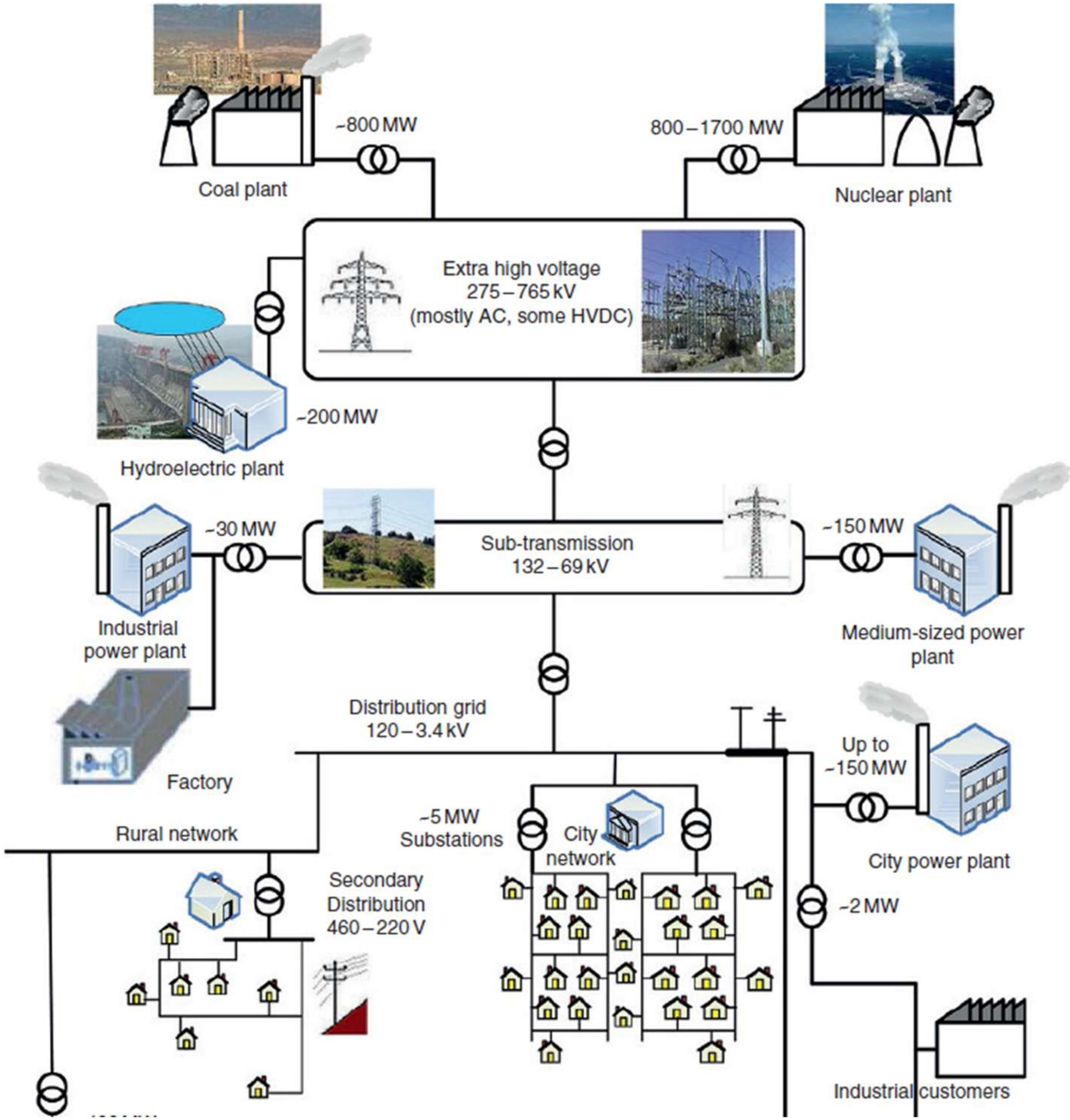
EES4404 : Renewable Energy and Smart Grid

Smart Grid

By Dr. Sahoo SK, NUS



Existing Power Grid

Source: Ali Keyhani

Power Grid

- A power grid provides electric energy to end users, who use electricity in their homes and businesses.

- In power grids, any device that consumes electric energy is referred to as a load.
  - In residential electrical systems, the loads are air conditioning, lighting, television, refrigeration, washing machine, dishwasher, etc.
  - Industrial loads are composite loads with induction motors forming the bulk of these loads.
  - Commercial loads consist largely of lighting, office computers, copy machines, laser printers, communication systems, etc.

- The nominal-rated voltage of each load is specified by the manufacturer for its safe operation.
  - The electric power grid network has to serve the loads at their rated voltage with a maximum of 5% above or 5% below the rated nominal values.

Existing Power Grid

- Historically, power plants are located away from heavily populated areas.
- The plants are constructed where water and fuel (often supplied by coal) are available. Large-capacity power plants are constructed to take advantage of economies of scale.
- The power is generated in a voltage range of 11–20 kV, and then the voltage is stepped up to a higher voltage before connection to the interconnected bulk transmission network.
- HV transmission lines are constructed in the range of 138–765 kV. These lines are mostly overhead. However, in large cities, underground cables are also used. The lines consist of copper or aluminium.
- A major concern in bulk power transmission is power loss in transmission lines that is dissipated as heat due to the resistance of the conductors.
- The distribution lines are normally considered lines that are rated less than 69 kV.

Distribution System

- Distribution systems are designed to carry power to the feeder lines and end-use customers.
- The distribution transformers are connected to the HV side of the transmission or the sub-transmission system.
- The distribution voltages are in the range of 120, 208, 240, 277, 400, and 480 V.
- The service voltage of distribution systems depends on the size of the loads. The higher commercial loads are served at 480 V and higher voltages.

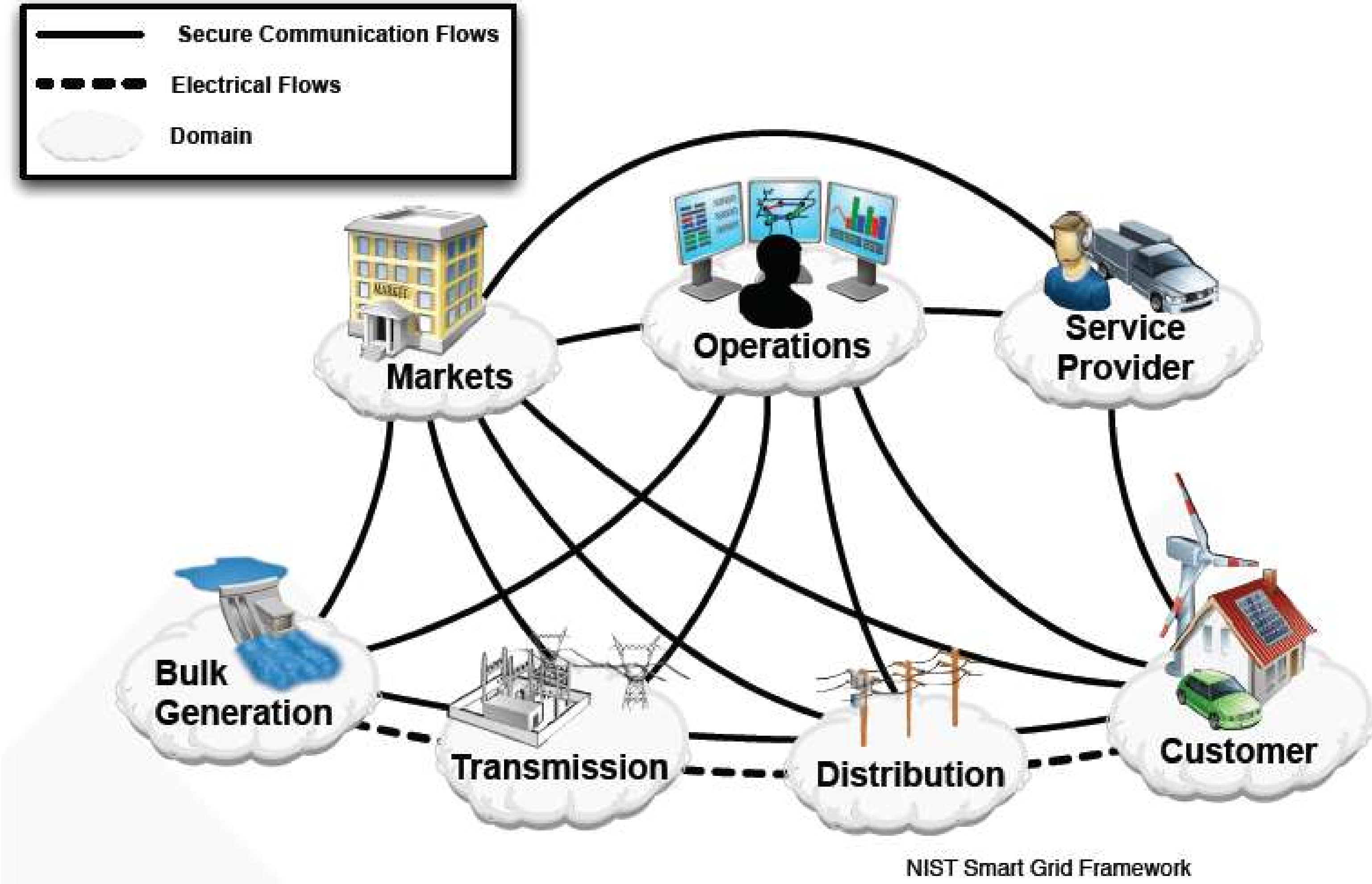
Factors affecting performance of existing grid

- Increasing demand of electricity
- Peak demand management
- Poor efficiencies of conventional power generation systems
- Integration of renewable energy generating systems
- Effective use of electric vehicles
- Overcoming difficulties in meter reading
- Better customer satisfaction
- Potential of technological advancements and new business opportunities

What makes the grid smart

- The digital technology that allows for two-way communication between the utility and its customers, and the sensing along the transmission lines is what makes the grid smart.
- The smart grid will be equipped with communication support schemes and real - time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats.

