Emerging Trends and Challenges in Electric Power Systems

Indian Institute of Technology Mandi

Dr. Bharat Singh Rajpurohit

Objective

- Introduction to Indian power systems and emerging trends
- Case Studies

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 1886 1889	Motors were developed by Frank Sprague 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 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)

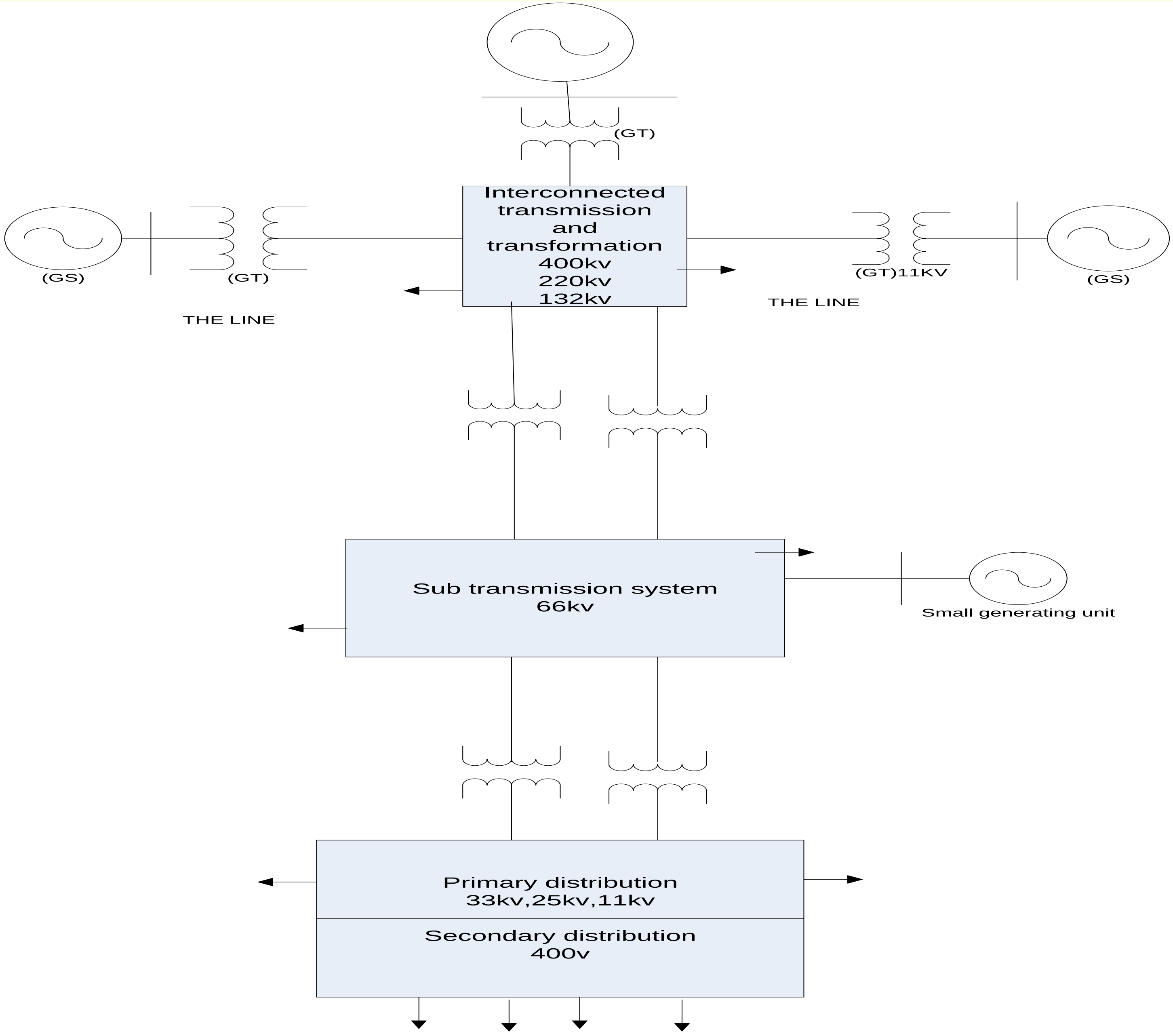
	Early Voltage (Highest)
1922	165 kV
1923	220 kV
1935	287 kV
1953	330 kV
1965	500 kV
1966	735 kV
1969	765 kV
19902	1100 kV
000s	1200 kV
	Standards are 115, 138, 161, 230 kV – HV 345, 400, 500 kV - EHV 765, 1100 1200 kV - UHV
	Earlier Frequencies were 25, 50, 60, 125 and 133 Hz; USA - 60 Hz and some countries - 50 Hz

