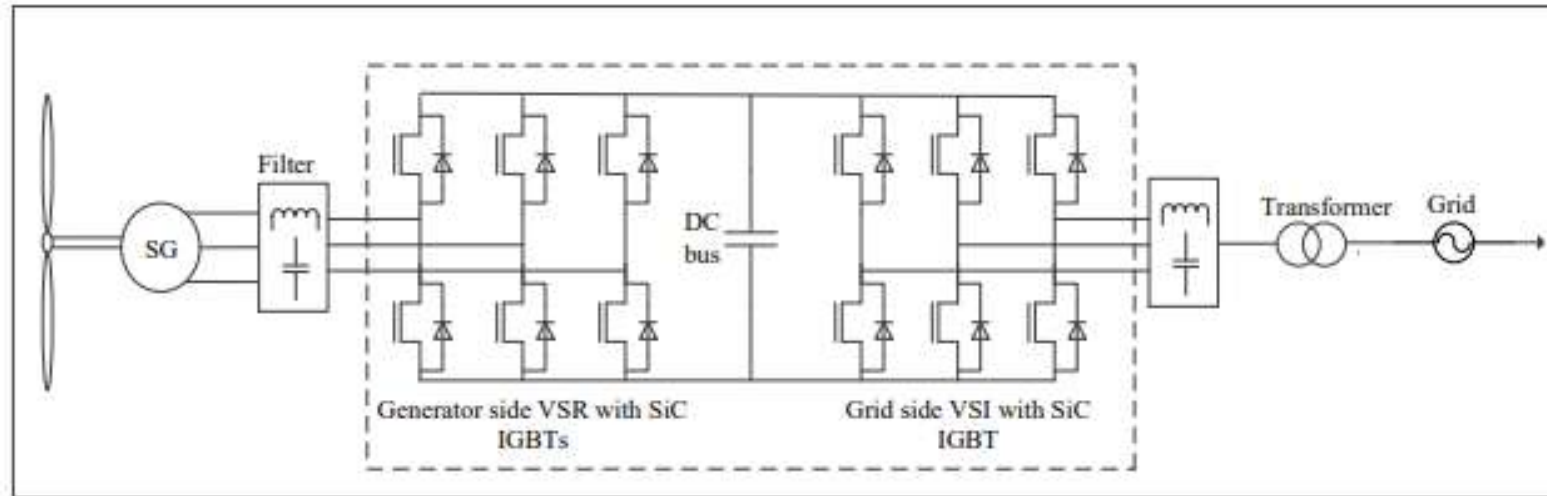
Nearness of site to local centre/users: This obvious criterion minimizes transmission line length and hence losses and cost. After applying all the previous string criteria, hopefully as one narrows the proposed WECS sites to one or two they would be relatively near to the user of the generated electric energy.

Nature of ground: Ground condition should be such that the foundation for a WECS are secured. Ground surface should be stable. Erosion problem should not be there, as it could possibly later wash out the foundation of a WECS, destroying the whole system.

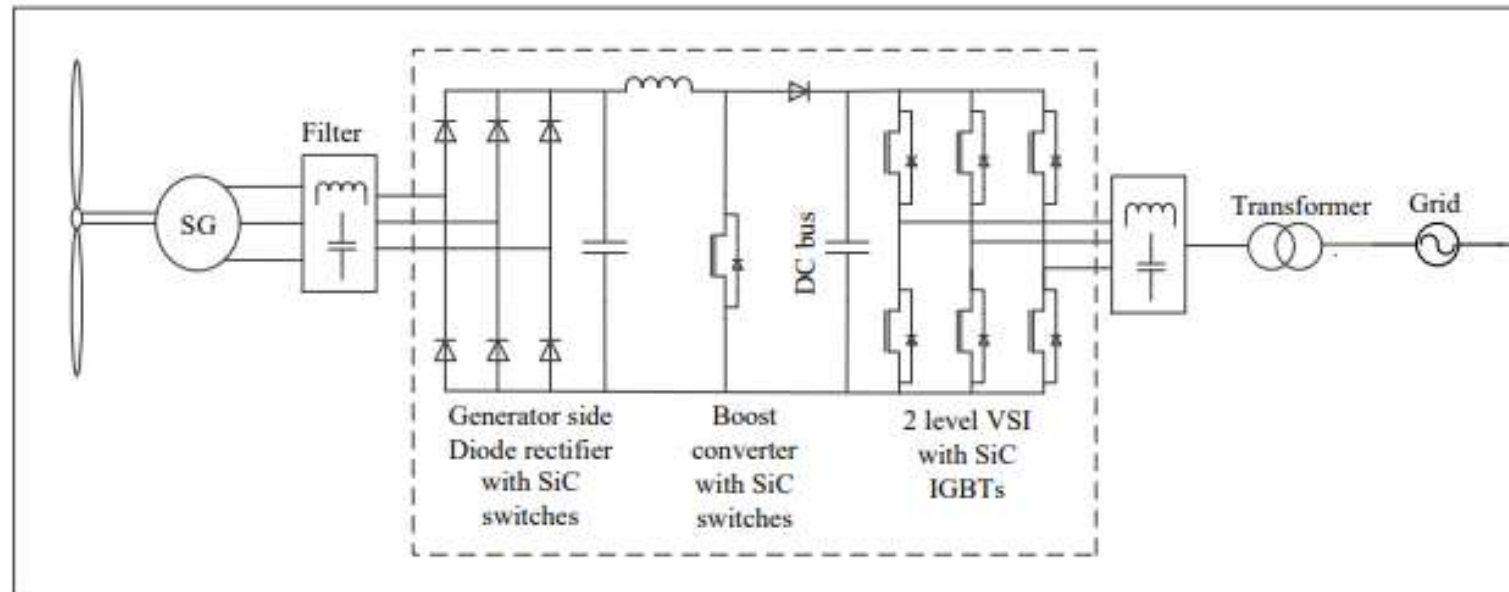
Favourable land cost: Land cost should be favourable as this along with other siting costs, enters into the total WECS system cost.