Interface of energy and communication network



NIST Smart Grid Framework

Standard Smart Grid Definitions

European Technology Platform for Smart Grids (2006)

"A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies. A Smart Grid employs innovative products and services together with intelligent monitoring, control, communications, and self healing technologies to:"

Standard Smart Grid Definitions

U.S. Department of Energy (DOE)

“Grid 2030 envisions a fully automated power delivery network that monitors and controls every customer and node, ensuring two-way flow of information and electricity between the power plant and the appliance, and all points in between”

Duties of Smart Grid

- More efficient transmission of electricity
- Quicker restoration of electricity after power disturbances
- Reduced operations and management costs for utilities, and ultimately lower power costs for consumers.
- Reduced peak demand, which will also help lower electricity rates
- Increased integration of large-scale renewable energy systems
- Better integration of customer-owner power generation systems, including renewable energy systems
- Improved security

Duties of Smart Grid

- Better facilitate the connection and operation of generators of all sizes and technologies.
- Allow consumers to play a part in optimizing the operation of the system
- Provide consumers with greater information and options for choice of supply
- Significantly reduce the environmental impact of the whole electricity supply system
- Maintain or even improve the existing high levels of system reliability
- Maintain and improve the existing services efficiently
- Foster market integration towards a European integrated market

Existing grid vs Smart Grid

Existing Grid	**Smart Grid**
Electromechanical relays	Digital relays
One-way communication	Two-way communication
Centralized generation	Distributed generation
Limited sensors	Sensors throughout
Manual Monitoring	Self monitoring
Failures and Blackouts	Adaptive and islanding
Limited control	Pervasive control
Manual restoration	Self healing

Smart Grid components

- Smart infrastructure
  - Smart Energy System
  - Smart Information System
- Smart communication
- Smart management
- Smart protection

Smart infrastructure system

Smart energy system

- Power Generation
- Transmission
- Distribution

Smart information system

- Smart metering
- Sensors
- Phasor measurement units (PMU)
- Information management

Power Generation

- Present electricity is generated at a few central power plants by electromechanical generators, primarily driven by the force of flowing water or heat engines fueled by chemical combustion or nuclear power

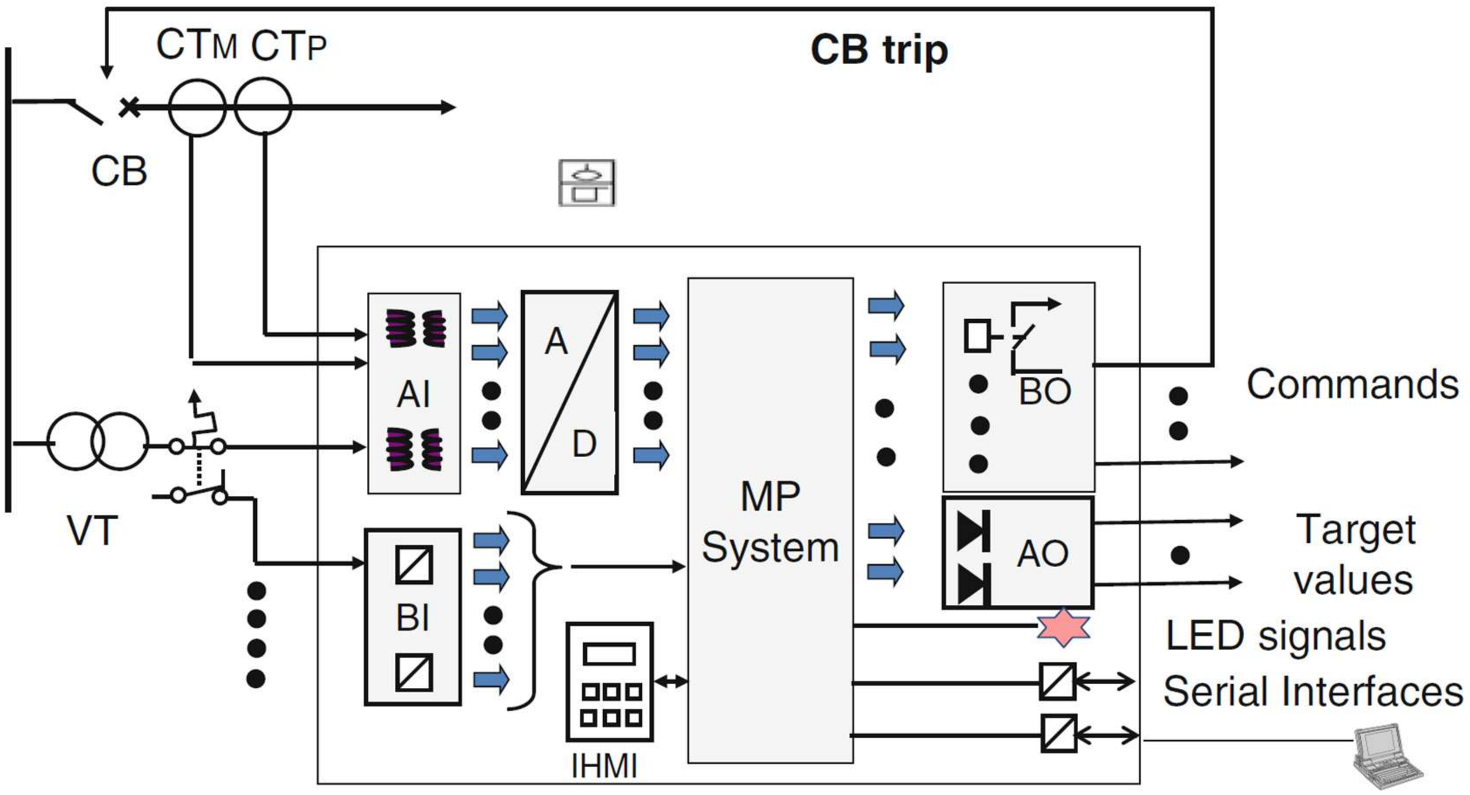
- Smart power generation becomes possible as the two-way flows of electricity and information are supported

- Distributed generation (DG) plays key role in Smart Grid

Transmission - Substations

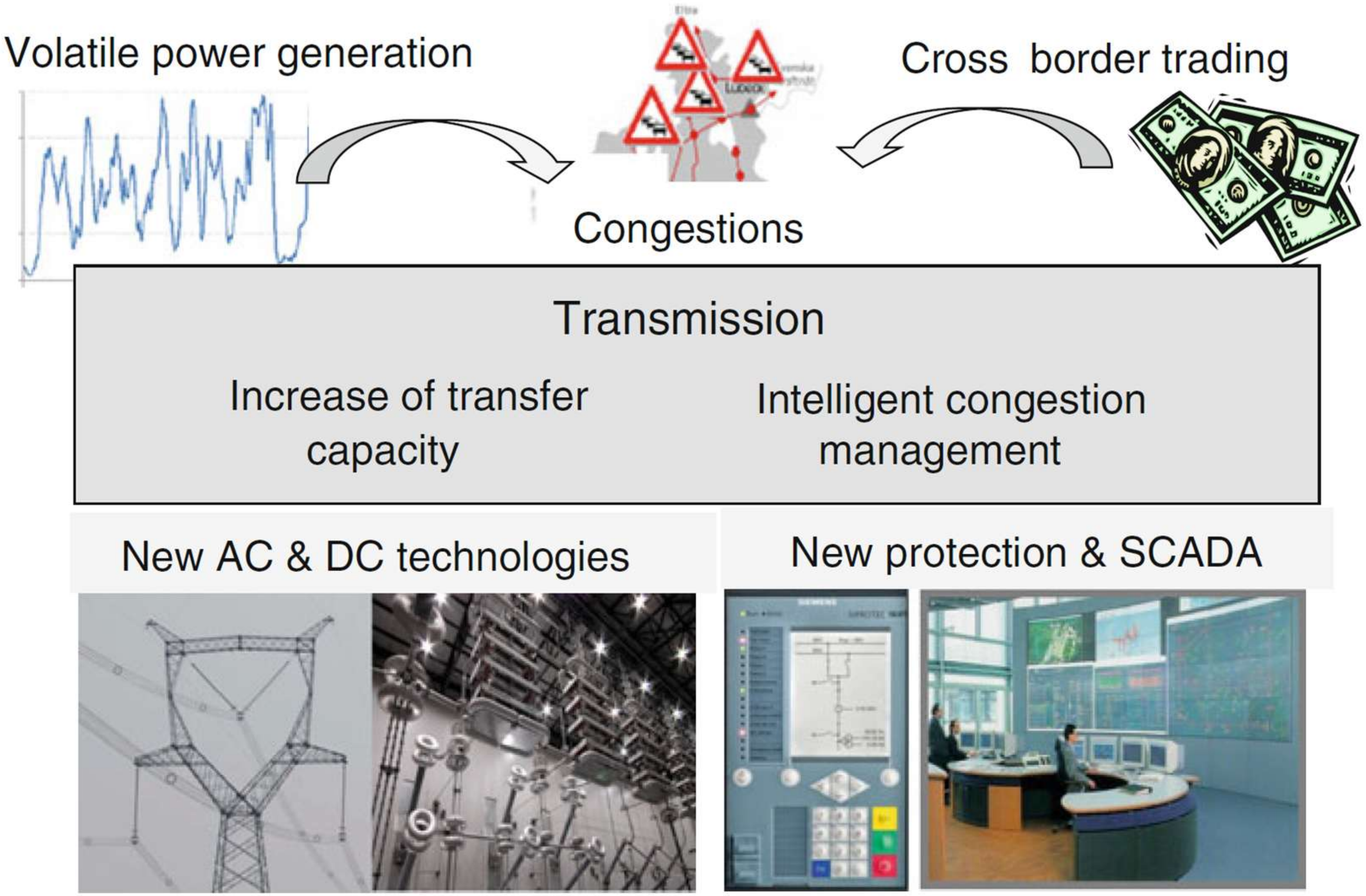
- Electric power flows through several substations at different voltage levels on its way between the bulk power stations and the end consumers.
- Transmission Substations may perform important functions like:
  - voltage control,
  - reactive power control or power factor correction,
  - power flow control by phase shifting transformers or power electronic plants,
  - UHV,EHV or HVDC/AC conversion to connect High Voltage DC (HVDC) lines, connection of two un-synchronous power systems by UHV/EHV/HV DC coupling.
- The substation protection technology has changed from the electromechanical relays to digital protection devices and Intelligent Electronic Devices (IEDs)