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

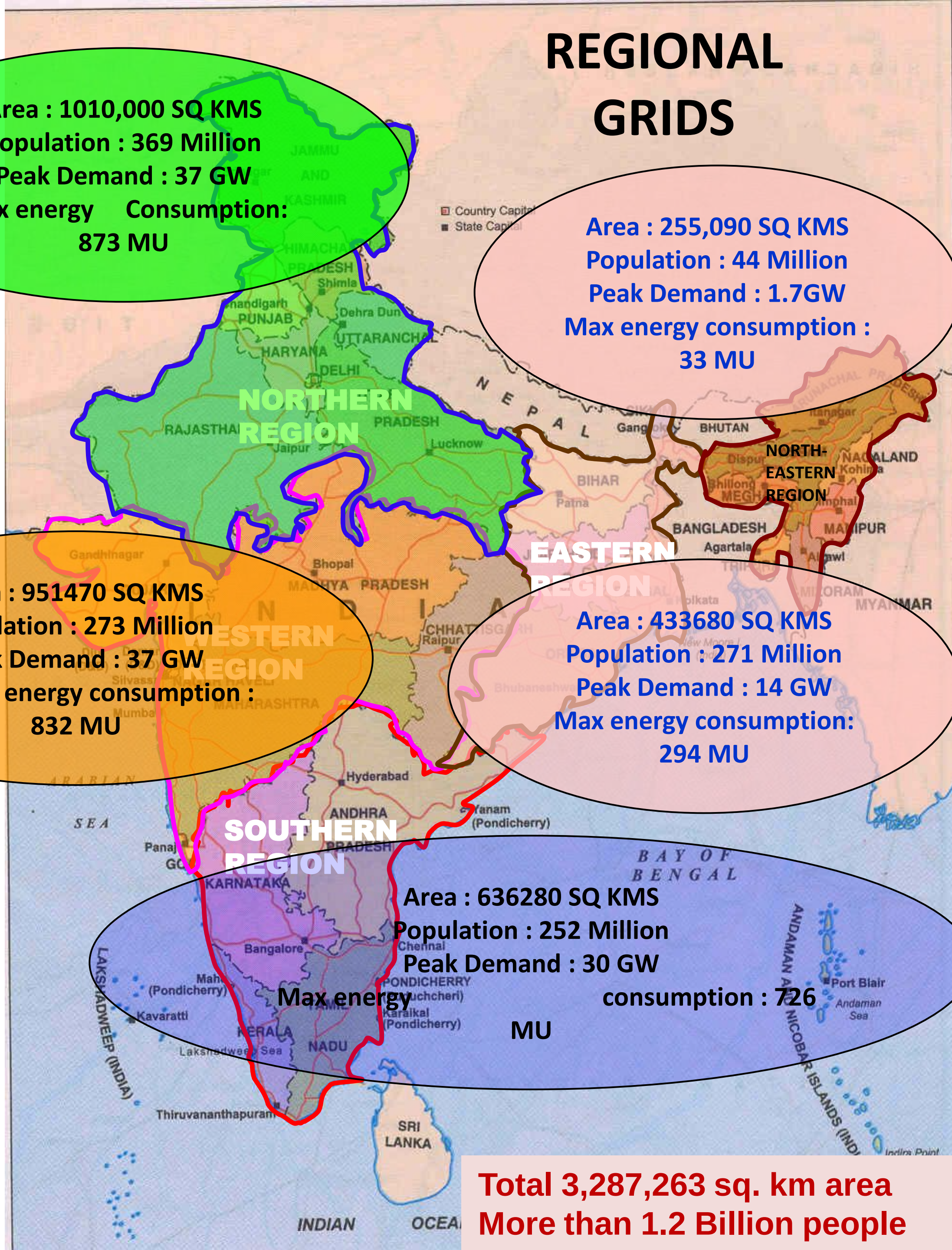
Limitations of HVAC Transmission

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

Structure of Power System



REGIONAL GRIDS



Northern Region
Area : 1010,000 SQ KMS
Population : 369 Million
Peak Demand : 37 GW
Max energy Consumption: 873 MU

North-Eastern Region
Area : 255,090 SQ KMS
Population : 44 Million
Peak Demand : 1.7GW
Max energy consumption : 33 MU

Western Region
Area : 951470 SQ KMS
Population : 273 Million
Peak Demand : 37 GW
Max energy consumption : 832 MU