Other conditions such as icing problem, salt spray or blowing dust should not be present at the site, as they may affect aeroturbine blades or environmental is generally adverse to machinery and electrical apparatus.

Different topology of WECS



Voltage source inverter topology



Boost converter and rectifier topology

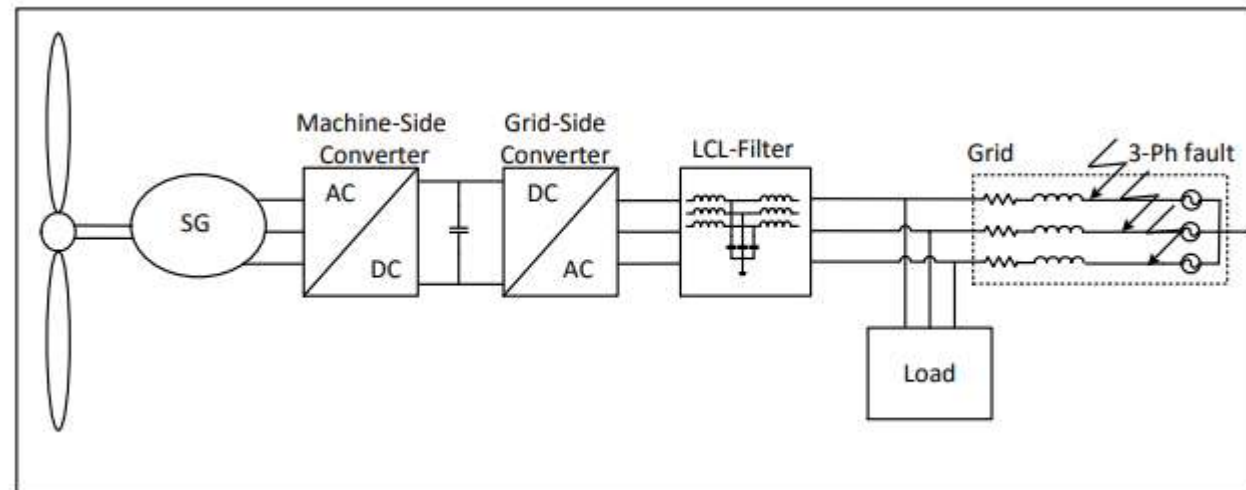
VSI topology	Boost converter topology
Here vector control strategy is used to maintain MPPT	Here duty ratio control strategy is used to maintain MPPT
This topology can be used for induction and synchronous generator system	This topology can be used only for synchronous generator
Speed control is fast	Speed control is slow
Speed control is more accurate	Speed control is less accurate as duty ratio varies
Control technique is complex so reliability decreases	Control technique is simple so reliability increases

LVRT in WECS

Low voltage ride through (LVRT) fulfillment is required by the wind generators when the voltage in the grid is temporarily reduced due to a fault or large load change in the grid. In solar systems when islanding occurs the total system is disconnected from grid but in WECS in LVRT condition the total system remain connected to grid and try to send reactive power to improve the grid condition. In electrical power system LVRT is the capability to stay connected in short period of lower electric network voltage. The required LVRT behavior is defined in grid codes issued by the grid operators in order to maintain system stability, thereby reducing the risk of voltage collapse. In LVRT condition three things can happen with a wind system.

