Department of Industrial and Management Engineering
Indian Institute of Technology Kanpur

Forum of Regulators

4th Capacity Building Programme for
Officers of Electricity Regulatory Commissions
18 – 23 July, 2011

"Technologies for Generation, Transmission and Distribution - Status & Performance Indicators"

Prof S.N. Singh
Department of Electrical Engineering,
Indian Institute of Technology, Kanpur
(Email: snsingh@iitk.ac.in)

Evolution of Power Systems

Late 1870s	Commercial use of electricity
1882	First Electric power system (Gen., cable, fuse, load) by Thomas Edison at Pearl Street Station in NY. - DC system, 59 customers, 1.5 km in radius - 110 V load, underground cable, incandescent Lamps
1884	Motors were developed by Frank Sprague
1886	Limitation of DC become apparent - High losses and voltage drop. - Transformation of voltage required. Transformers and AC distribution (150 lamps) developed by William Stanley of Westinghouse
1889	First ac transmission system in USA between Willamette Falls and Portland, Oregon. - 1- phase, 4000 V, over 21 km

Evolution of Power Systems (Contd.)

1888	N. Tesla developed poly-phase systems and had patents of gen., motors, transformers, trans. Lines. Westinghouse bought it.
1890s	Controversy on whether industry should standardize AC or DC. Edison advocated DC and Westinghouse AC. - Voltage increase, simpler & cheaper gen. and motors
1893	First 3-phase line, 2300 V, 12 km in California. ac was chosen at Niagara Falls (30 km)

	Early Voltage (Highest)
1922	165 kV
1923	220 kV
1935	287 kV
1953	330 kV
1965	500 kV
1966	735 kV
1969	765 kV
1990s	1100 kV
	Standards are 115, 138, 161, 230 kV – HV 345, 400, 500 kV - EHV 765, 1100 kV - UHV
	Earlier Frequencies were 25, 50, 60, 125 and 133 Hz; USA - 60 Hz and some has 50 Hz, Which Frequency is better?

	HVDC Transmission System
1950s	Mercury arc valve
1954	First HVDC transmission between Sweden and Got land island by cable

Limitations of HVAC Transmission

1. Reactive Power Loss
2. Stability
3. Current Carrying Capacity
4. Ferranti Effect
5. No smooth control of power flow

Advantages of HVDC Transmission

- ❖Requires less space
- ❖Ground can be used as return conductor
- ❖Less corona loss & No reactive power loss
- ❖Cheaper for long distance transmission
- ❖No skin & Ferranti effect
- ❖Asynchronous operation possible
- ❖No switching transient
- ❖No transmission of short circuit power control possible
- ❖No stability problem

Disadvantages of HVDC Transmission

- ➢Cost of terminal equipment high
- ➢Introduction of harmonics
- ➢Blocking of reactive power
- ➢Point-to-point transmission is possible

Key Drivers to Technological Changes in Power Sector

- **Development of New Materials - Polymeric, Composite, Nano, Superconducting materials.**
- **Supply-demand gap and Environmental Concerns in Generation Sector**
- **Development of New Devices and Technologies**

  - Power Electronic Devices, DSP, Sensors, Information & Communication Technology
- **Maintaining Stable & Secure Operation of Large Interconnected Transmission System**
- **Increased losses and Poor Quality of Supply and Revenue Collection in Distribution Sector**
- **Regulatory Changes in the Electricity Sector**

New Transmission Technologies

- **High Voltage Overhead Transmission**
  - Voltage up to 1200 kV ac, ± 800 kV DC
  - High EM radiation and noise
  - High corona loss
  - More ROW clearance
- **Gas Insulated Cables/Transmission lines**
- **HVDC-Light**
- **Flexible AC Transmission Systems (FACTS)**

Gas insulated Transmission Lines

- For the transmission of high power over long distances GITLs are a good technical solution as an alternative to O/H lines and in addition to cables.
- If the diameter of outer shield is more compared to core, it is called gas insulated transmission lines. Normally tunnels are used in GITL.
- GITLs are used since more than 35 years for linking power plants to transmission network. **First was commissioned in 1975 in Germany of about 700m.**
- First mixed GITL in the world successfully completed its field trials with an endurance test in 1999.
- In Japan, 275 kV , 3.3 km double circuit GITLs which can transport power of 300 MVA.
- The cost of GITL is 8-10 times those on overhead power lines which was earlier 30 times. The basis for reduction of cost is:

Gas insulated Transmission Lines

  - Adaptation of installation techniques are similar to those used in laying pipelines.
  - Simplification and standardization of individual components.
  - Use of SF_6 (20%) and N_2 (80%)gases mixture.

- Basic Design
  - Enclosing tube is made of aluminum alloy and designed to be a pressure vessel as well as carrying mechanical load of conductors.
  - Enclosing tube is also used for carrying the inductive return current which is same as rated current.
  - The inner conductor is an aluminum tube held in place by bushings spaced at 100 m.
  - Sliding-contact plugs and sockets accommodate the thermal expansion of the conductor.
  - GITLs are installed in segments.

Gas insulated Transmission Lines

- Benefits of GITL
  - Low resistive losses (reduced by factor 4)
  - Low capacitive losses and less charging current
  - No external electromagnetic fields
  - No correction of phase angle is necessary even for long distance transmission
  - No cooling needed
  - No danger of fire
  - Short repair time
  - No aging
  - Lower total life cycle costs.