Advanced IED Technology



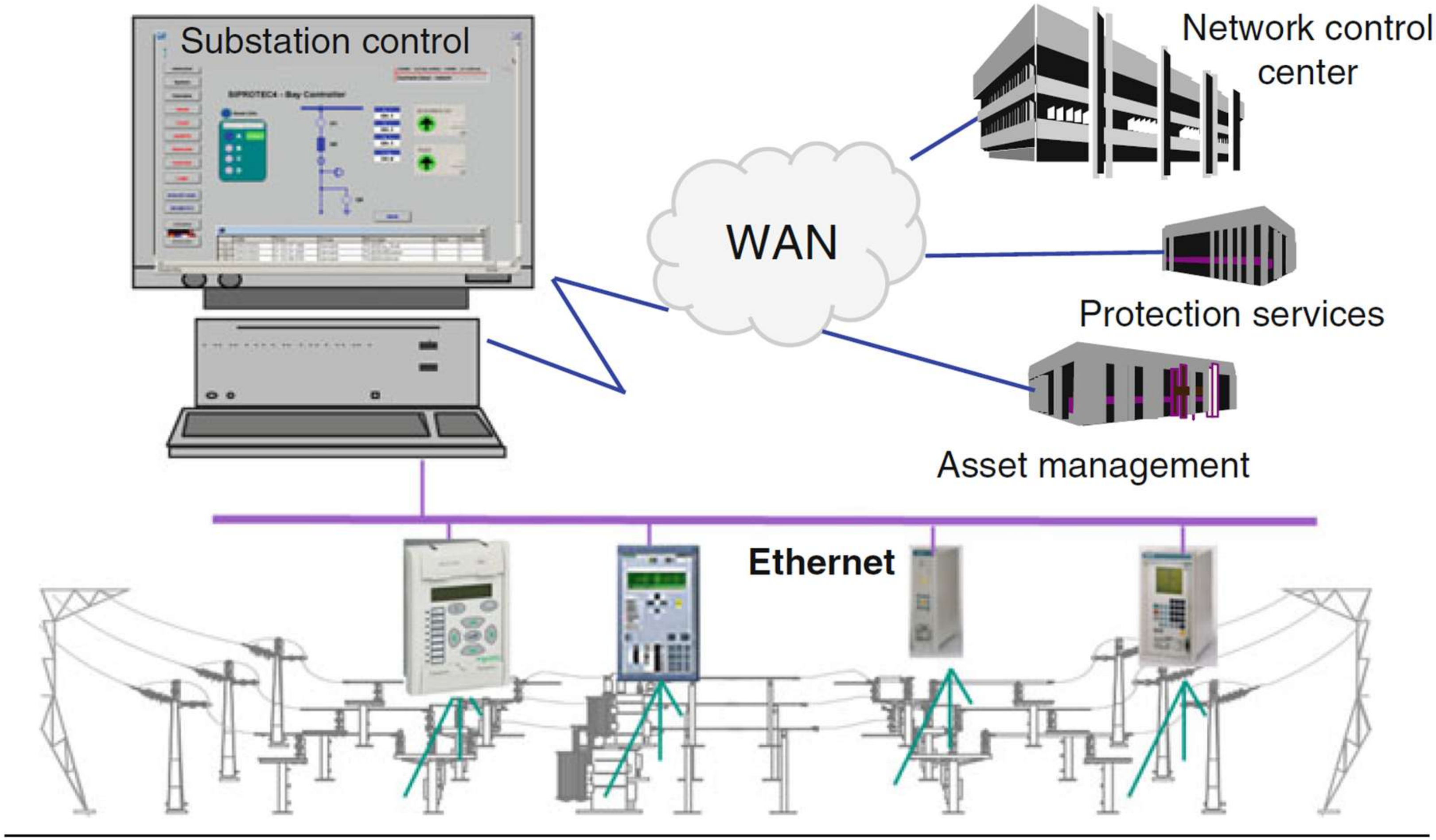
A/D Analogue digital converter,
AI Analogue input signal
AO Analogue output signal
BI Binary input signal
BO Binary output signal
CB Circuit breaker
CTM Current transformer measurement
CTP Current transformer protection
VT Voltage transformer
IHMI Integrated Human Machine Interface LED – light emitter diodes MP Micro processor

Smart grid challenges, toolbox and solutions for transmission networks



AC-Alternating current , DC- Direct current,
SCADA – Supervisory control & data acquision

Modern architecture of substation automation systems (SAS)

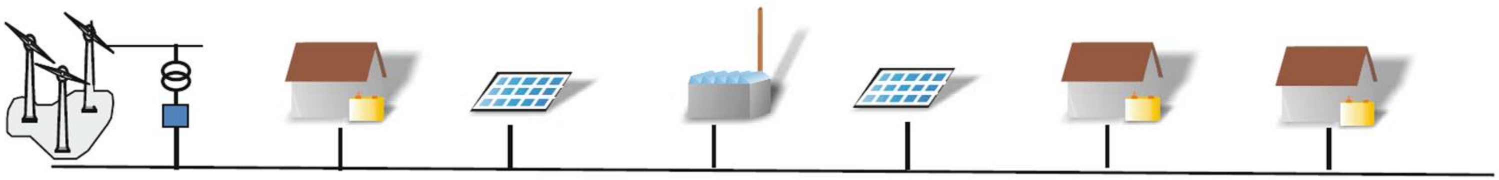


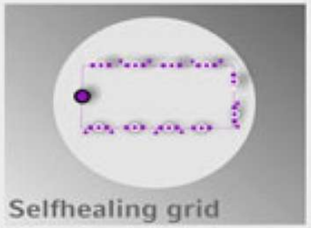
Distribution

- Increase in deployment of distributed generators (DG) at distribution level makes the power flow control much more complicated, necessitating the investigation of smarter power distribution and delivery mechanisms.

- Distributed generation promotes the development of a new grid paradigm, called microgrid, which is seen as one of the cornerstones of the future SG.

The three pillars of smart distribution



Distribution Automation	Smart Aggregation	Smart Metering
		
Main Tasks, Functions, Targets		
Voltage and load flow control, Remote control of switches Remote reading of fault indications, Automated elimination of faults **Improved quality of supply**	Aggregation of dispersed generators storage and loads for balancing and optimizing participation on prospective markets **Economic benefits**	Market integration of consumers by variable tariffs–Online visibility of demand , costs & savings **Energy efficiency and economic benefits**

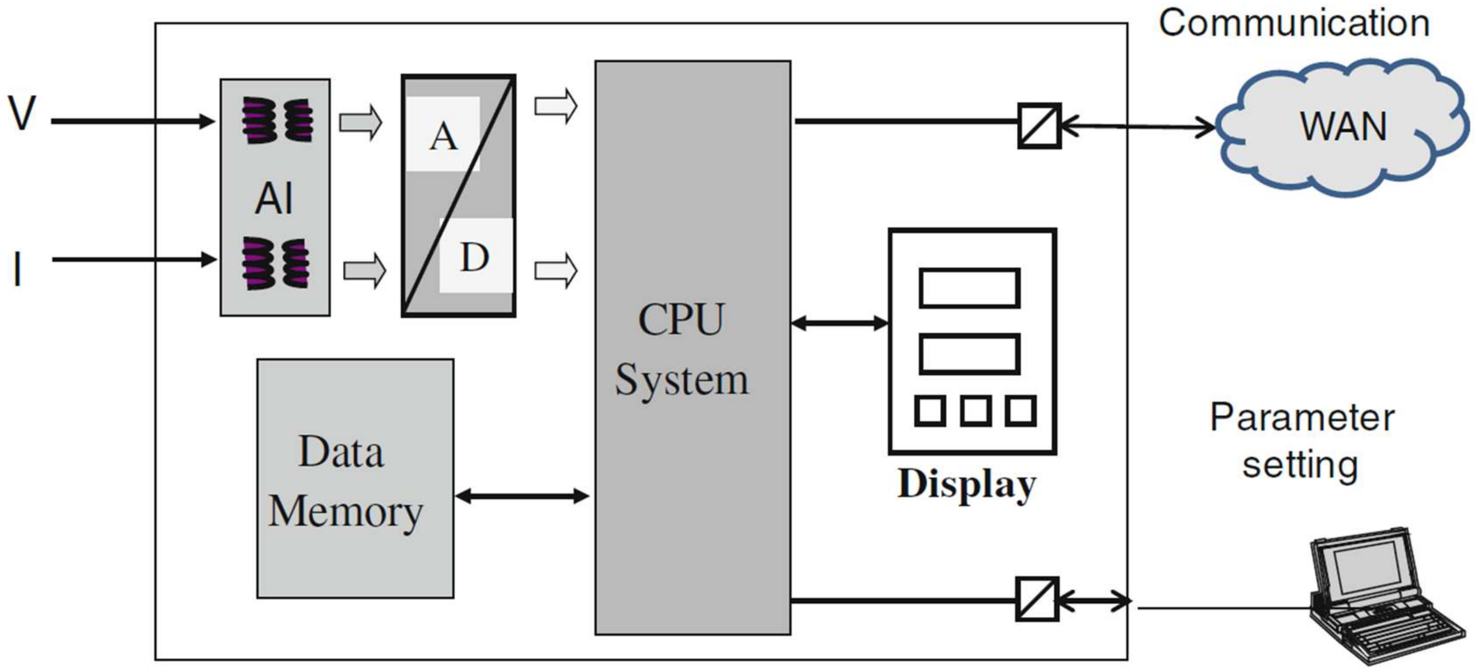
Smart metering

- Smart meter is usually an electrical meter that records consumption in intervals of an hour or less and sends that information a least daily to the utility for monitoring and billing purposes.

- Automatic meter reading (AMR) is the technology of automatically collecting diagnostic, consumption and status data from energy metering devices and transferring that data to a central database for billing, troubleshooting and analyzing.

- Automatic meter infrastructure (AMI) differs from traditional AMR in that it enables two-way communications with the meter. Therefore nearly all of this information is available in real time.

The principle of digital metering technology



AI Analogue input signal converter, A/D Analogue digital converter,
CPU – Central processor unit, WAN – Wide Area Network

Smart metering functions

Communication interface
Remote reading of metered data
Metering active & reactive energy
Receiving tariff signals and forecasts
Time synchronization
Visualization of tariffs, demand & costs
Voltage and power measurements

Data provision in short intervals
Voltage quality monitoring
Load profile recording
Gateway to Home Automation
Digital setting of parameters
Disturbance diagnostics
Detection of manipulations

Sensor networks used as a monitoring and measurement unit for grid

Need of sensors in the smart grid

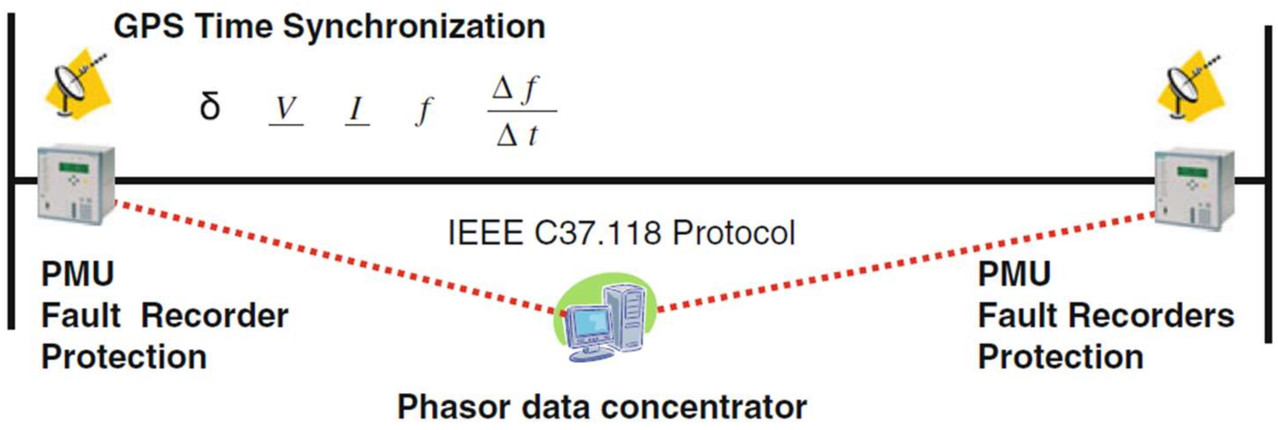
- Quality of service (QoS) requirements
- Resource constraints
- Remote maintenance and configuration
- High security requirements
- Harsh environmental conditions

Phase Measurement Unit (PMU)

- PMU measures the electrical waves on an electrical grid to determine the health of the system

Phasor Measurement Unit (PMU)

- Phasor measurement units (PMU) are installed in selected nodes of the network system.
- The PMUs form time stamped measurement sets and communicate these packages to the phasor data concentrator via high-speed communication channels using an IEEE standard protocol with a delay of 20 ms.
- The measurements will be refreshed in time intervals between 20 and 100 ms.
- To achieve accuracy in the comparison and suitable analysis results, the measurements have to be acquired with a high time accuracy using satellite synchronisation.