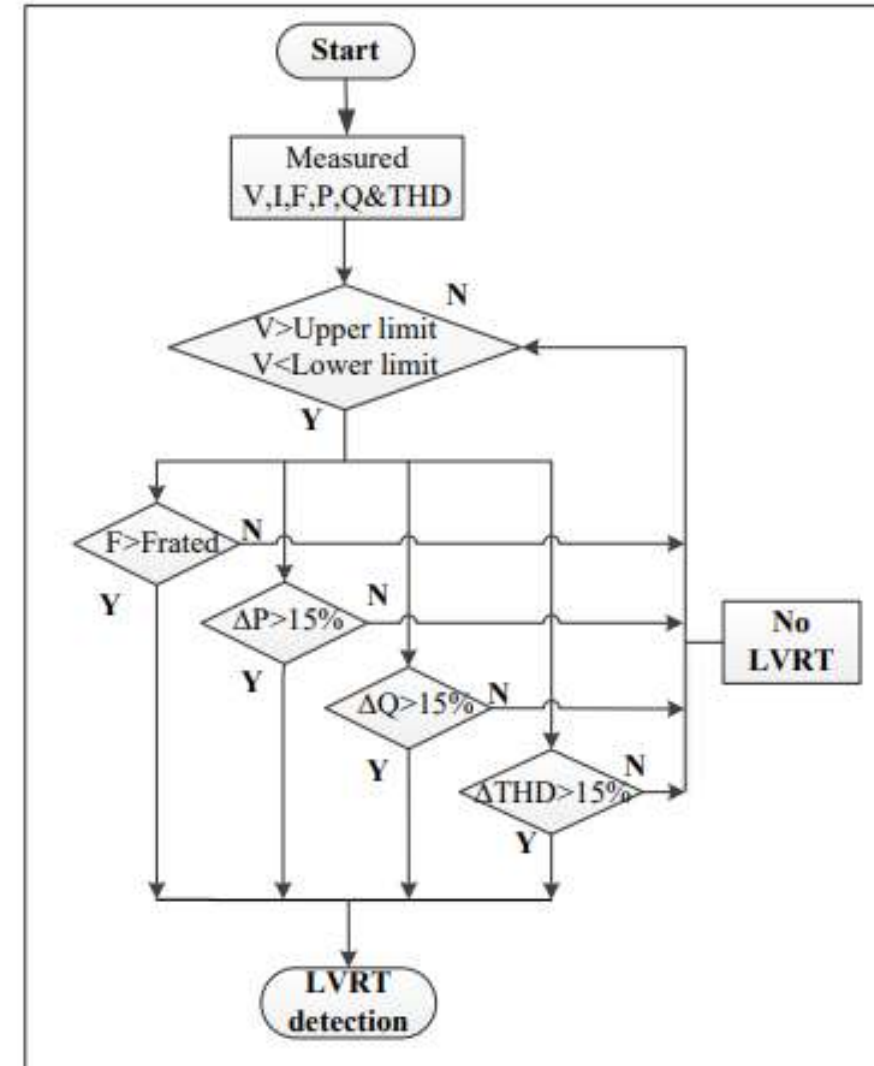
- Disconnect temporarily from the grid but reconnect and continue operation after LVRT.
- Stay operational and not disconnected.
- Stay connected and support grid by reactive power. Generally wind generator remains connected in LVRT and try to improve grid condition.

Even a quarter second voltage sag can cause the entire machine or process to shut down for hours causing expensive downtime, scrap material, lost productivity and long restart times. Voltage sag leads to slowdown or stopping of motors, trips contactors or circuit breakers and leads to failure of inverters. LVRT prevents all these problems.



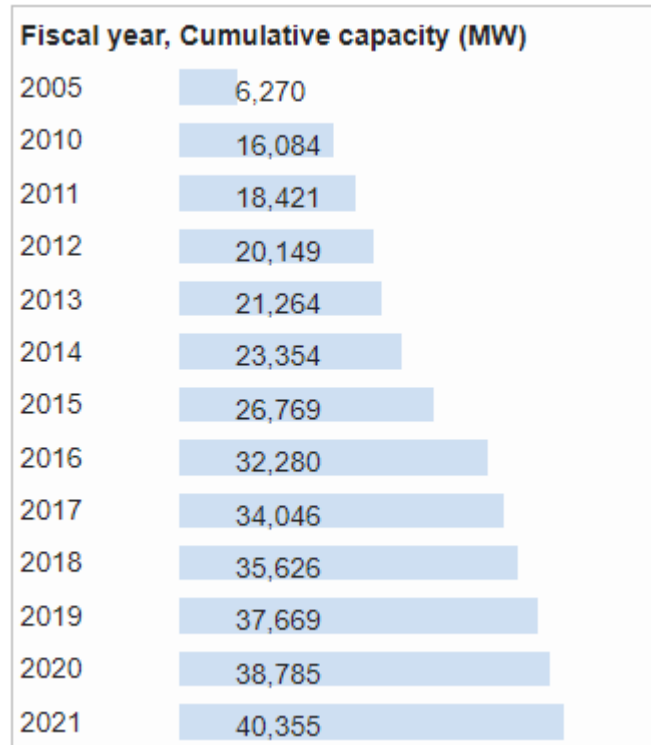
Algorithm for LVRT detection

- The detection technique first checks the voltage level (0.88 p.u to 1.1 p.u).
- If the voltage is out of limit then it check four parameters. They are frequency (50.5 to 49.3 Hz), change in active power (15%), change in reactive power (15%) and change in THD (15%).
- If voltage is out of limit and any one of the four parameters is out of limit then LVRT condition is detected. Otherwise WECS operated in normal condition.