HVDC-Light

- **Classical HVDC technology**
  - Mostly used for long distance point-to-point transmission
  - Requires fast communication channels between two stations
  - Large reactive power support at both stations
  - Thyristor valves are used.
  - Line or phase commutated converters are used.
- **HVDC-Light**
  - Power transmission through HVDC utilizing voltage source converters with insulated gate bipolar transistors (IGBT) which extinguishes the current more faster and with less energy loss than GTOs.

HVDC-Light

- It is economical even in low power range.
- Real and reactive power is controlled independently in two HVDC light converters.
- Controls AC voltage rapidly.
- There is possibility to connect passive loads.
- No contribution to short circuit current.
- No need to have fast communication between two converter stations.
- Operates in all four quadrants.
- PWM scheme is used.
- Opportunity to transmit any amount of current of power over long distance via cables.

HVDC-Light

- Low complexity-thanks to fewer components
- Small and compact
- Useful in windmills
- Offers asynchronous operation.

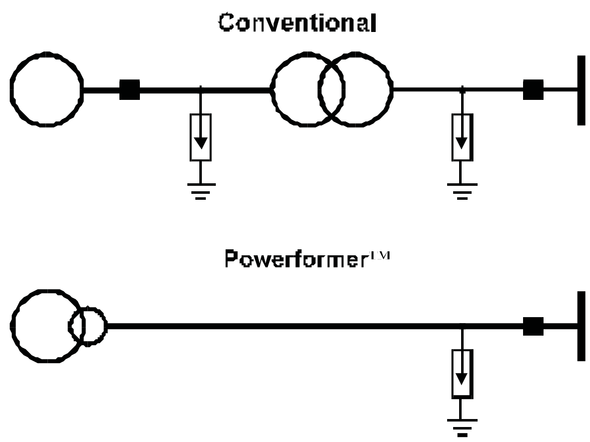
- **First HVDC-Light pilot transmission for 3 MW, ±10kV in March, 1997 (Sweden)**
- **First commercial project 50 MW, 70 kV, 72 km, in 1999.**

- Transmission system limitations:
  - **System Stability**
    - Transient stability
    - Voltage stability
    - Dynamic Stability
    - Steady state stability
    - Frequency collapse
    - Sub-synchronous resonance
  - **Loop flows**
  - **Voltage limits**
  - **Thermal limits of lines**
  - **High short-circuit limits**

FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

- **Developments in Generation side**
  - Powerformer Energy System
  - Distributed Generations
    - Wind Power (upto 6 MW)
    - Fuel Cells
    - Biomass etc.
  - Combined Cycle Power Plants

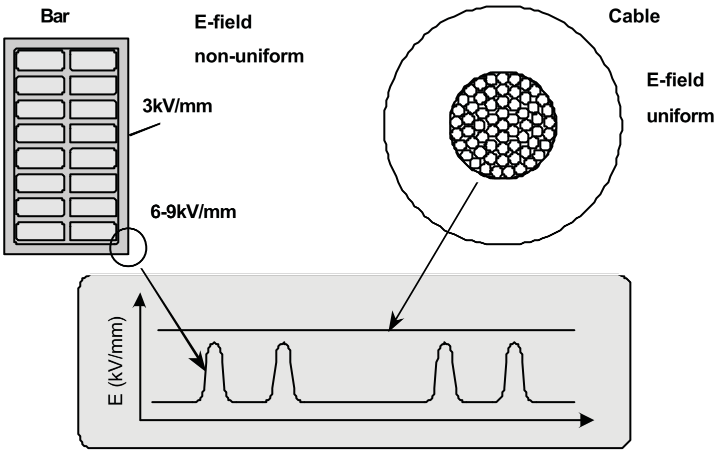
Powerformer Energy System



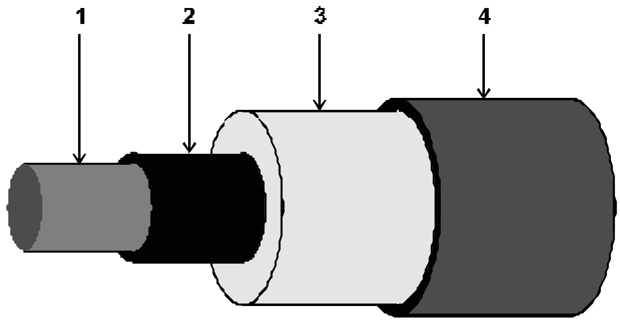
Powerformer™ Benefits

- Higher performance (availability, overload)
- Environmental improvement
- Lower weight
- Less total space requirement
- Lower cost for Civil Works
- Less maintenance
- Reduced losses
- Lower investment
- Lower LCC

Electrical Field Distribution



Stator winding



Conductor (1), Inner semi-conducting layer (2),
Insulation (3) and an outer semi-conducting layer (4).

Distributed Generation/Dispersed Generation

- ❖ DG includes the application of small generations in the range of **15 to 10,000 kW**, scattered throughout a power system
- ❖ DG includes all use of small electric power generators whether located on the utility system **at the site of a utility customer**, or **at an isolated site not connected to the power grid**.
- ❖ By contrast, **dispersed generation** (capacity ranges from **10 to 250 kW)**, a subset of distributed generation, refers to generation that is **located at customer facilities** or **off the utility system**.

- DG includes traditional -- **diesel, combustion turbine, combined cycle turbine, low-head hydro**, or **other rotating machinery** and renewable -- **wind, solar,** or **low-head hydro** generation.
- The **plant efficiency** of most existing **large central generation units** is in the range of **28 to 35%**.
- By contrast, **efficiencies of 40 to 55%** are attributed to **small fuel cells** and to various **hi-tech gas turbine** and **combined cycle units** suitable for DG application.
- Part of this **comparison** is **unfair**. Modern DG utilize prefect hi-tech materials and incorporating advanced designs that minimize wear and required maintenance and include extensive computerized control that reduces operating labor.