Functions of PMUs

- Providing loss-of-mains protection
- Monitoring fault event
- Locating disturbance
- Estimating grid state
- Studying synchronous islanded operation
- Monitoring power quality

Smart information

- The evolution of SG relies on not only the advancement of power equipment technology, but also the improvement of sophisticated computer monitoring, analysis, optimization, and control from exclusively central utility locations to the distribution and transmission grids.

- Many of the concerns of distributed automation should be addressed from an information technology perspective, such as interoperability of data exchanges and integration with existing and future devices, systems.

- Smart information subsystem is used to support information generation, modelling, integration, analysis, and optimization in the context of the SG.

Information Management

- Large amount of data and information will be generated from metering, sensing, monitoring
- Smart grid needs advanced information management techniques which handles data modelling, information analysis, integration and optimization.
- Information analysis is needed to support the processing, interpretation and correlation of the flood of new grid observations.
- Information integration aims at the merging of information from disparate sources with differing conceptual, contextual and typographical representations.

Smart communication

- Deals with connectivity and information transmission among systems, devices and applications.
- Reliable and effective information exchange is a key to the success of the future SG
- Basic functional requirements
  - Critical data (e.g. grid status information) must be delivered promptly.
  - High reliability: Guaranteeing the reliability of such a large and heterogeneous network is not a trivial task
  - High availability: this is mandated by the principle that the SG can respond to any event in the grid in time.
  - It must guarantee security and privacy.

Smart communication

Wireless communication

- Wireless : IEEE 802.15
- Mesh network : Satellite communications
- Cellular communications: Microwave or Free space
- Cognitive Radio: Optical communications

Wired Communication

- Fiber-Optic communication
- Power-line communication

Wireless communication

- **Cellular communication systems:**
  - It is a radio network distributed over land areas called cells, each served by at least one fixed location transceiver known as cell site or base station.
  - Proved mature technology for data transmission for several decades.
- **Cognitive radio**
  - Based on IEEE 802.22 Standard
  - It is used as secondary radios to handle high volumes of non-critical data and also act as backup radios in emergency situations.

Wired communication

- It has been used by large power companies to connect their generation network with their network control facilities
- Furthermore, its electromagnetic and radio interference immunity make fibre-optic communication ideal for high voltage operating environment.
- It has high bandwidth capacity.
- Although it is well-known that installation cost of optical fibres may be expensive, fibre-optic network is still a cost-effective communication infrastructure for high-speed communication network backbone in future SG.

Power line communication (PLC)

- Power line communication (PLC) is a technology for carrying data on a conductor also used for electric power transmission.
- In the last decades, utility companies around the world have been using PLC for remote metering and load control applications.
- Technically, in PLC power electronics are used to manipulate high-voltage waveforms for signal and information-oriented applications.
- First, narrowband PLC is well suited for smart metering infrastructure.
- Second, PLC enables communications between electric vehicles and power grid via power line without introducing other wired or wireless equipment.
- Third, broadband PLC can provide the service of transferring data seamlessly from SG controllers to home network and vice-versa.

Smart Management

- Energy efficiency improvement
- Operation cost reduction
- Demand and supply balance
- Emission control
- Utility maximization

Smart Protection System

Prediction and prevention

- Predicting the weak points of the region of stability existence in its energy subsystem
- PMU data can be utilized to compute the region of stability existence and operational margins
- Major blackouts can be prevented by proper predictions.

Identification, diagnosis and recovery

- Locating and identifying the failure to avoid cascading events
- Due to the wide deployment of PMUs, the phasor information used for line outage detection and network parameter error identification
- Self healing can be effective if power grid is divided small sections.
- During post fault, decision-making ability should be distributed to the substation and/or field devices for immediate action.

Challenges in Smart Protection System

- Interoperability between cryptographic systems
- Conflict between privacy preservation and information accessibility
- Impact of increased system complexity and expanded communication paths
- Impact of increasing energy consumption and asset utilization
- Complicated decision-making process.

Security and Policy-issues

- Cyber security is regarded as one the biggest challenges in Smart Grid
- Vulnerabilities may allow an attacker to penetrate a system, obtain user privacy, gain access to control software, and alter load conditions to destabilize the grid in unpredictable ways
- Smart meters are extremely attractive targets for malicious hackers, since vulnerabilities can easily be monetized
- Wide deployment of monitoring and measurement devices(e.g. sensors and PMUs) could also lead to system vulnerabilities.

Barriers to Smart Grid Technologies

- Huge amount of investment and lack of financial resources
- Market uncertainty
- Lack of regulatory framework
- Low public awareness and engagement
- Lack of innovativeness in the industry
- Lack of infrastructure
- Technology immaturity
- Integration of the grid with large scale renewable regeneration
- Need of advanced bi-directional communication systems, Cyber security and data privacy

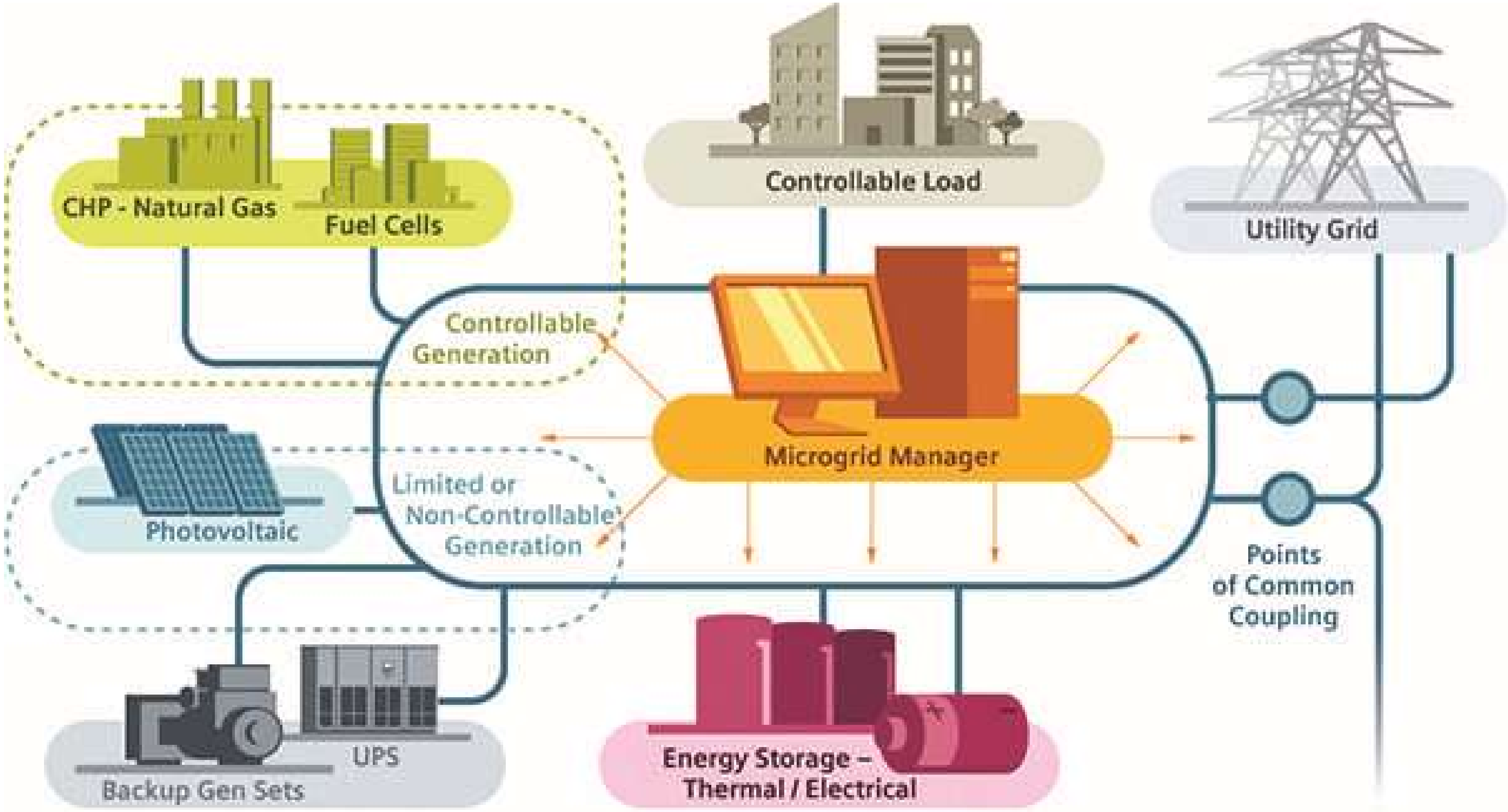
Microgrid

What is a Microgrid?

- Micro grids comprise LV distribution systems with distributed energy resources (DER) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads.
- Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid.
- The operation of micro sources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently.
- Microgrid is an integration platform for supply-side (microgeneration), storage units and demand resources (controllable loads) located in a local distribution grid.
- A microgrid should be capable of handling both normal state (grid-connected) and emergency state (islanded) operation.

NUS National University of Singapore

Microgrid schematic



Source: www.powermag.com

Intermittent Renewable Energy Sources

- Controllability of intermittent RES units is limited by the physical nature of the primary energy source.

- Moreover, limiting RES production is clearly undesirable due to the high investment and low operating costs of these units and their environmental benefits over carbon emission.

- It is generally not advisable to curtail intermittent RES units, unless they cause line overloads or overvoltage problems.