Wind energy in INDIA

Wind power generation capacity in India has significantly increased in recent years. As of 31 January 2023, the total installed wind power capacity was 41.983 gigawatts (GW), the fourth largest installed wind power capacity in the world.



State	Total Capacity (MW)
Gujarat	9,918.12
Tamil Nadu	9,964.22
Maharashtra	5,012.83
Karnataka	5,269.65
Rajasthan	4,618.82
Andhra Pradesh	4,096.65
Madhya Pradesh	2,844.29
Telangana	128.10
Kerala	62.50
Others	4.30
Total	41,983.18

Numericals

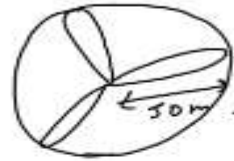
1. Determine the power in the wind if the wind speed is 20 m/s and blade length is 50 m.(air density of 1.2 kg/m³).
2. A horizontal axis wind turbine has the blade radius of 6 m and situated in a place where wind speed is 8 m/s with a air density of 1.2 kg/m³. The generator speed is 600 rad/s.
 - a) Find out the tip speed ratio of the turbine.
 - b) Wind turbine output power ($C_p=0.48$).
 - c) Wind turbine output torque.

$$P_{\text{wind}} = \frac{1}{2} \rho A v^3$$

$$v = 20 \text{ m/s}, \quad \rho = 1.2 \text{ kg/m}^3$$

$$r = 50 \text{ m}$$

$$\begin{aligned} A &= \pi r^2 \\ &= \pi \times (50)^2 \\ &= 7853.9 \text{ m}^2 \end{aligned}$$



$$\begin{aligned} P_{\text{wind}} &= \frac{1}{2} \times 1.2 \times 7853.9 \times (20)^3 \\ &= 47.123889.8 \text{ watt} \\ &= 47.12 \text{ Mwatt} \end{aligned}$$

$$2. \quad \lambda = \frac{\omega_m R}{v}$$

$$\omega_m = 600 \text{ rad/s}$$

$$R = 6 \text{ m}$$

$$v = 8$$

$$\begin{aligned} \lambda &= \frac{600 \times 6}{8} \\ &= 450 \end{aligned}$$

$$P_m = 0.5 C_p \rho A v^3$$

$$A = \pi r^2 = \pi \times 6^2 = 113.1 \text{ m}^2$$

$$\begin{aligned} P_m &= 0.5 \times 0.48 \times 1.2 \times 113.1 \times 8^3 \\ &= 16676.88 \text{ watt} \\ &= 16.67 \text{ KW} \end{aligned}$$

$$\text{Gen speed} = \text{Tur speed}$$

$$\omega_m \times T_T = T_P = 16676.88$$

$$\Rightarrow T_T = \frac{16676.88}{600} = 27.8 \text{ N} \checkmark$$

Future Aspects of Microgrid

By Dr. Rajdip Dey
EE Department
NIT Durgapur

Role of Microgrids in the Electricity Ecosystem of the Future

Decarbonization: Every step we take to decrease reliance on conventional energy sources brings us closer to a decarbonized, healthier planet. The term decarbonization literally means the reduction of carbon. Precisely meant is the conversion to an economic system that sustainably reduces and compensates the emissions of carbon dioxide (CO₂). The long-term goal is to create a CO₂-free global economy. Future microgrid will help the electrical ecosystem to be decarbonized.

Digitalization: The future grids will be “smarter” and comprise increasingly more digital control and communication components and subsystems. Indeed, the grid is becoming a true cyber-physical system. With the opportunities brought by cyber-physical technologies, complexity in the grid will increase and drive the demand for more efficient testing tools. The **Internet of Things, Artificial Intelligence, and Blockchain technology** are key enablers in the power sector transformation, helping to manage large amounts of data collection and analysis, optimizing increasingly complex energy systems.

Decentralization: A decentralized energy system is characterized by locating of energy production facilities closer to the site of energy consumption. A decentralized energy system allows for more optimal use of renewable energy as well as combined heat and power, reduces fossil fuel use and increases eco-efficiency. A decentralised microgrid is a localized group of multiple electricity sources (usually solar panels) that can operate in either a grid-connected system, connected to the wider energy grid, or as a standalone system. Microgrids serve as a decentralized energy system, where you are independent of the public network and, at the same time, can generate additional revenue by feeding any excess energy back to it.