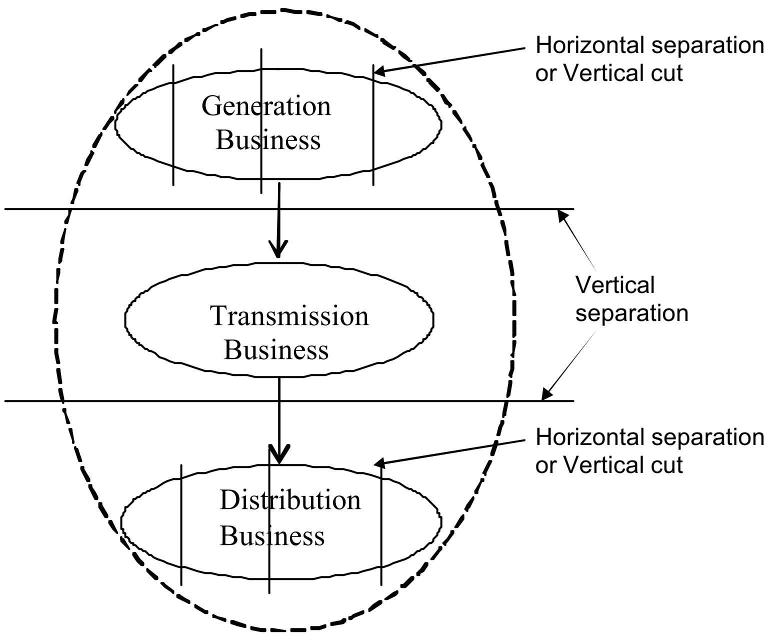
DG "Wins" Not Because It is Efficient, But Because It Avoids T&D Costs

Operational Changes

- Power System Restructuring (Privatization or Deregulation)
  - But not only Privatization

- **Deregulation is also known as**

  - Competitive power market
  - Re-regulated market
  - Open Power Market
  - Vertically unbundled power system
  - Open access



- **Why Restructuring of Electric Supply Industries?**
  - Better experience of other restructured market such as communication, banking, oil and gas, airlines, etc.
  - Competition among energy suppliers and wide choice for electric customers.
- **Why was the electric utility industry regulated?**
  - Regulation originally reduced risk, as it was perceived by both business and government.
  - Several important benefits:
    - It legitimized the electric utility business.

- **It gave utilities recognition and limited support from the local Govt. in approving ROW and easements.**
- **It assured a return on the investment, regulated as that might be.**
- **It established a local monopoly in building the system and quality of supply without competitors.**
- **Simplified buying process for consumers.**
- **Electricity of new and confusing to deal with the conflicting claims, standards and offerings of different power companies.**
- **Least cost operation.**
- **Meeting social obligations**
- **Hugh investments with high risk**

- **Forces behind the Restructuring are**
  - High tariffs and over staffing
  - Global economic crisis
  - Regulatory failure
  - Political and ideological changes
  - Managerial inefficiency
  - Lack of public resources for the future development
  - Technological advancement
  - Rise of environmentalism
  - Pressure of Financial institutions
  - Rise in public awareness
  - Some more . . . .

- **Reasons why deregulation is appealing**

- **What will be the transformation ?**
  - Vertically integrated => vertically unbundled
  - Regulated cost-based ==> Unregulated price-based
  - Monopoly ==> Competition
  - service ==> commodity
  - consumer ==> customer
  - privilege ==> choice
  - Engineers ➔ Lawyer/Manager

- **A number of questions to be answered**
  - Is a Restructuring good for our society?
  - What are the key issues in moving towards the restructuring ?
  - What are the implications for current industry participants?
  - What type of new participants will be seen and why ?
  - What should be structure of market and operation?
  - What might an electricity transaction of future look like?

- **Electricity Market is very risky**
  - Electricity is not storable in bulk quantity
  - End user demand is typically constant
  - Trading is directly related to the reliability of the grid
  - Demand and supply should be exact
  - Electricity prices are directly related with other volatile market participants.
  - Cost of continuity is more than cost of electric.

Electric Power

- Electricity must be
  - Economical
  - Secure
  - Stable
  - Reliable
  - Good quality
    - Power Quality is defined as "***any power problem manifested in voltage, current, and/or frequency deviations that results in the failure and/or mal-operation of end user's equipment.***

Quality of Supply?

Refers to: **Supply reliability + Voltage Quality**

- *Supply Reliability*: relates to the availability of power at given point of system (continuity).
- *Voltage Quality:* relates to the purity of the characteristics of the voltage waveform including the absolute voltage level and frequency.

QoS= "Uninterrupted supply of power with **sinusoidal** voltage and current waveform at acceptable frequency and voltage magnitude."

Quality of Service = Quality of Supply + Customer relations

Voltage or Power Quality

- Due to Disturbances e.g. transients (switching/ lightning), faults etc. (resulting in voltage sag, swell, oscillatory and impulsive waveform, interruption)
- Due to Steady State Variations e.g. nonlinear characteristics of loads, furnace/induction heating loads, switching of converters etc. (resulting in harmonics, notching and noise).