- The operation strategy for intermittent RES units can therefore be described as "priority dispatch", that is, intermittent RES units are generally excluded from the unit commitment schedule, as long as they do not violate system constraints.

Importance of Storage System

During renewable excess/deficit

In grid connected mode batteries can store excess of renewable energy when demand is less and supply the required deficit power when renewable generation is less

During Islanded mode

Grid support action: Helps to regulate the grid voltage by its charging/discharging action.

To flatten load curve

Since both renewable generation and loads are variable by nature, usage of batteries can flatten the load curve.

Storage technology options and modes

- Potential energy (pumped hydro, compressed air, springs)
- Kinetic energy (mechanical flywheels)
- Thermal energy without phase change
- Thermal energy with phase change (ice, molten salts, steam)
- Electrochemical energy (batteries, flow cells)
- Electrostatic energy (capacitors)
- Electromagnetic energy (superconducting magnets)

Performance factors for energy storage systems

- Energy capture rate and efficiency
- Discharge rate and efficiency
- Dispatchability and load following characteristics
- Scale flexibility
- Durability – cycle lifetime
- Mass and volume requirements – footprint of both weight and volume
- Safety – risks of fire, explosion, toxicity
- Ease of materials recycling and recovery

Energy and power density are both important!!

Energy Storage Technologies

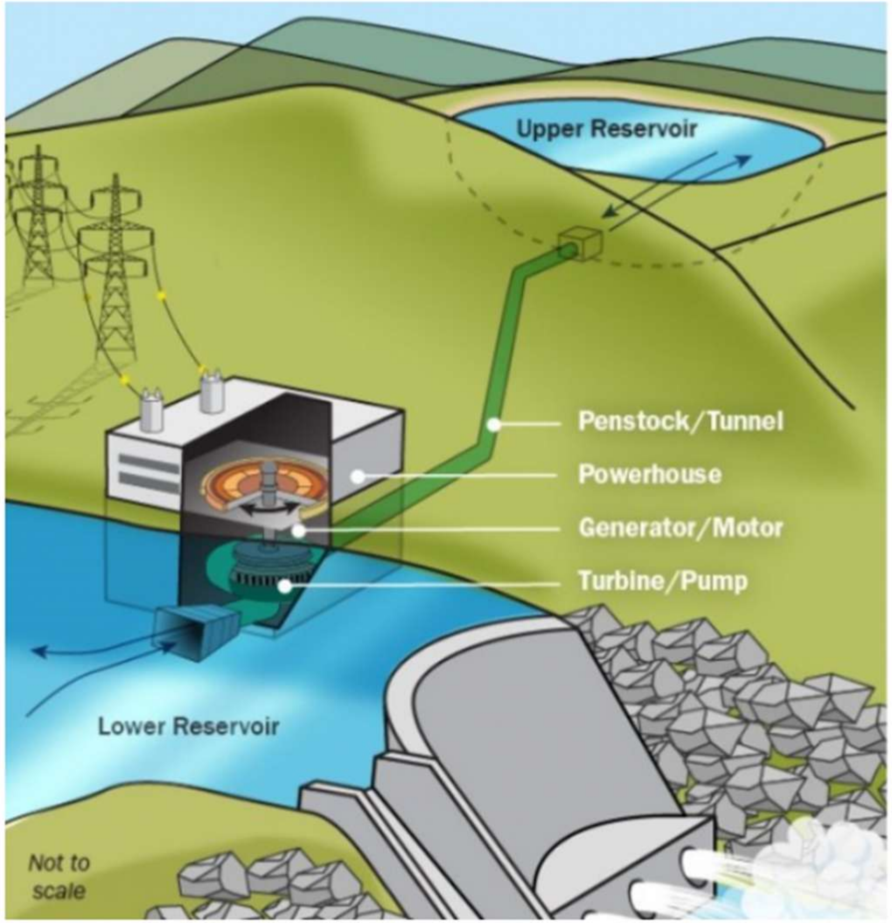
Mode	Primary Energy Type	Characteristic Energy Density kJ/Kg	Application Sector
Pumped Hydropower	Potential	1(100m head)	Electric
Compressed Air	Potential	15,000 Kg/m3	Electric
Flywheels	Kinetic	30-360	Transport
Batteries	Electrochemical	Lead Acid - 60-180 NMH - 300 Li-Ion - 400 – 600 Li-Polymer – 1,400	Transport, Grid, Buildings
Super Conducting Magnetic Energy Storage	Electromagnetic	100 – 1,0000	Electric
Super Capacitor	Electrostatic	18-36	Transport

Cost projection of energy storage systems

System	Typical Size Range MWe	$/kWe	$/kWh
Pumped hydropower	100-1000	600-1000	10-15
Batteries Lead acid Nickel metal hydride Li-ion	 0.5–100 0.5-50 0.5-50	 100-200 200-400 200-400	 150-300 300 500
Mechanical flywheels	1-10	200-500	100-800
Compressed air energy storage (CAES)	50-1,000	500-1,000	10-15
Superconducting magnetic energy storage (SMES)	10-1,000	300-1,000	300-3,000
Supercapacitors	1-10	300	3,600

Pumped Hydro System

- Water is pumped from a lower reservoir uphill and then allowing it to flow downhill to through turbines to produce electricity.
- Readily available and widely used in high power applications
- Lower cost of power, frequency regulation on the grid, and reserve capability
- Can only be implemented in areas with hills .



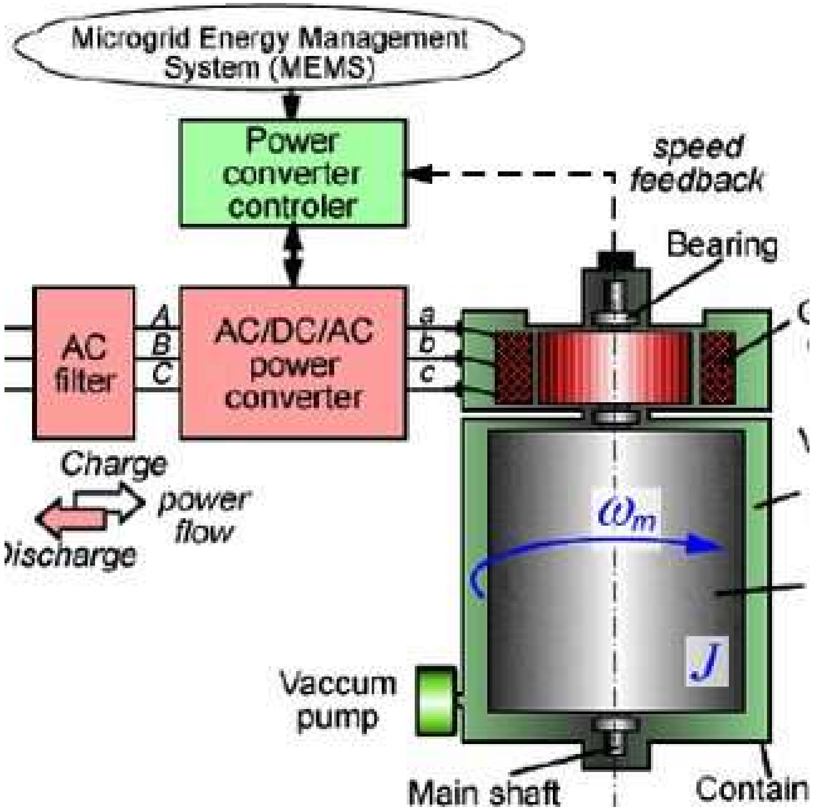
Pumped hydro installations

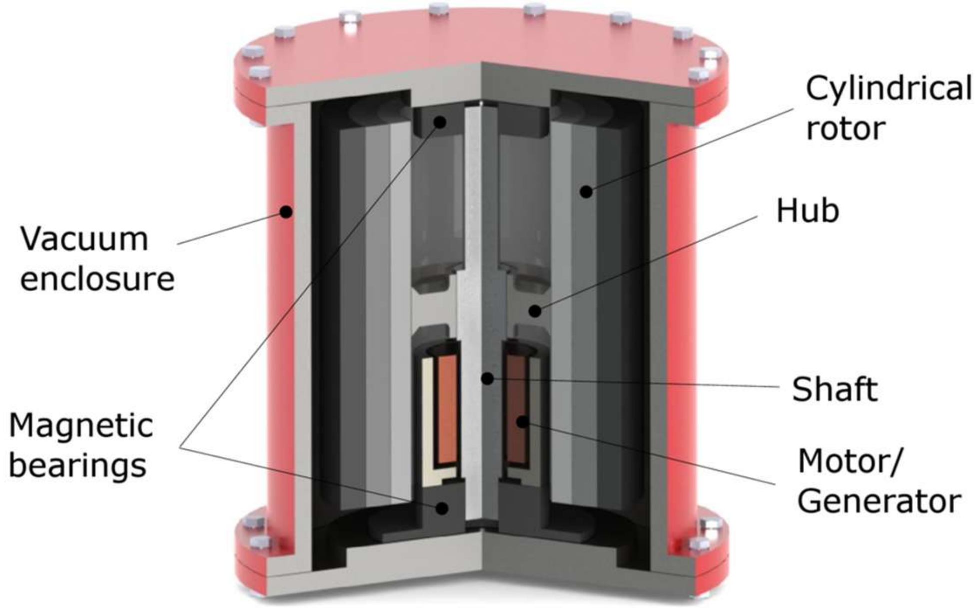
Station	Country	Capacity (MW)
Bath County Pumped Storage Station	United States	3,003
Guangdong Pumped Storage Power Station	China	2,400
Huizhou Pumped Storage Power Station	China	2,400
Okutataragi Pumped Storage Power Station	Japan	1,932
Ludington Pumped Storage Power Plant	United States	1,872

Source: Wikipedia

Flywheels

A cylinder that spins at a very high speed, storing kinetic energy.





Advantages of Flywheels

- Charge and discharge rapidly
- Affected little by temperature fluctuations
- Take up relatively little space
- Long life span
- Tolerant of abuse
- Lower maintenance requirements than batteries
- Flywheels with magnetic bearings and high vacuum can maintain 97% mechanical efficiency, and 85% round-trip efficiency
- Flywheels may be used to store energy generated by wind turbines during off-peak periods or during high wind speeds.

- Disadvantage: Power loss faster than batteries.

Compressed Air Energy Storage (CAES)

- Utilities use electricity generated during off-peak hours (i.e., storage hours) to compress air and store it in airtight underground caverns.
- When the air is released from storage, it expands through a combustion turbine to create electricity.
- Conserves some natural gas by using low-cost, heated compressed air to power turbines and create off-peak electricity.
- Has low efficiency due to the extra reheating energy needed to turn on the turbines.
- For every kWh of energy going in, only 0.5 kWh of energy can be taken out.