Decentralised power has a range of benefits including:

- Resilient power source.
- Kinder on the environment.
- Cheaper power with more competition.
- More efficient – less loss of power through transmission.
- More reliable and you're in control.
- Lower infrastructure costs.
- More efficient use of resources.



Microgrid future growth



- A potential application of microgrids is in the military sector. Microgrids can provide a secure and reliable power source for military bases and other critical infrastructure, reducing the vulnerability of these facilities to energy-related disruptions. In addition, microgrids can help to reduce the military's dependence on fossil fuels, providing a more sustainable and resilient energy system.
- One exciting area of research in microgrids is the development of community-based microgrids. These microgrids are owned and operated by local communities rather than large utilities or private companies. By giving local communities control over their energy systems, community-based microgrids can promote more significant social equity and empower communities to actively manage their energy needs. It is essential to develop new financing mechanisms and business models to provide the necessary funding to get these projects off the ground. Local financing may involve community ownership models, where local communities pool resources to finance microgrid development. By involving community members in the development process, it is possible to create microgrid systems tailored to the community's specific needs. Promoting the development of community-based microgrids may create a more decentralized and democratized energy system. A decentralized microgrid can promote greater energy security and reduce the risk of power outages or other disruptions in centralized energy systems.

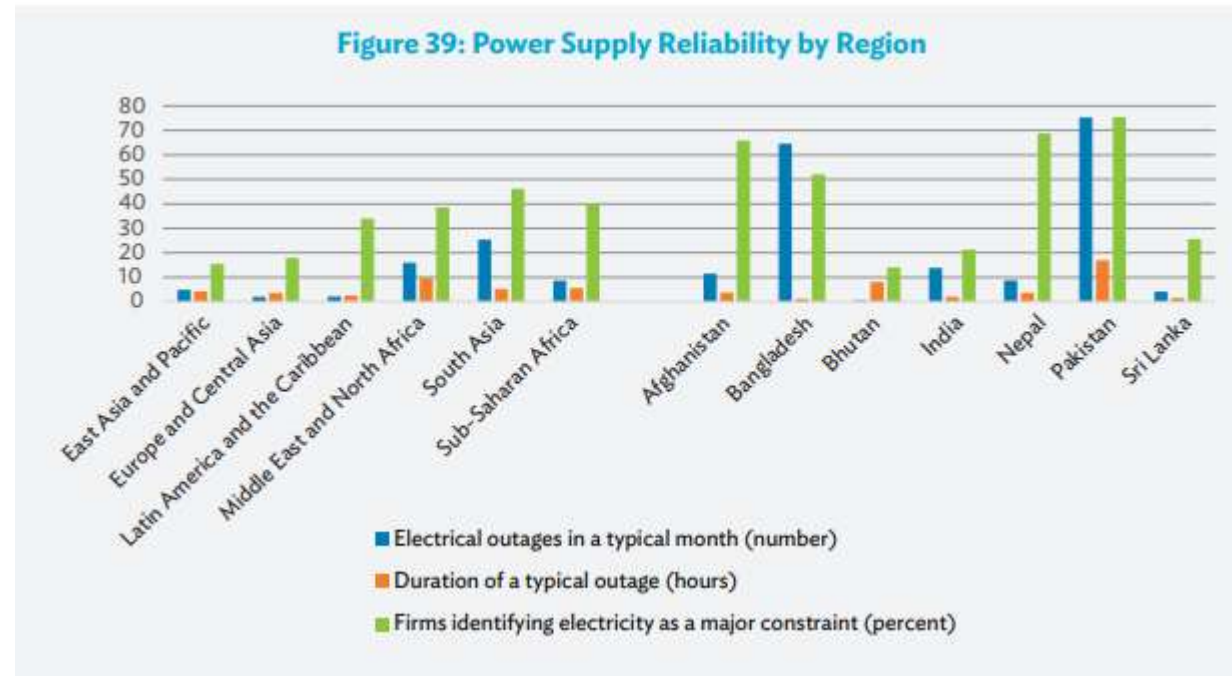
- One crucial development area for microgrids is disaster response and recovery. The primary power grid is often severely impacted during natural disasters such as hurricanes, earthquakes, and floods. These disturbances lead to prolonged power outages and significant damage to critical infrastructure. In these situations, microgrids can provide a reliable and flexible source of power that can help to support disaster response efforts and facilitate recovery. For example, microgrids can power critical infrastructure such as hospitals, emergency shelters, and communication systems, ensuring these services can operate even after a disaster. In addition, microgrids can power temporary housing units or other infrastructure necessary for recovery efforts. Standardized designs may involve using pre-fabricated microgrid systems that can be quickly transported and installed in disaster-impacted areas.
- Another potential growth area for microgrids is in the context of sustainable urban development. As urban populations continue to grow, there is a growing need for sustainable and resilient energy systems that can meet the energy needs of these communities. Microgrids can provide a localized and community-based approach to energy management that is well-suited to urban environments. For example, microgrids can power individual buildings or neighborhoods, reducing the strain on the main power grid and improving the overall resilience of the energy system. In addition, microgrids can integrate renewable energy sources such as solar or wind power into the overall energy system. Renewable integration reduces carbon emissions and promotes a more sustainable energy system. Developing standards and best practices for microgrid design for urban communities' unique needs is essential. This procedure includes the development of new financing mechanisms and business models that can make microgrid development more accessible and affordable.