Effects of Poor Power Quality

➲ **Possible effects of poor power quality are:**

- **Maloperation (of control devices, mains signaling systems and protective relays)**
- **More loss (in electrical system)**
- **Fast aging of equipments.**
- **Loss of production**
- **Radio, TV and telephone interference**
- **Failure of equipments**

PQ DISTURBANCES AND THEIR CAUSES

PQ Disturbances

- Transients
- Short Duration Voltage Variations
- Long Duration Voltage Variations
- Interruptions
- Waveform Distortion
- Voltage Fluctuation (flicker)
- Frequency Variation
- Harmonics

Main causes of poor PQ

- Nonlinear loads
- Adjustable-speed drives
- Traction drives
- Start of large motor loads
- Arc furnaces
- Intermittent loads transients
- Lightning
- Switching, transients
- Faults

Some typical PQ disturbances

Voltage sags

Major causes: faults, starting of large loads, and

Major consequences: shorts, accelerated aging, loss of data or stability, process interrupt, etc.

Capacitor switching transients

Major causes: a power factor correction method

Major consequences: insulation breakdown or sparkover, semiconductor device damage, shorts, accelerated aging, loss of data or stability

Harmonics

Major causes: power electronic equipment, arcing, transformer saturation

Major consequences: equipment overheating, high voltage/current, protective device operations

Lightning transients

Major causes: lightning strikes

Major consequences: insulation breakdown or sparkover, semiconductor device damage, shorts, accelerated aging, loss of data or stability

High impedance faults

(One of the most difficult power system protection problems)

Major causes: fallen conductors, trees (fail to establish a permanent return path)

Major consequences: fire, threats to personal safety

Service reliability indicators

Reliability of supply can be defined as the ability of the power system to deliver electrical power to a given consumer over a specified period of time.

For a given customer, the reliability of supply can usually be assessed by two parameters:

- –The number of Interruption during a year
- –The average duration of an interruption

Indicators based on system performance

- SAIDI: System Average Interruption Duration Index (Minutes/ customer . year)

$$\frac{\sum \text{Duartion of all Customers interruptions}}{\text{Total no. of Customers}}$$

- SAIFI: System Average Interruption Frequency Index (Interruptions/ customer. year)

$$\frac{\text{Total annual no. of interruptions}}{\text{Total no. of Customers}}$$

- ASAI: Average Service Availability Index (% or pu)

$$\frac{(\text{No.of Customers} \times 8760) - \sum \text{Duartion of all Customers interruptions}}{\text{Total no. of Customers} \times 8760}$$

- ASAI: Average Service Unavailability Index =1-ASAI
- AENS: Average Energy Not Supplied (kWh/customer.year)

$$= \frac{\text{Energy Not Supplied}}{\text{Number of Customers}}$$

- **Indicators related to individual customer**

- CAIDI: Customer Average Interruption Duration Index Number (Minutes/ year)

$$= \frac{\sum \text{Duartion of all Customers interruptions}}{\text{Total no. of Interruptions}}$$

- CAIFI: Customer Average Interruption Frequency Index Number

$$= \frac{\text{Total annual no. of interruptions}}{\text{No. of Customers affected}}$$

- **CTAIDI: Customer Total Average Interruption Duration Index (Minutes/ year)**

$$= \frac{\sum \text{Duartion of all Customers interruptions}}{\text{Total no. of Customers affected}}$$

- **MICIF: Maximum Individual Customer Interruption Frequency (occurrences /year)**

  = max. interruptions experienced by any customer during the period

- **MICID: Maximum Individual Customer Interruption Duration (occurrences /year)**

  = max. total interruptions time experienced by any customer during the period

- **MAIFI : Momentary Average Interruption Frequency Index**

  relates to momentary interruptions of < 3 . 5 min duration

Reliability index monitoring in India

Reliability monitoring is based on the following parameters:

- **No. of outages of 11 kV feeders.**
- **Duration of outages of 11 kV feeders.**

Feeder Reliability

$$\frac{A - B}{A} \times 100$$

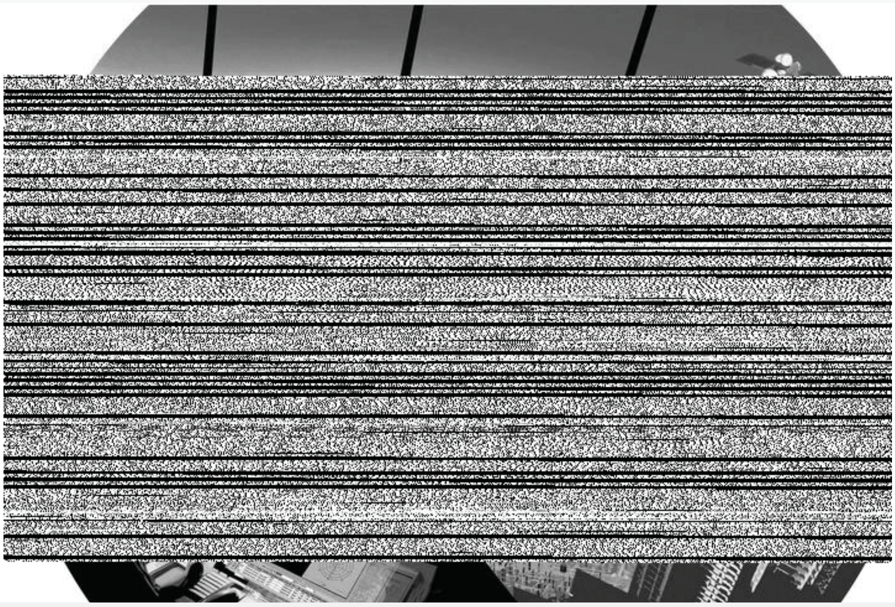
where A = No of feeders x24x60xNo of days in a month