Batteries

Lead Acid Batteries

- Suitable for large storage application
- Low cost but high maintenance

Sodium Sulphur (NaS)

- High energy density (Four times of lead acid),
- Long cycle capability
- Suitable for stationary energy storage applications

Lithium-Ion

- Environmental friendly
- Suitable for portable devices like mobile phones, laptops, power tools and also in Electric vehicles

Lithium-Ion Polymer

- Higher specific energy than other lithium battery types and are being used in applications where weight is a critical feature
- Suitable for portable devices like mobile phones and notebook computers

DC Microgrid

Importance of DC

- Various conversion stages like AC-DC/DC-AC can be avoided by forming DC Grid and Overall System efficiency can be improved.
- No problem of reactive power, harmonics, frequency control.
- No synchronization issues and Controlling becomes easier.
- Eddy current, hysteresis losses and skin effect are absent.
- Reduces stress on conventionally grid, congestion of transmission line will be reduced.

DC operation based on Voltage Level

HVDC

- Operating voltage range 500kV and above, Economical and efficient over AC at long distance transmission.
- Power transfer between two separate AC networks.

MVDC

- Operating voltage level is 11kV and 33kV
- Can provide controlled power transfer between two 11kV and 33kV networks for better utilization of existing network.

LVDC

- Operating voltage levels are 48V/380V/600V
- Reduces dependency on main grid, reliability to the consumer can be improved, and provide supply to remote villages.

DC Microgrid Topologies

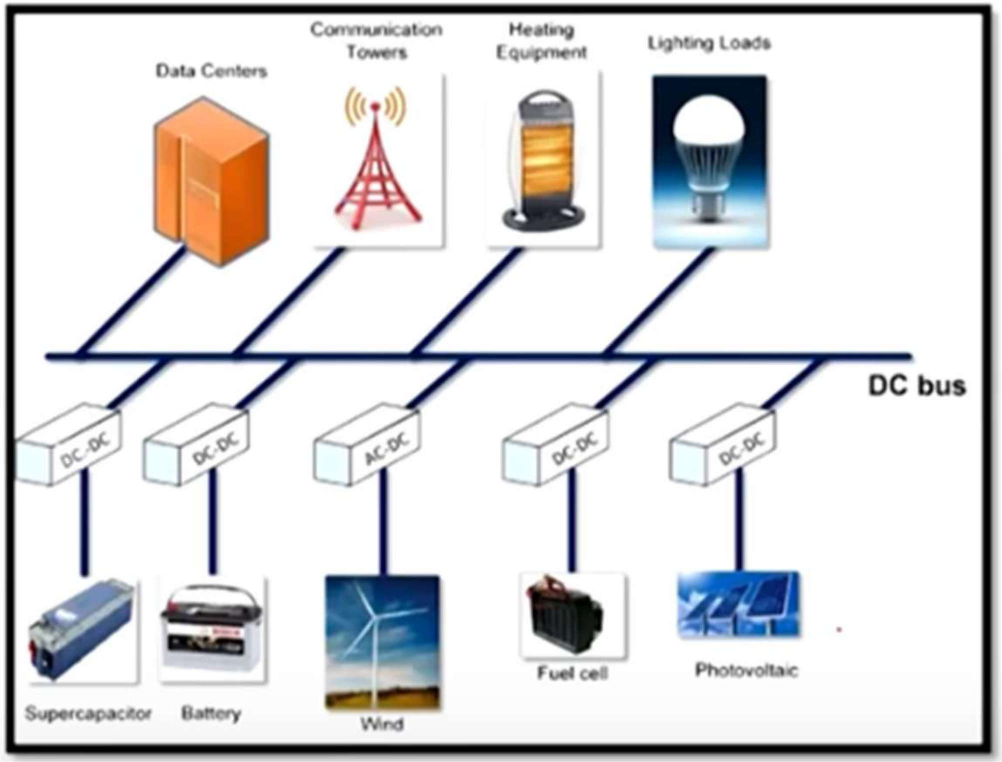
Single Bus Topology

- ESS directly connected to DC bus

  Suitable for low voltage applications likely 48V.

- ESS Connected with converter

  More flexible control and also improves reliability of the system

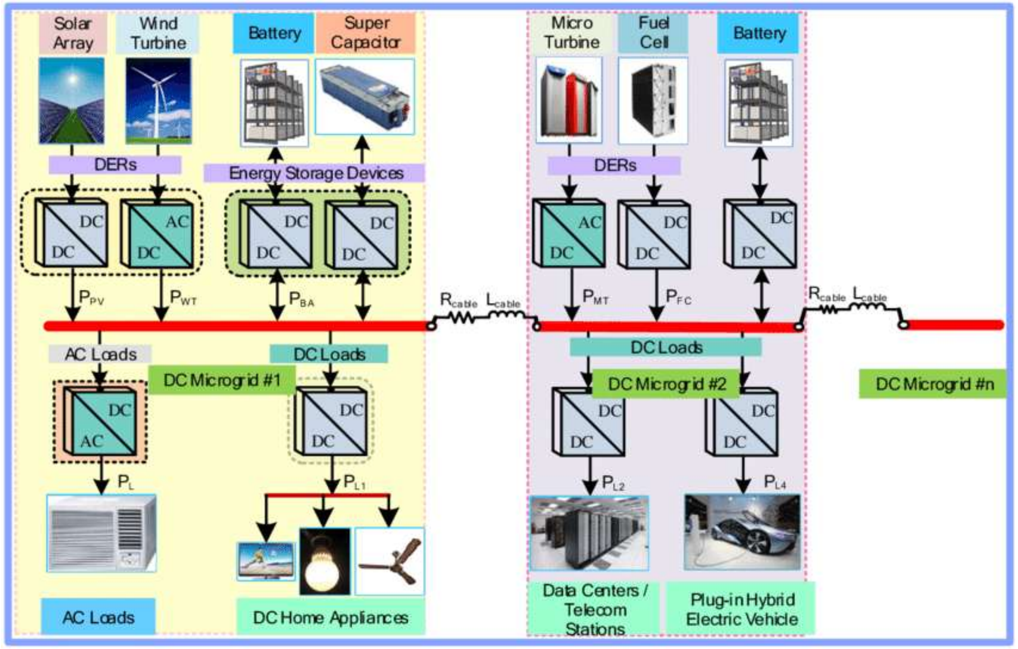


Multi-bus DC Microgrid Topology

- **Dual bus separately fed DC Microgrid**
  Simultaneous supply from multiple buses is possible and hence total efficiency is improved.

- **Multiple DC microgrid cluster configuration**
  - Every Microgrid is able to absorb/inject power from its neighbor in case of shortage/surplus
  - Some corrupted buses can be automatically isolated.

- **Solid State Transformer (SST) enabled DC Microgrids**
  Energy management in lower voltage levels will be in SST domain.



Reconfigurable DC Microgrid Topologies

DC ring bus architecture

High reliability and redundant operation are the main merits

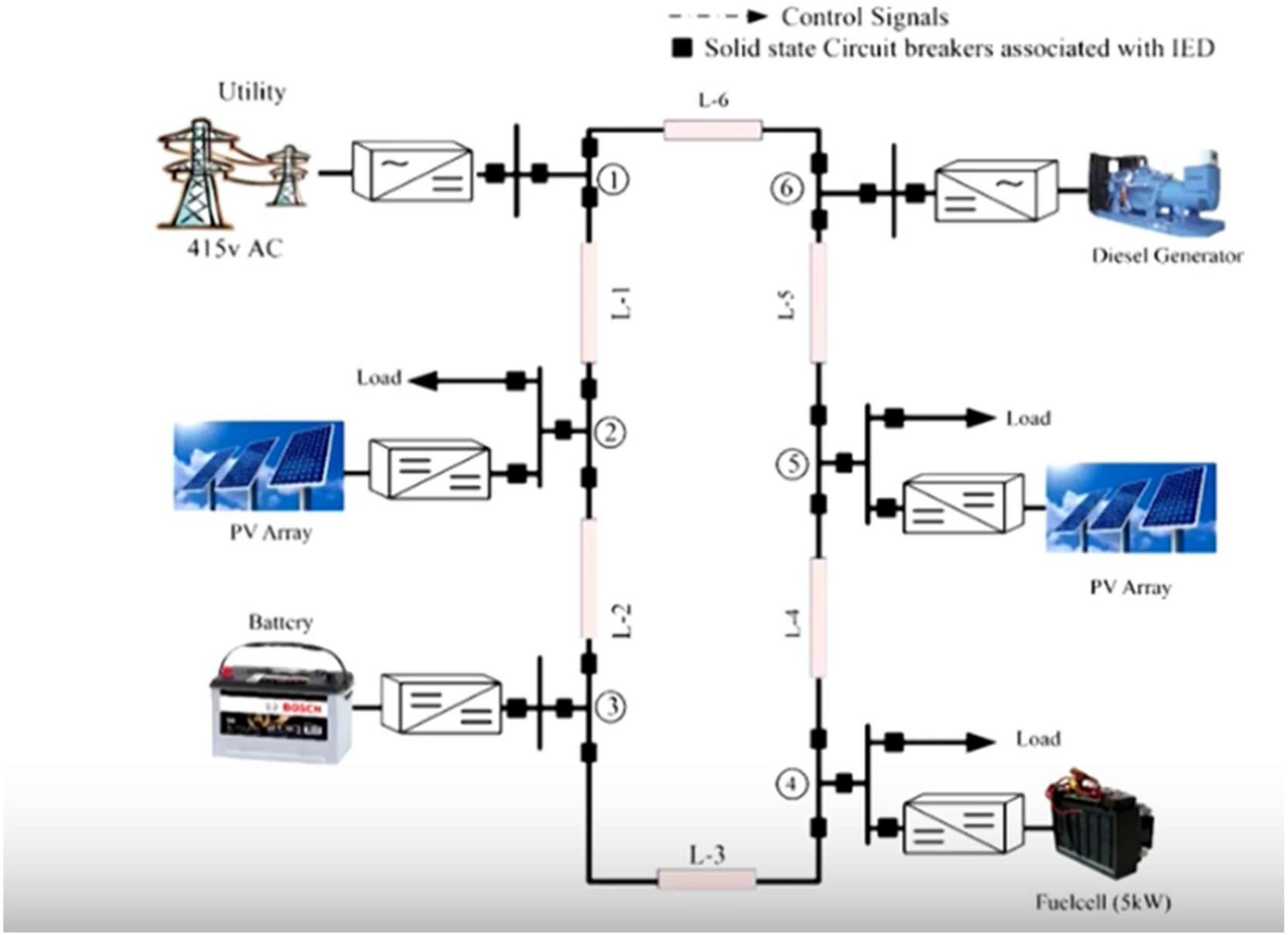
Zonal configuration

- Highly redundant and reliable
- Fault can be isolated within each unit without disturbing other zone

Multi-terminal DC system

System connection provide multiple paths for power transmission

DC ring-bus architecture



Switched Mode Converters

- Switched mode converters came into existence due to hefty losses incurred in linear mode converters (series or shunt).