Eastern Region
Area : 433680 SQ KMS
Population : 271 Million
Peak Demand : 14 GW
Max energy consumption: 294 MU

Southern Region
Area : 636280 SQ KMS
Population : 252 Million
Peak Demand : 30 GW
Max energy consumption : 726 MU

ALL INDIA INSTALLED CAPACITY

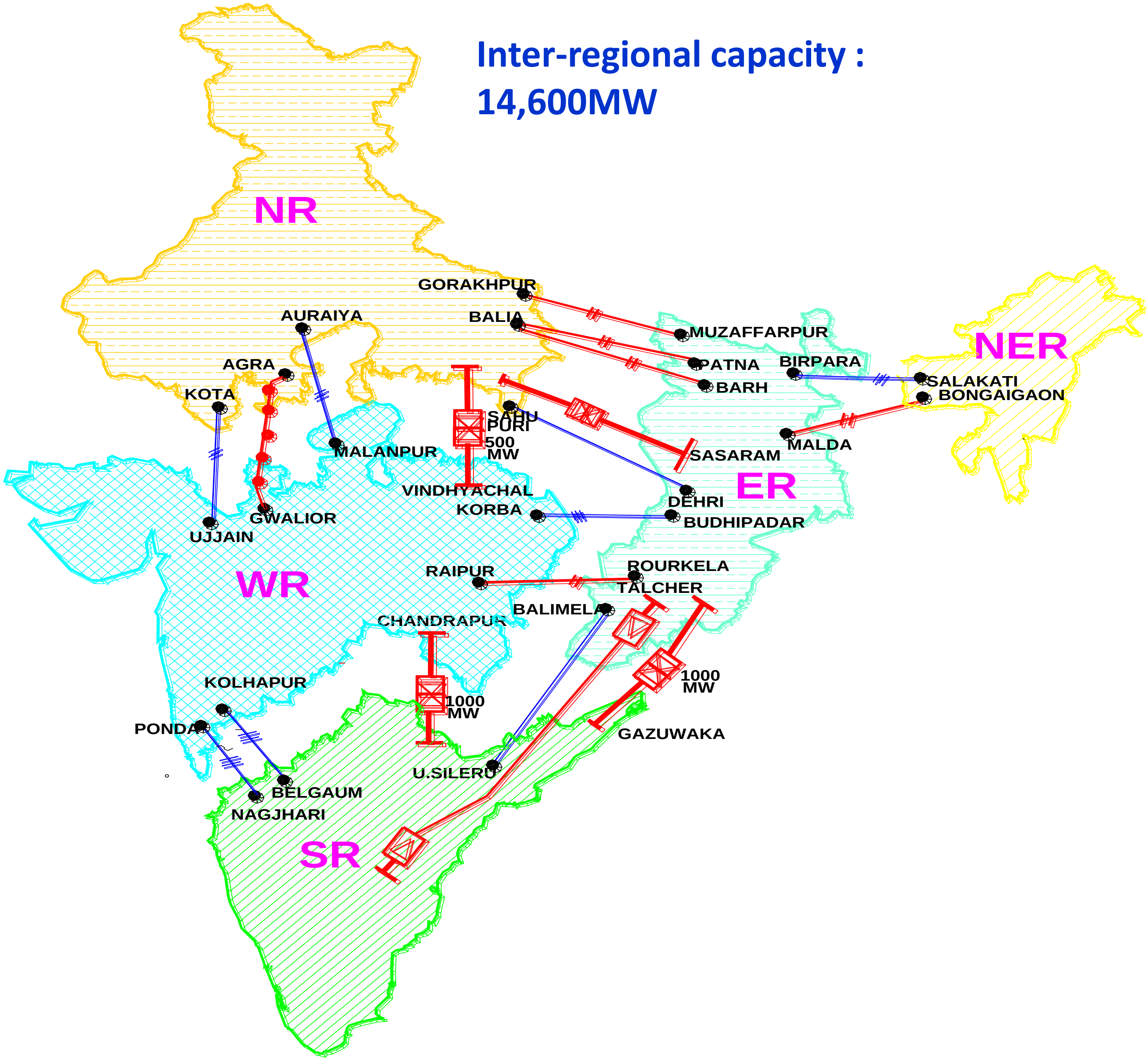
NORTH	:-	53.9 GW
EAST	:-	26.3 GW
SOUTH	:-	52.7 GW
WEST	:-	64.4 GW
NORTH-EAST	:-	2.4 GW
TOTAL	:-	**200 GW**