B = Outage duration in minutes

Future Technologies - Intelligent Grid

- **Need for infusion of Intelligence in the Grid for :**
  - Knowing the state of the Grid
  - Predict the catastrophic situation in advance
  - Take corrective actions accordingly so as to protect the grid
- **Features of Intelligent Grid**
  - adoptive islanding,
  - self-healing
  - demand/generation management etc.
- **To Accomplish, need for Wide Area Monitoring System (WAMS).**
  - To gather and processing the data from any number of GPS-synchronized phasor measurement units (PMUs) along with a system monitoring centre and take corrective action through advance software and control system

Intelligent Grid - WAMS



Leader not a follower

Intelligent Grid to Smart Grid

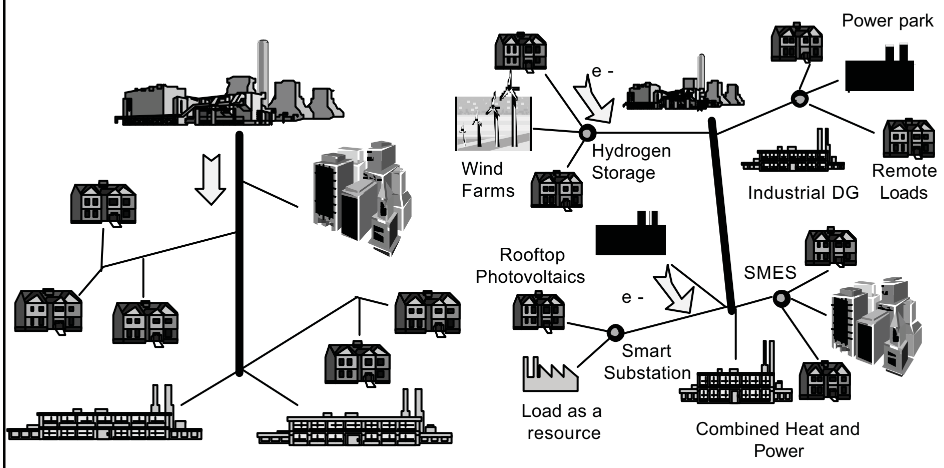
Present Power System

- Heavily relying on fossil fuels
- Generation follows load
- Limited ICT use

Future Power System

- More use of RES, clean coal, nuclear power
- Load follows generation
- More ICT & Smart meter use

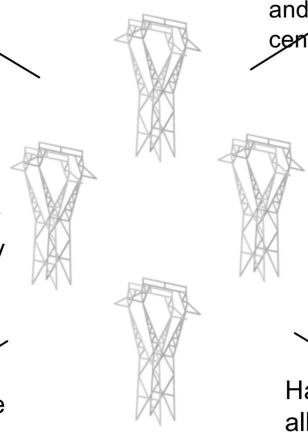
Today's Electricity … → *Tomorrow's Choices …*



Future Grid – Smart(er) Grid

Wide area monitoring and control systems

Coordinated, full energy management and full integration of DG with large central power generation



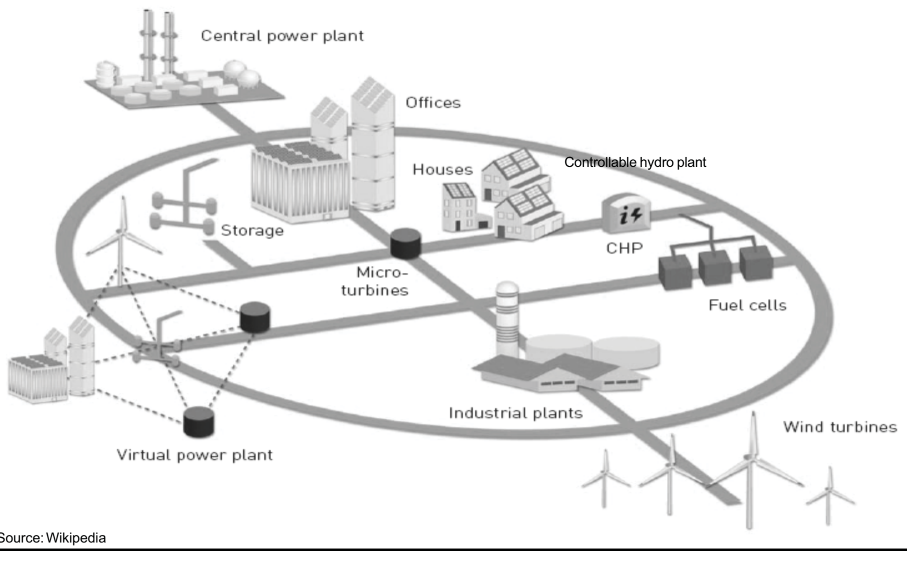
Extensive small, distributed generation close to end user