- Switched mode converter topologies commonly referred as DC-DC converters are categorized as isolated and non-isolated converter topologies.

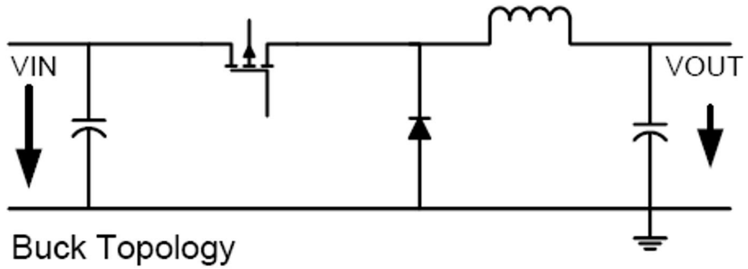
- In general DC-DC converters non-isolated topologies are preferred due to the added cost of transformer specifically designed for higher switching frequency.

Classic DC-DC converter topologies

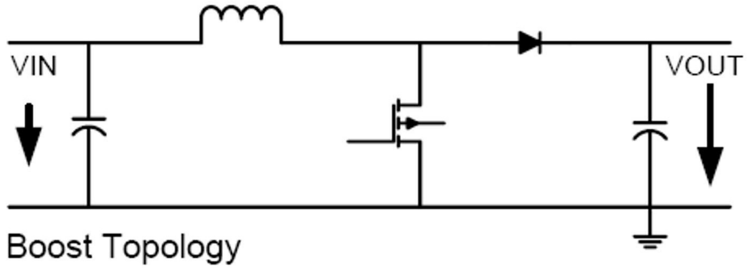
- Classic DC-DC converter topologies include Buck, Boost, Buck-boost, Cuk

- These topologies are used when there is a need for unidirectional power flow

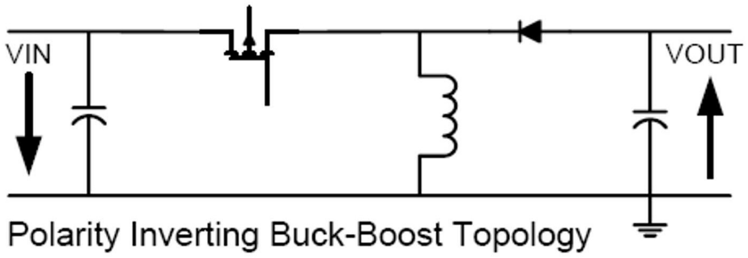
Buck, Boost, Buck-Boost Converters



$$\frac{V_o}{V_{in}} = D$$



$$\frac{V_o}{V_{in}} = \frac{1}{1 - D}$$



$$\frac{V_o}{V_{in}} = \frac{D}{1 - D}$$

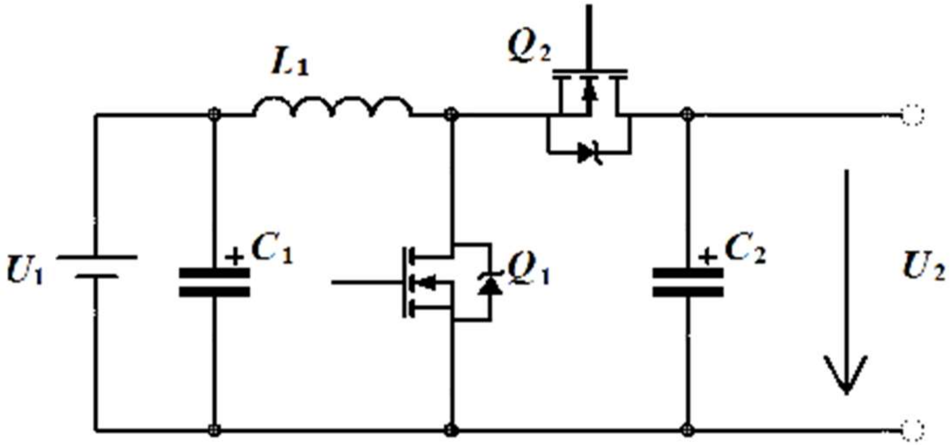
Bi-Directional DC-DC converters

The key constraints of bidirectional DC-DC converter are:

- Single converter
- Simplicity using minimal storage elements.
- Allow bi-directional power flow from one source to other and vice versa.

Non-isolated bi-directional converter topology

- Half-bridge converter
- Cascaded half-bridge converte



Commonly Used Protection Devices in LVDC

Fuses

Moulded Case Circuit Breakers

LV power CBs

Isolated case CBs

Challenges in DC Microgrid

- Lack of Standards
- Protection issues : no DC circuit breaker
- Lack of DC infrastructure
- Circulating currents in parallel operation, Grounding issues.
- Unable to feed AC loads of Industries, Commercial and Residential applications.

Microgrid Control

MG Control

- In conventional power grids, stability analysis is well established with standard models of synchronous generators, governors, and excitation systems of varying orders that are known to capture the important modes for particular classes of problems.

- This does not yet exist for the MGs and may be difficult to achieve because of the wide range of power technologies that might be deployed.

- New high-level control strategies and management rules are required to ensure system reliability.

MG Control

- Current, voltage/amplitude, frequency/angle, and active and reactive power are the main feedback variables used in the existing MG control loops in both grid-connected and islanded operation modes.

- The MG control is responsible for providing proper load sharing and DG coordination, voltage/frequency regulation in both operating modes, MG resynchronization with the main grid, operating cost optimization, and power flow control between the MG, neighbourhood grids, and the main grid.

MG Control

- MGs should be able to not only operate autonomously but also interact with the main grid.

- In the grid-connected operation mode, the MGs are integrated into a constantly varying electrical grid with changing tie-line flow, voltages, and frequency. To cope with those variations, to respond to grid disturbances, and to perform active power/frequency regulation, as well as reactive power/voltage regulation, MGs need to use proper control loops.

- Furthermore, suitable islanding detection feedbacks/algorithms are needed to ensure a smooth transition from the grid-connected to islanded mode to avoid cascaded failures.

Hierarchical Control

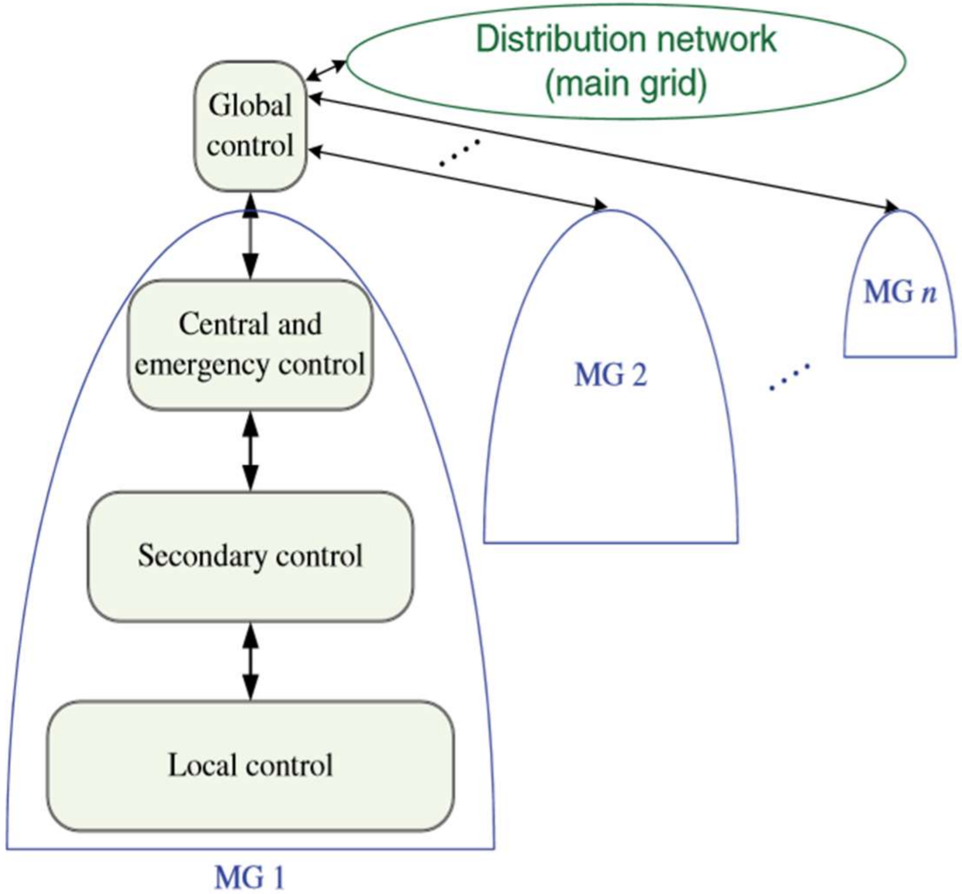
- MG has a hierarchical control structure with different operation layers.

- Hierarchical control scheme provides a compromise between fully centralized and decentralized control schemes, and the performed control levels are mainly different in their infrastructure requirements and dynamic timescale in which they are operating.