Total 3,287,263 sq. km area
More than 1.2 Billion people

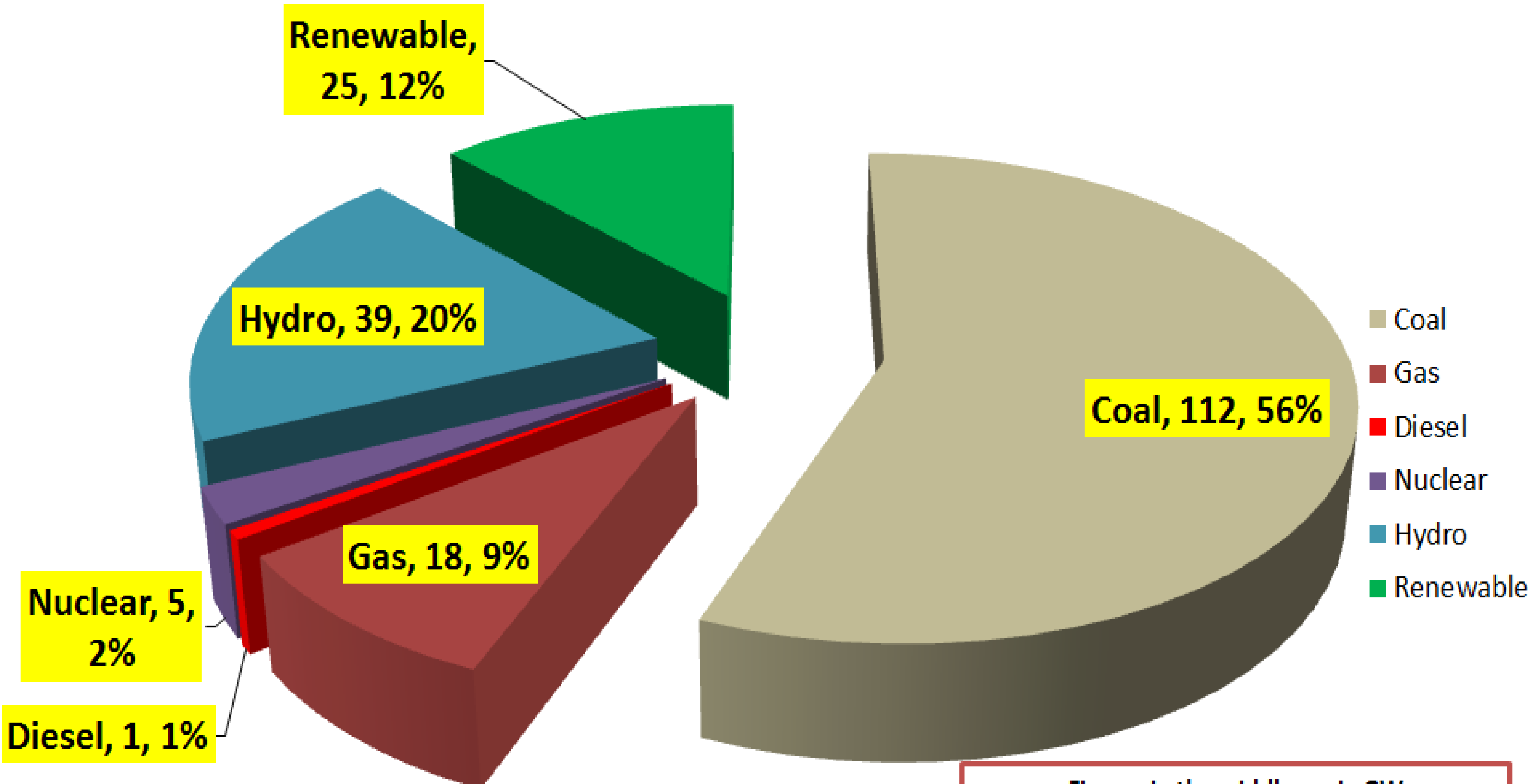
As on 31st March 2012

Inter-regional links – At present

Inter-regional capacity :
14,600MW



Installed Capacity in India-Source Wise
As on 31 Mar 2012