Secure, reliable and green power supply

Customer driven value added services

Harmonized legal framework allowing cross border power trading

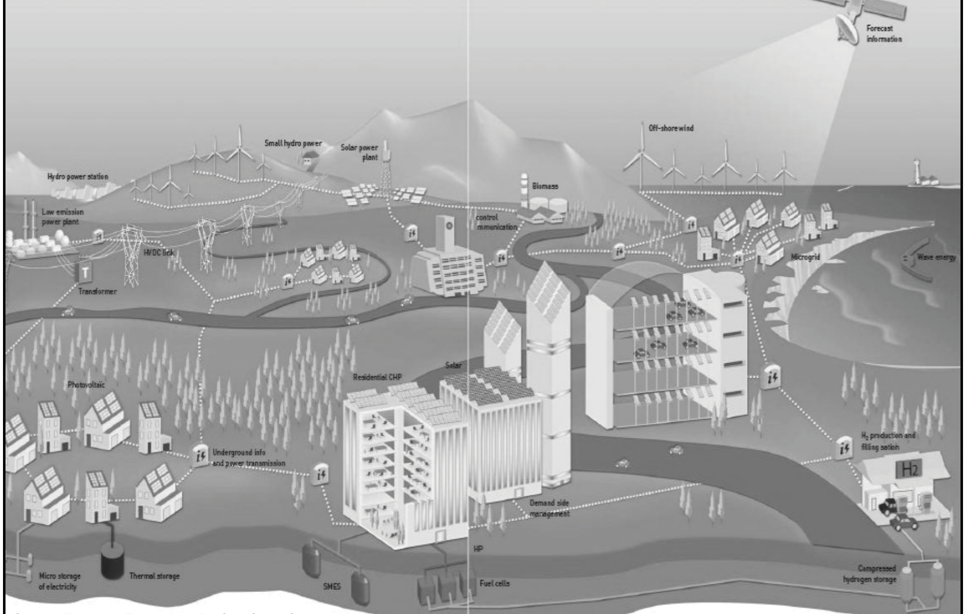
What a Smart Grid would look like? *Distributed, Networked*



Source: Wikipedia

What a Smart Grid would look like?

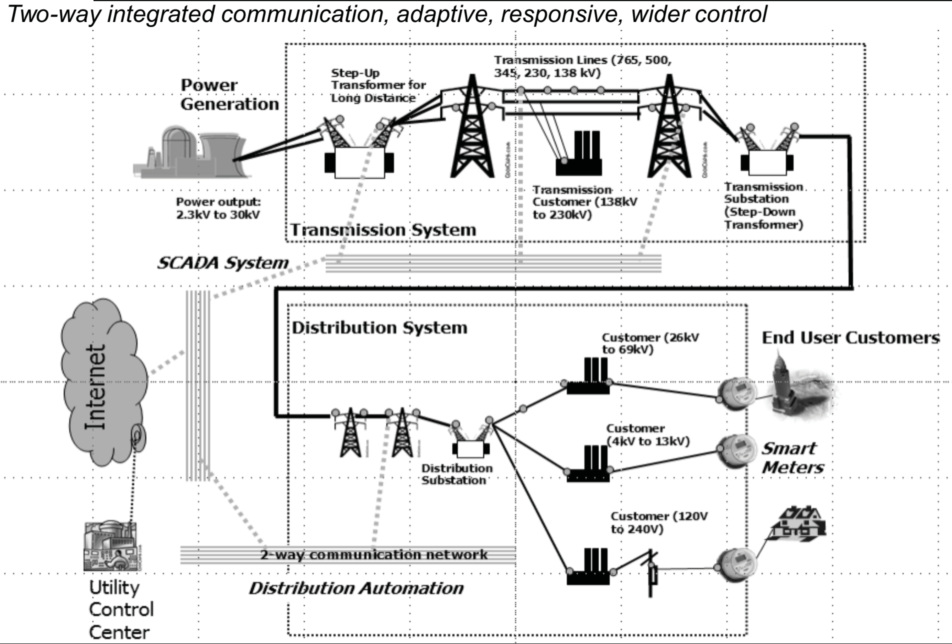
Green, Environment friendly



Source: European Technology PlatformSmartGrids

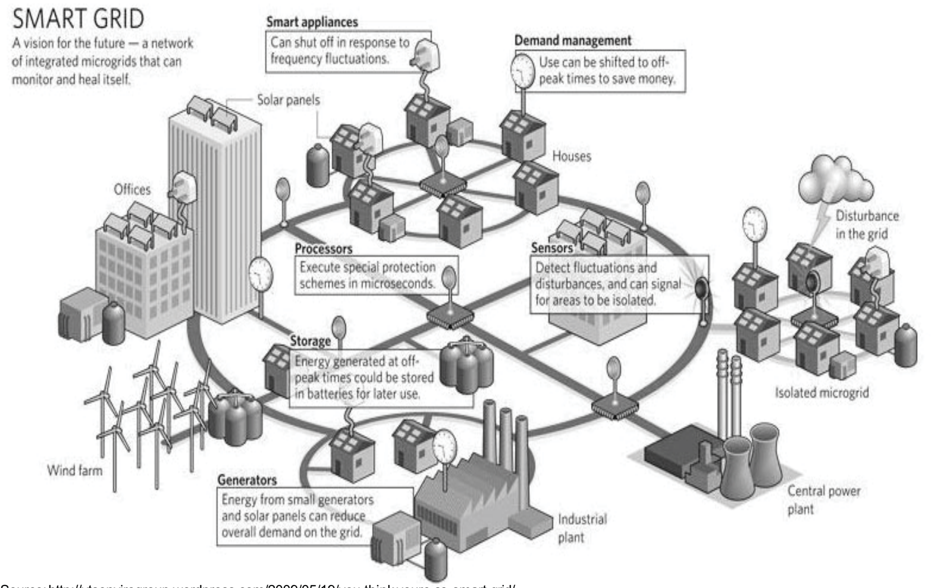
What a Smart Grid would look like?

Two-way integrated communication, adaptive, responsive, wider control



What a Smart Grid would look like?