Future transportation sector based on microgrid

- EV transportation ecosystem is a foundational sector that deserves specific highlight, as this is an area where microgrids have an enormous ability to help transform. This is partly because of the **sheer size** of the sector.
- To ensure adequate energy, this new charging infrastructure will have to be installed on the utility grid in combination with grid edge technologies, like DERs and energy storage. But sometimes, utility support might not be possible, and in such cases microgrid infrastructure can fill the gap to **enable charging stations to cater to the charging demand**. In addition, a decentralized infrastructure will allow the many actors in the EV ecosystem to capitalize on the flexibility of EVs. One promising way to do this being “vehicle-to-grid” (V2G), wherein **EVs can sell DR services** to the power grid, either by throttling their charging rate or even returning power to the grid.
- One of the fundamental impediments to growth of the EV ecosystem is the lack of better aligned business models and pricing structure associated with the sale of energy. This results in the paucity of readily available charging stations. The current EV charging infrastructure is as “dirty” as the local utility grid is, and new energy solutions, including renewable energy, energy storage and microgrids, if integrated, can enable a **more robust, widespread, and cleaner EV charging infrastructure**.
- In summary, the reliable EV charging infrastructure that microgrids can enable is something that needs to be widespread and readily available, to truly enable a vibrant EV ecosystem. In addition to workplaces and communities, EV charging stations will need to be developed in three key types of locations: **at destination points, along highways, and near public transportation nodes like airports, and bus and train stations**

Relevance of Microgrids to the Current Power System Situation in Developing Member Countries

- The current power system situation, in terms of both technology level and regulations wise, varies significantly across globe. In general, power consuming end users in developing countries typically do not have access to **high-quality reliable power** and have to contend with **frequent power outages**, in contrast to their counterparts in developed countries. Developing countries also often have **weak grid infrastructures** due to underinvestment and poor management, leading to high power losses and theft, thereby hindering the success of business and industry and depriving people of a better quality of life.
- This is the value proposition for grid-connected microgrids in developing countries, and the reason why the indirect costs of the status quo outweigh the huge initial investment required to change it. Furthermore, grid-connected microgrids are the building blocks of smart grids and smart supergrids, which have the potential to help developing countries leapfrog, by revolutionizing the power sector, similar to what the internet did to information.



DMC	Power Situation	Key Microgrid Drivers
Bangladesh	• Low installed generation capacity (20 GW in 2019 mostly natural gas); and low per capita consumption • Problems include poor transmission and distribution infrastructure high system losses, low plant efficiency, electricity theft • Low renewable energy generation (<20 MW) currently, but moderately high potential of 3.6 GW	• Affordable electricity from DG • Environmental benefits of DG to supplement utility scale renewable energy • Overall reliability and resilience in the face of inadequate T&D infrastructure
India	• Third largest producer and consumer of electricity in world but low per capita consumption • Surplus generation capacity (365 GW in 2019) but low capacity factor and inadequate distribution infrastructure • 55% coal; 12% hydro; 10% solar; 12% wind (2019) • Ambitious target to increase renewable energy from 80 GW in 2019 to 175 GW by 2022	• Affordable electricity from microgrids with DG in remote or rural areas • Reliability and resilience in the face of inadequate distribution infrastructure for remote or rural and C&I customers
Myanmar	• Low installed capacity (5 GW); low per capita • Limited grid coverage • 75% hydro, 20% NG; Good potential for renewable energy	• Affordable electricity from DG as poor grid coverage • Reliability and resilience for C&I and grid stability
Nepal	• 23% electricity is imported. Remaining is mostly run of river hydro (1 GW) • No known fossil fuel reserves, but large 44 GW potential from hydro • Low per capita electricity consumption • Limited T&D infrastructure	• Affordable electricity from DG as poor grid coverage • Reliability and resilience for C&I and grid stability • DG in rural or remote weak grid and off-grid areas
Philippines	• 20 GW installed with moderately low per capita • Restructuring has resulted in heavy cost burden to government and consumers • 43% coal; 24% NG; 12% hydro; 13% geothermal; <0.5% solar, wind, and biomass (scope to increase)	• Affordable electricity from DG as load centers are far from generation location • DG in remote islands weak grid and off-grid areas • Reliability and resilience for C&I
Thailand	• 90% of electricity is thermal generation (60% NG, 25% coal) • Thailand+GMS can achieve 100% renewable energy (mostly via hydro) by 2050	• Environmental friendly renewable energy DG to supplement the mostly thermal utility generators • Reliability and resilience for C&I