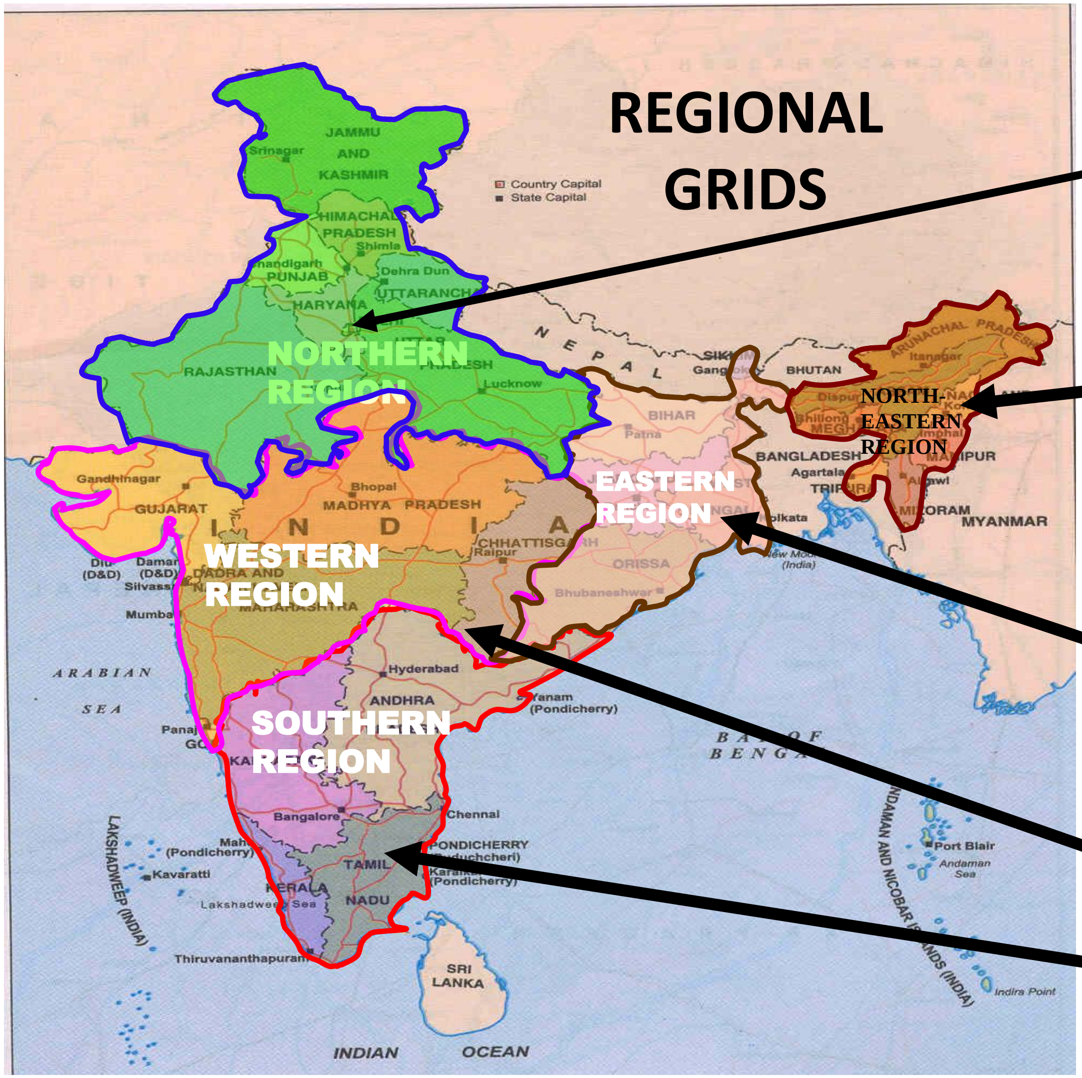


Figures in the middle are in GW

Total: 200 GW

Based on Monthly Review of Power SectorMar 2012, www.cea.nic.in

Peculiarities of Regional Grids in India



Deficit Region

Snow fed – run-of -the -river hydro

Highly weather sensitive load