Sensors throughout, self healing & monitoring, remote check & test



Source: http://vtsenvirogroup.wordpress.com/2009/05/19/you-think-youre-so-smart-grid/

Features of a Smart Grid

Ref: DOE document at http://www.oe.energy.gov/smartgrid

Self-Healing to correct problems early

Interactive with consumers and markets

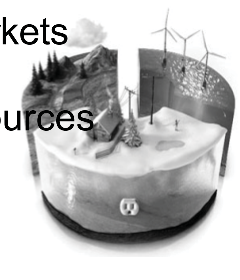
Optimized to make best use of resources

Predictive to prevent emergencies

Distributed assets and information

Integrated to merge all critical information

More Secure from threats from all hazards

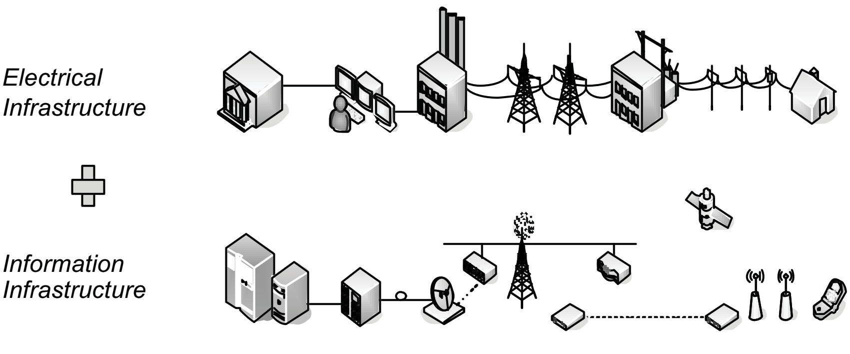


Existing Grid	Intelligent Grid
Centralized Generation	Distributed Generation
One-Way Communication	Two-Way Communication
Electromechanical	Digital
Hierarchical	Networked
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive/Wider Control

Ref: Hassan Farhangi, "The Path of the Smart Grid", *IEEE Power and Energy Magazine*, Jan. 2010, pp.18-28

Merging Two Technologies

The integration of two infrastructures… securely…



Source: EPRI® Intelligrid at http://intelligrid.epri.com

Smart Grid Advantages

Operational Efficiency

- Reduced Onsite Premise Presence / Field Work Required
- Shorter Outage Durations
- Optimized Transformer Operation
- Standards & Construction
- Improved Network Operations
- Reduce Integration & IT maintenance cost
- Condition-based Asset Maintenance / Inspections

Energy Efficiency

- Reduced Energy Losses
- Active/Passive Demand-side Management

Smart Grid

Customer Satisfaction

- Enable Customer Self-Service / Reduce Call Center Inquiries
- Improved Revenue Collection

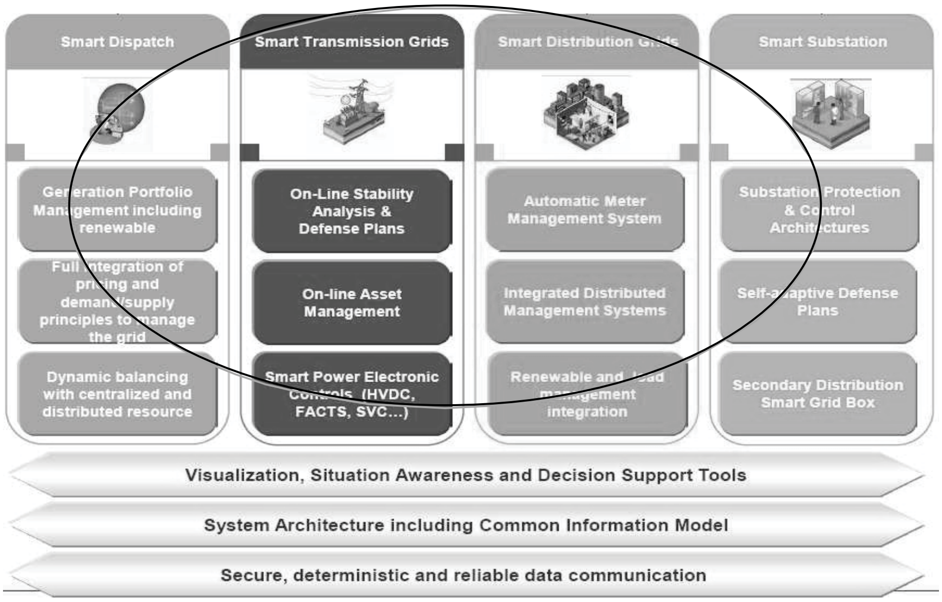
Environmental Impact

- Reduced Greenhouse Gas Emissions
- Delayed Generation & Transmission Capital Investments

Smart Grid : Building Blocks

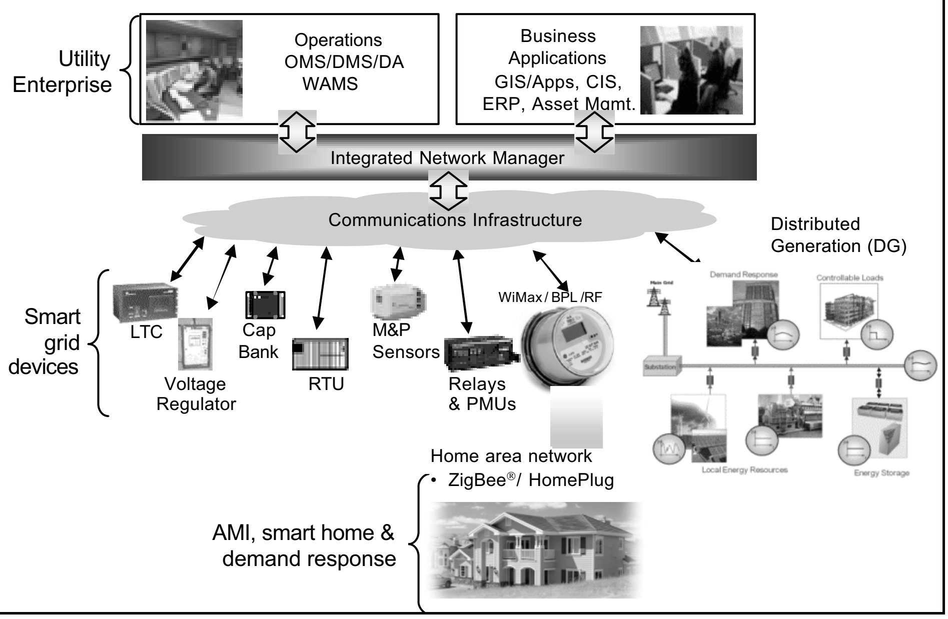
- **Advanced Metering & Communication**
  - Smart Meters (single phase & polyphase), 2-way communication, interface to enterprise applications, Wide Area Monitoring System
- **Distribution Automation**
  - Fault Detection, Isolation, Restoration (FDIR), Integrated Volt/VAR management, including switched capacitors & voltage regulator
- **Substation Automation/M&D**
  - Substation controller and transformer monitoring and diagnostics
- **Distribution Operations**
  - DMS/OMS software and interface to existing applications, control center digitization, and enterprise integration
- **Utility Enterprise Applications**
  - Electric, Gas & Telecommunications utility geospatial based applications, DSM application, and advanced analytics & visualization