Disadvantages of microgrids based on transmission capacity

- Good solar resource and good wind resource are often at **different locations**, so while they complement each other in terms of time of day, that electricity still needs to be transported over **long distances**. This needs adequate transmission capacity, and when the transmission is intercountry, the role of regional cooperation and integration becomes important. This is why **distribution level investments alone may not be enough** for the future scenario, rather it needs to be a mix of more transmission capacity in conjunction with grid edge investments like microgrids.
- To generate electricity from renewables **requires a lot of land**. This land tends to be farther away from the population centers and load centers. On the other hand, urban areas having large demand lack the land for renewables or the land is prohibitively expensive. This scenario also requires a grid to transmit power over longer distances.
- If we target electrifying the transport sector, additional transmission would be needed. For example, Tesla super charger for trucks is rated at 2 MW.
- **Transmission line approvals, land acquisition, and financial closure** (payback model) are complicated, so transmission projects face the risk of getting delayed. Another disadvantage is the “single point of failure” type loss of resilience when fault in large transmission line. Undergrounding reduces some of the problems of transmission line fault, but is much more expensive.
- So new construction is required.

Areas for Additional Technical Research

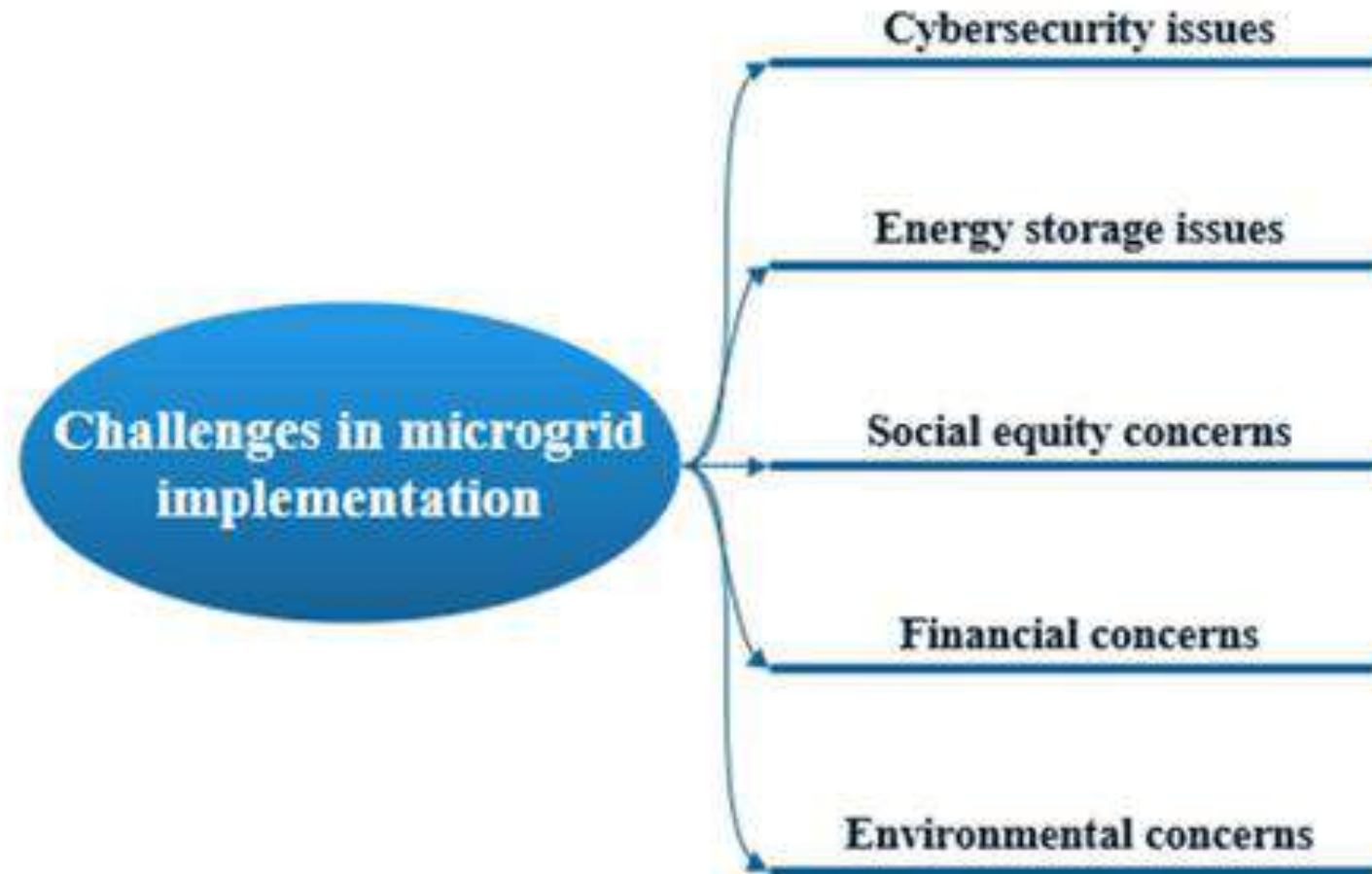
For any microgrid:

- **Decentralized control:** Most of the existing microgrids around the world use centralized control. This type of control is optimal for small microgrids in which all the elements share the same goals. As these elements present different needs and the microgrid gets more complex, the alternative of decentralized control becomes more suitable. Thus, additional research is needed to develop the decentralized control approach.
- **Protections:** Microgrids are able to operate connected or disconnected from the main grid at any time. This dynamic scheme complicates the design of the protection scheme which must guarantee a safe operation in any case. Although some protection schemes have been proposed, they are customized solutions that do not provide a standardized approach for applicable to any microgrid.

For DC microgrid:

- **Bus selection:** The bus selection procedure is based on switching mechanisms that can lead to unwanted voltage oscillations. Achieving a smooth bus selection requires an appropriate control approach and implementation. Nowadays, there are few works that deal with this problem, thus more research efforts are needed.
- **Standards:** The standardization of AC microgrids has improved in the last few years. DC microgrids on the other hand, do not have yet a specific standard. Some organizations have already taken the first steps into standardization of DC distribution lines.
- **Islanding detection techniques:** Islanding detection is a key requirement for electrical safety and equipment protection. Islanding detection algorithms in AC systems are based on systems frequency and phase parameters that are not present in DC lines. Thus, new methods for islanding detection in DC systems are required to guarantee the reliability of the system.

Challenges of microgrid



- One of the potential challenges for microgrid development is the issue of cybersecurity. As microgrids become more common, they are increasingly vulnerable to cyber-attacks. There is a growing need for cybersecurity solutions designed explicitly for microgrids. These solutions may include advanced encryption techniques, intrusion detection and prevention systems, sophisticated authentication, and access control mechanisms. In addition, microgrid developers must take a proactive approach to cybersecurity, incorporating security considerations into the design and implementation of microgrid systems.
- Another challenge for microgrid development is the issue of energy storage. While battery storage is becoming more cost-effective and reliable, it still represents a significant upfront cost for many microgrid projects. In addition, using batteries can create environmental concerns. To address these challenges, researchers are exploring new energy storage technologies such as flow batteries and thermal energy storage. These technologies offer the potential for improved energy density, longevity, and reduced environmental impact. In addition, researchers are exploring new business models and financing mechanisms that can make energy storage more accessible and affordable for microgrid developers.
- As the use of microgrids becomes more widespread, there is a growing need for collaboration and information-sharing between stakeholders. The stakeholders are utilities, regulators, researchers, and local communities. These stakeholders can help develop common standards and best practices for microgrid development.

- There is a risk that microgrids may exacerbate existing social inequalities if they are not presented equitably and inclusively. For example, suppose only specific community segments can afford the upfront costs of microgrid development. In that case, this could lead to a situation where the benefits of the technology are not uniform. It is crucial to involve local communities in developing and implementing microgrids and to prioritize equity and inclusion in the design and operation of these systems.
- One additional challenge for microgrid development is the financing issue. Microgrid development often requires a significant upfront investment. There are limited financing options for developers, particularly in developing countries. In addition, microgrid developers may face challenges in attracting investment due to the perceived risks associated with the technology and the lack of a well-defined business case. Researchers and policymakers are exploring new business models and financing mechanisms to address these financing challenges. For example, some microgrid projects explore pay-as-you-go models, where users pay for energy services per use. This method can reduce the upfront costs of microgrid development and make it more accessible to low-income households. In addition, governments and international organizations are exploring the use of grants, subsidies, and other financial incentives to support microgrid development. These incentives can provide the necessary funding to get microgrid projects off the ground and make them financially viable over the long term. Another potential financing mechanism for microgrid development is using carbon credits.
- While microgrids have the potential to reduce carbon emissions and promote a more sustainable energy system, there is a risk that they may also have negative environmental impacts, such as the degradation of local ecosystems or the depletion of natural resources.