Adverse weather conditions: Fog & Dust Storm

Very low load

High hydro potential

Evacuation problems

Low load

High coal reserves

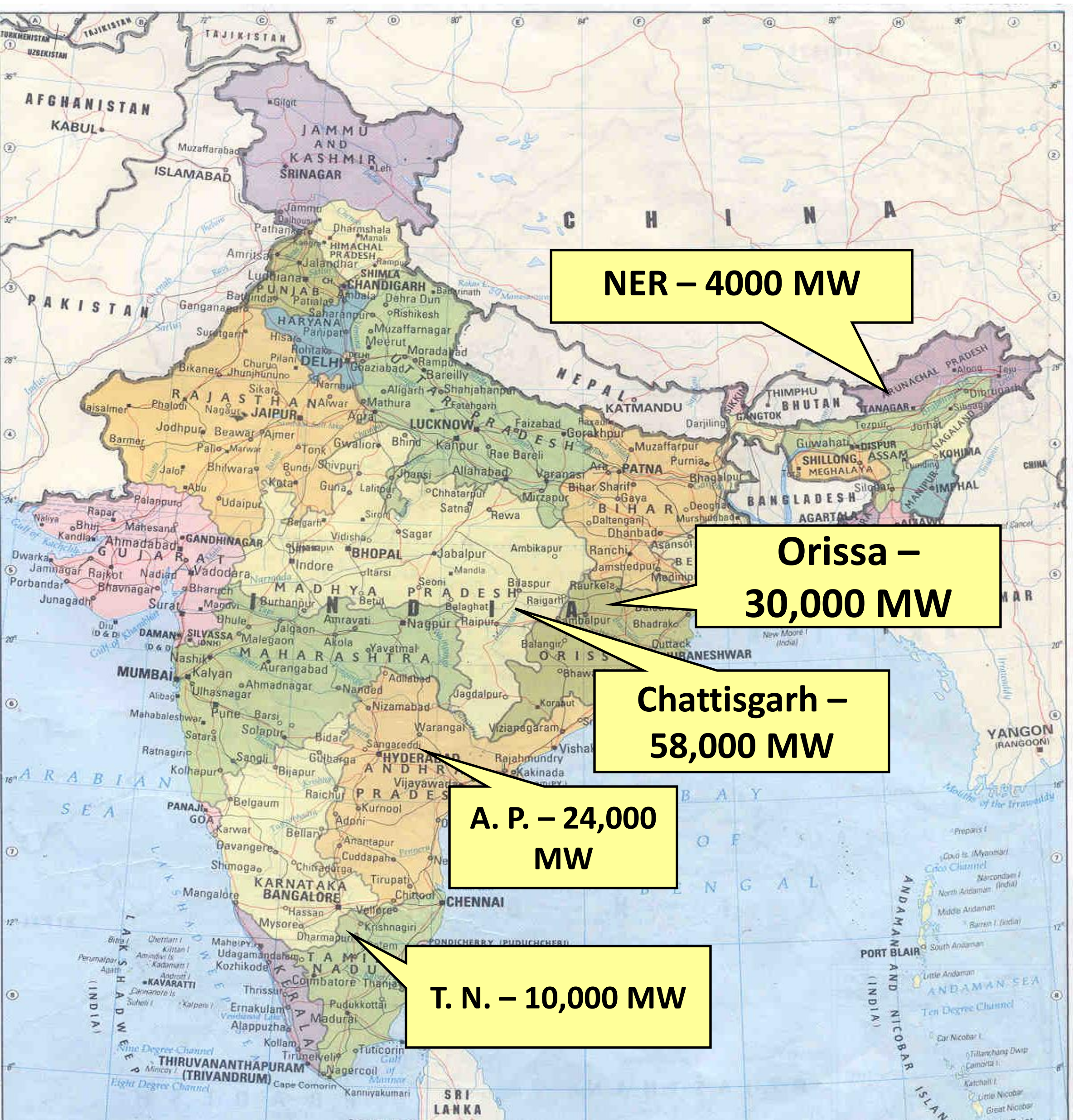
Pit head base load plants

Industrial load and agricultural load

High load (40% agricultural load)