Smart Grid Environment

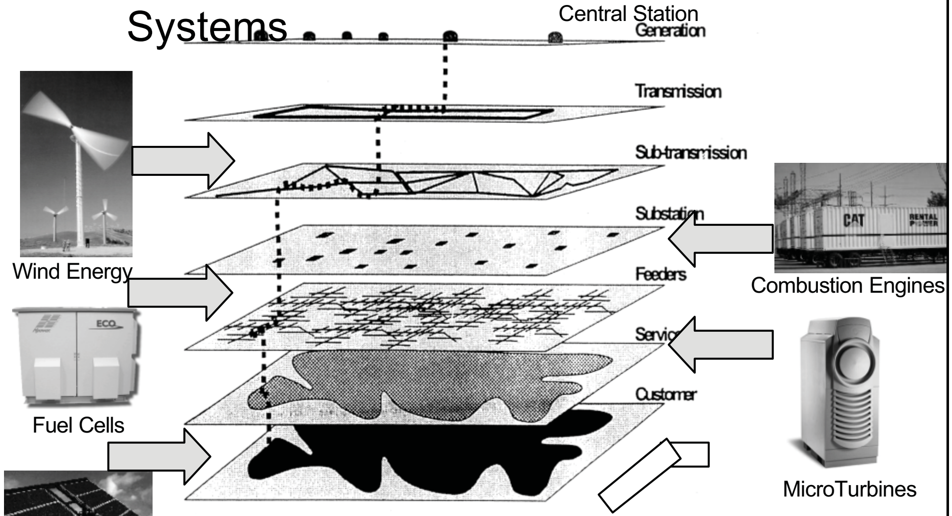


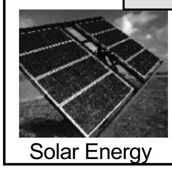
Source: Generation Dispatch, AREVA – IEEE Smart Grid Conference January 2010.

Smart Grid Architecture

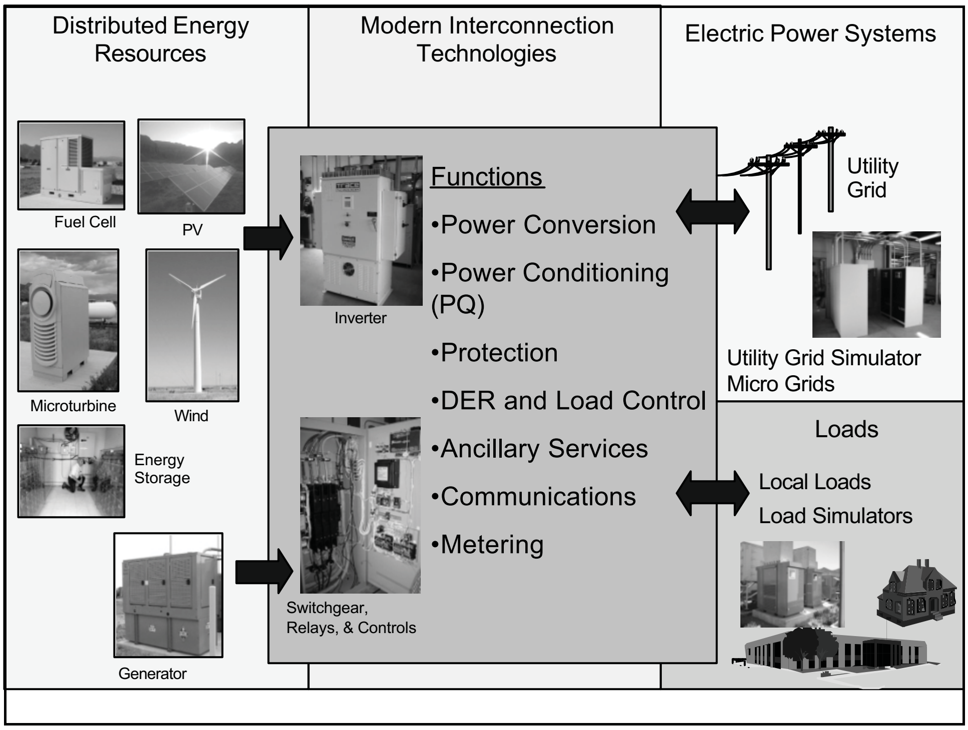


Interconnecting Distributed Power Systems





The overall power system is traditionally viewed in terms of 7 layers; each performing its function from central station generation supplying power out to customers.



Thank You .. ?