Hierarchical Control Strategy

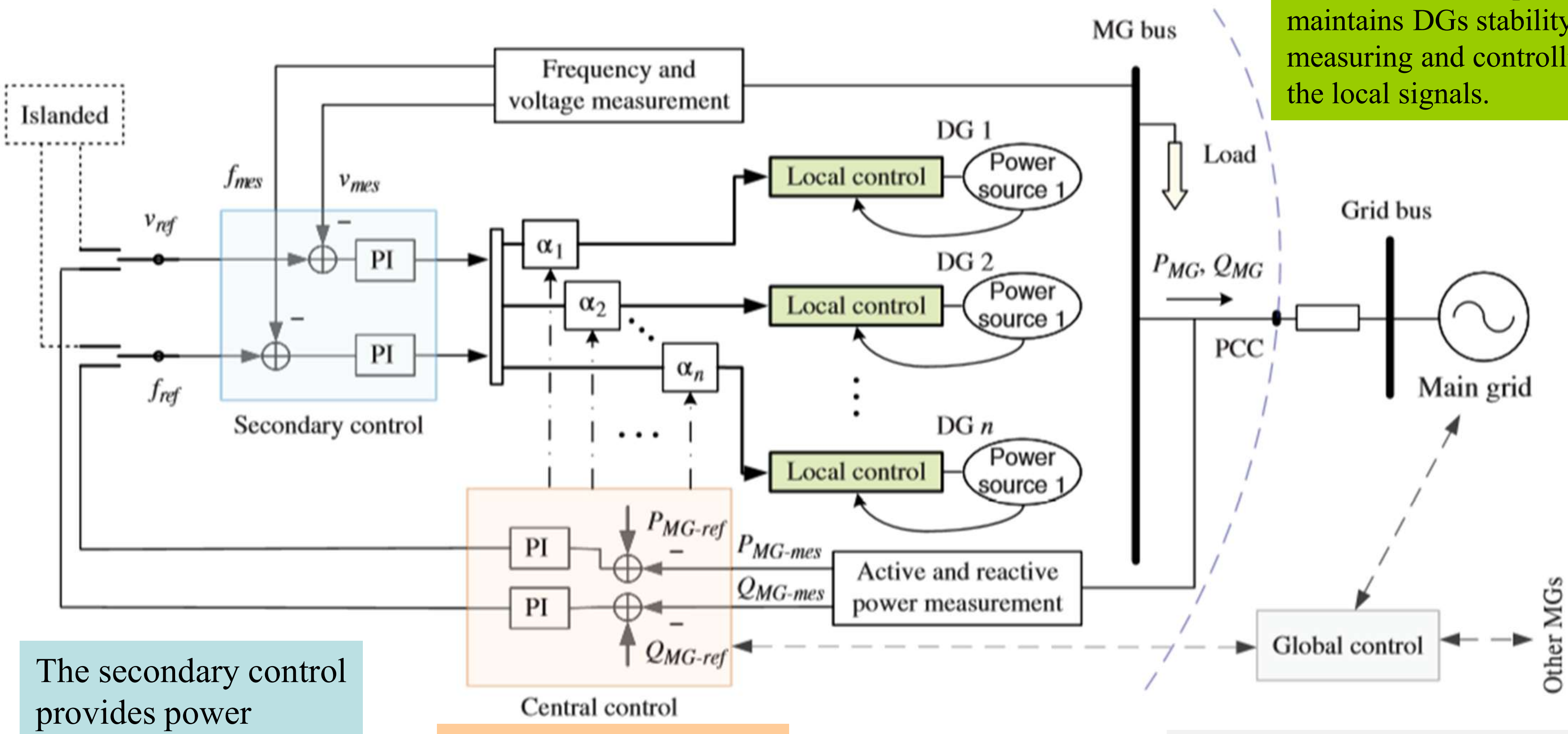
Consists of four levels:

1. local (primary) controls,
2. secondary controls,
3. central/emergency controls, and
4. global controls



Hierarchical Control schematic

The local control comprises DGs internal voltage and current control loops, maintains DGs stability by measuring and controlling the local signals.



The secondary control provides power sharing as a communication-based method for parallel configuration of DGs

The central/emergency control level facilitates MG supervision activities.

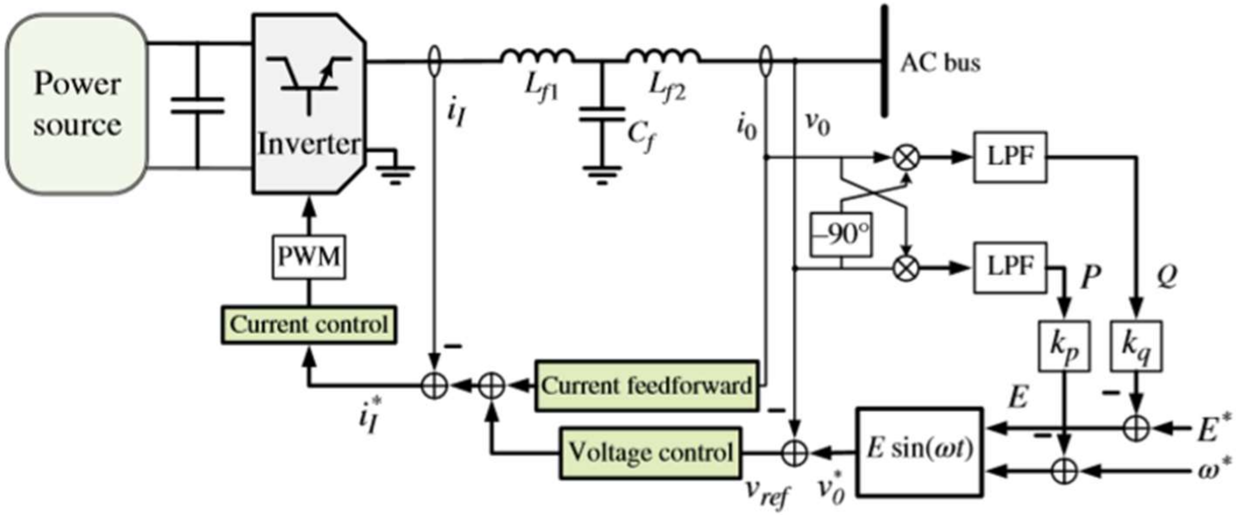
The global control manages the power flow between the given MG, other interconnecting MGs and the main grid

Time scales of control levels

- The global control level typically operates in the order of several of minutes to hour, providing signals to the central level controls at MGs and other subsystems that form the interconnected distribution grid.
- Central controls, on the other hand, coordinate internal secondary and local controls within the MGs in the span of a few minutes.
- Secondary control reacts in the order of few seconds to minute.
- Finally, local controls are designed to operate independently and operate in predefined ways instantaneously to local events.

Local Control

- The local controllers deal with the inner control of the DG units.
- They appear in different forms depending on the type of DGs: induction generators, synchronous generators, and PE inverters/converters in Renewable energy sources.
- The local controllers design usually should be based on a detailed dynamic model of the DGs, including the resistive, reactive, and capacitive local load and the distribution system.



Secondary controls

- Secondary controls as second layer control loops complement the task of inner control loops to improve the power quality inside MGs and to enhance the system performance by removing the steady-state errors. They are closely working with local and central control groups.

- They take care of steady-state voltage and frequency deviations in the presence of load changes and action of the local controllers in the islanded operation mode. The voltage/frequency reference signals(E^* and ω^*) are provided by secondary control loops.

- Secondary control operates on a slower time scale compared to the local control.

- In contrary to the local control, in secondary control, it may need to use low band width communications.

Central/Emergency Control

- It is responsible for the reliable, secure, and economical operation of the MG in either grid-connected or islanded operation mode.

- Central/emergency control is the highest level in the MG hierarchical control structure with a significant role in the islanded operation mode.

- The central control can be also used to synchronize the MG before connecting to the main grid, to facilitate the transition from islanded to grid-connected mode.

- Following a load disturbance within the MG, the produced appropriate secondary control signal is distributed among DGs according to their participation rate, to compensate the generation-load imbalance. In a given MG, the sum of participation factors is equal to 1. The α_i is a participation factor of the i^{th} DG in the MG frequency or voltage regulation.

$$\sum_{i=1}^{n} \alpha_i = 1, 0 \leq \alpha_i \leq 1.$$

Global Control

- The global control is the highest level of control for coordinating the operation of multiple interconnected MGs, and communicating requirements with the main grid.

- For instance, coordination features for active/reactive power management of a grid comprising the main grid and interconnecting MGs could be accomplished by the global control.

- On the other hand, in the global control point of view, the MG can be controlled to interact with the distribution grid as a dispatchable and constant impedance load.

Stability of Microgrid

- MG can have small signal instability, transient instability, voltage instability, and frequency instability problem.
- Dynamic impacts of feedback controllers, continuous load switching and oscillation modes are causes of small signal stability.
- Unexpected islanding, DG outage, large and sudden load change, and cascaded faults are known as reasons of the transient instability problems.
- Reactive power limits, load dynamics, and tap changers create most of the voltage stability problems.
- Load-generation imbalance and active power limits can be considered as the main reasons for frequency instability in an MG.

Low inertia of MGs

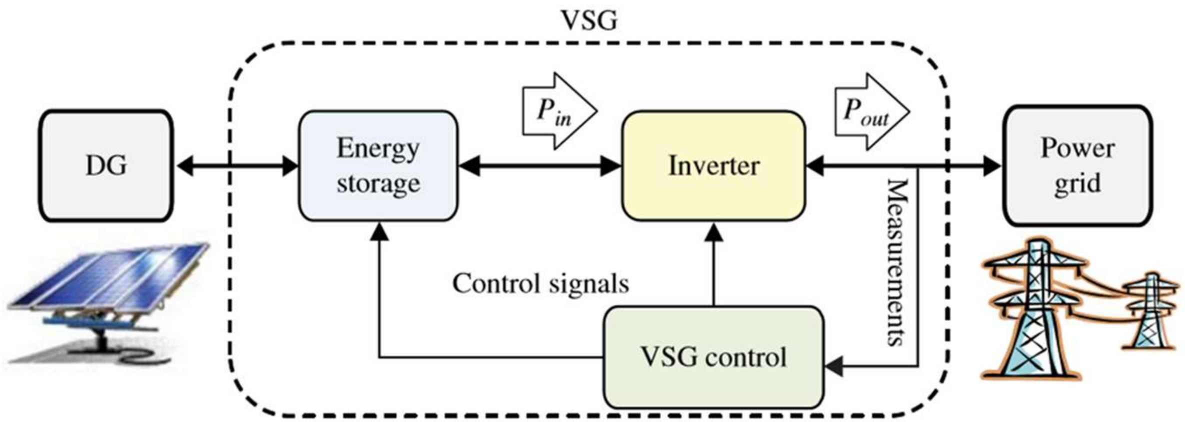
- Compared to conventional power systems with bulk power plants, microgrids (MGs) with DG/RES units have either small or no rotating mass and damping property.

- Relatively high integration of inverter-based distributed generators (DGs) and renewable energy sources (RESs) will have some impacts on power grid dynamics, frequency, and voltage regulation, as well as other control and operation issues.

Virtual Synchronous Generators : Dynamic Performance and Characteristics

- A solution towards stabilizing a grid/MG with numerous low-inertia DGs is to fortify the system with additional inertia, virtually.

- Virtual inertia can be established by using short-term energy storage together with a power electronics inverter/converter and a proper control mechanism in a system that is called virtual synchronous generator(VSG).



Microgrid Protection

- Protection of Microgrid especially when it is islanded is quite challenging
- The first and foremost challenge is to detect the islanding of the microgrid
- The second important challenge is how to provide segments of the microgrid with sufficient coordinated fault protection while operating as an island separated from the utility

References

"Microgrid Dynamics and Control",
by Hassan Bevrani, Bruno Francois and Toshifumi Ise.

"Smart Grid: Fundamentals of Design and Analysis",
by James Momoh, Wiley-IEEE Press.

"Design of Smart Power Grid Renewable Energy Systems", Third Edition," by Ali Keyhani, Wiley

"Smart Grids – Fundamentals and Technologies in Electricity Networks", by Bernd M. Buchholz, Zbigniew Styczynsk