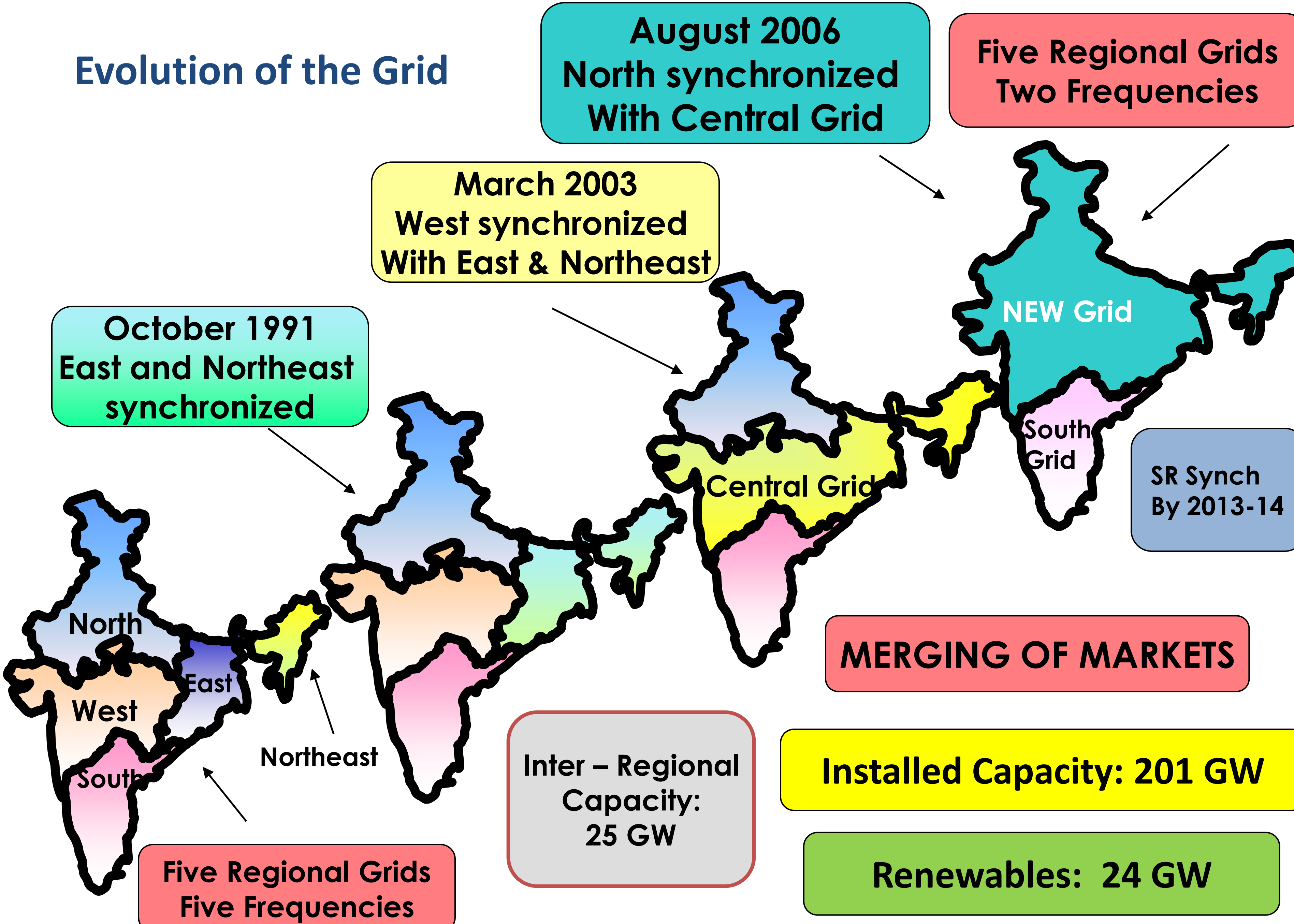
Monsoon dependent hydro

Concentrated Generation Pockets



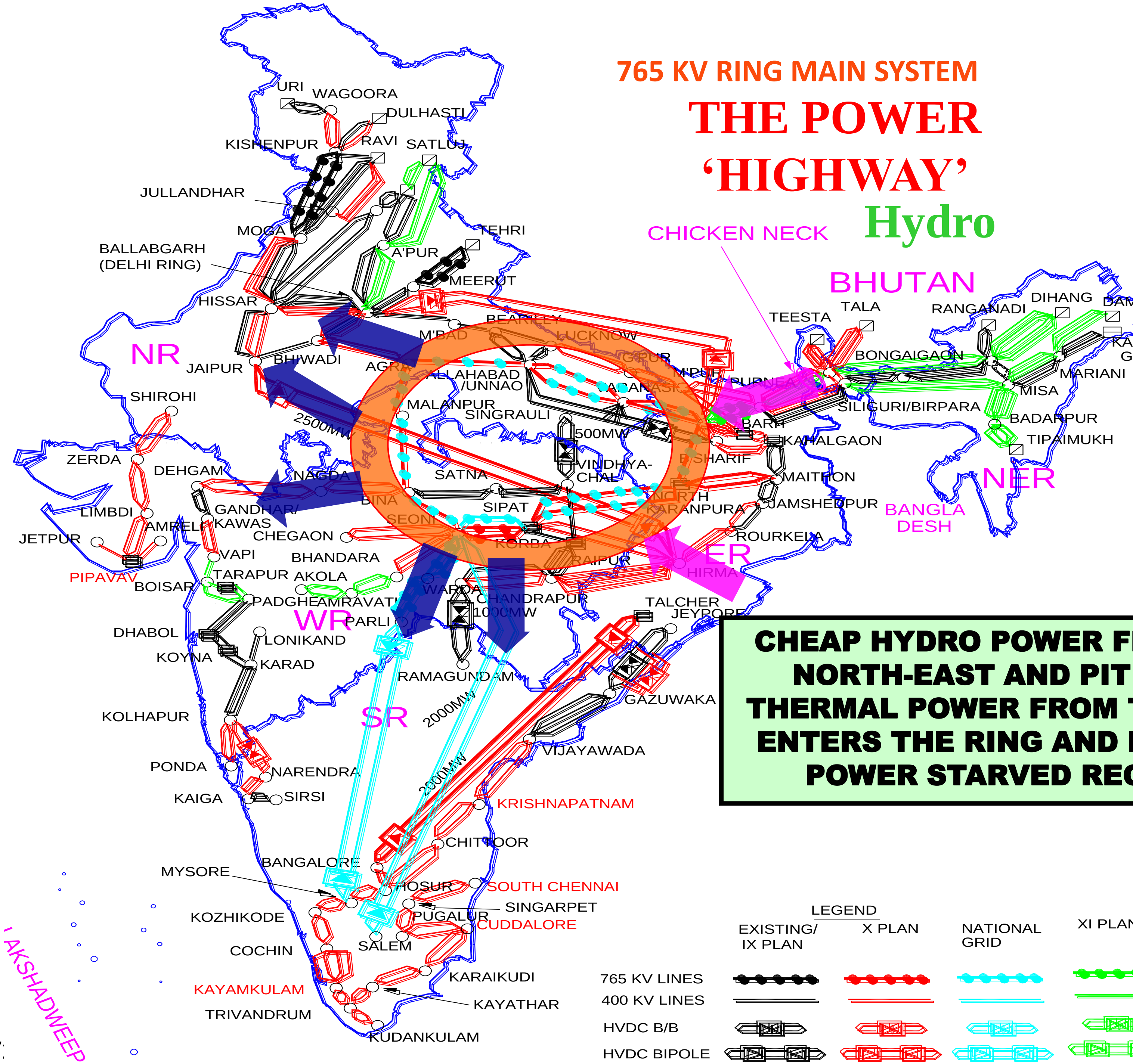
- **Massive investment by private sector**
  - IPPs
  - Merchant Plants
- **New challenges**
  - New actors in the arena
  - Connectivity and Access to grid
  - Control Area Jurisdiction
  - Access to Market
  - Breach of PPAs
  - Transfer Capability
- **Ultra – Mega Power Projects**
  - 4000 MW Capacity
  - Super – Critical Technology
- **Upcoming Nuclear Stations**
  - 1000 MW Sets

Evolution of the Grid



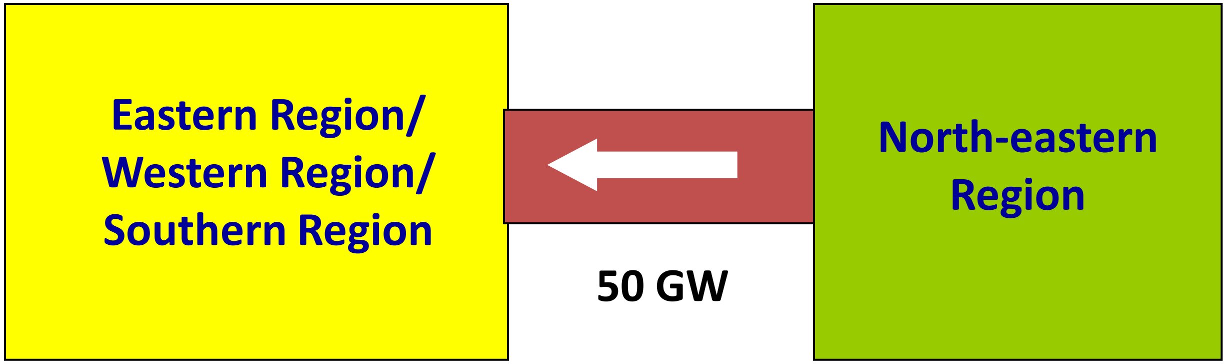
765 KV RING MAIN SYSTEM

THE POWER 'HIGHWAY'



CHEAP HYDRO POWER FROM THE NORTH-EAST AND PIT HEAD THERMAL POWER FROM THE EAST ENTERS THE RING AND EXITS TO POWER STARVED REGIONS

Transmission System through Narrow Area



- **Requirement of Power Flow between NER & ER/WR/NR: 50 GW**
- **Required Transmission Capacity : 57.5 GW (15% redundancy)**
- **Existing & planned Capacity : 9.5 GW**
- **Additional Trans. Capacity to be planned : 48 GW**

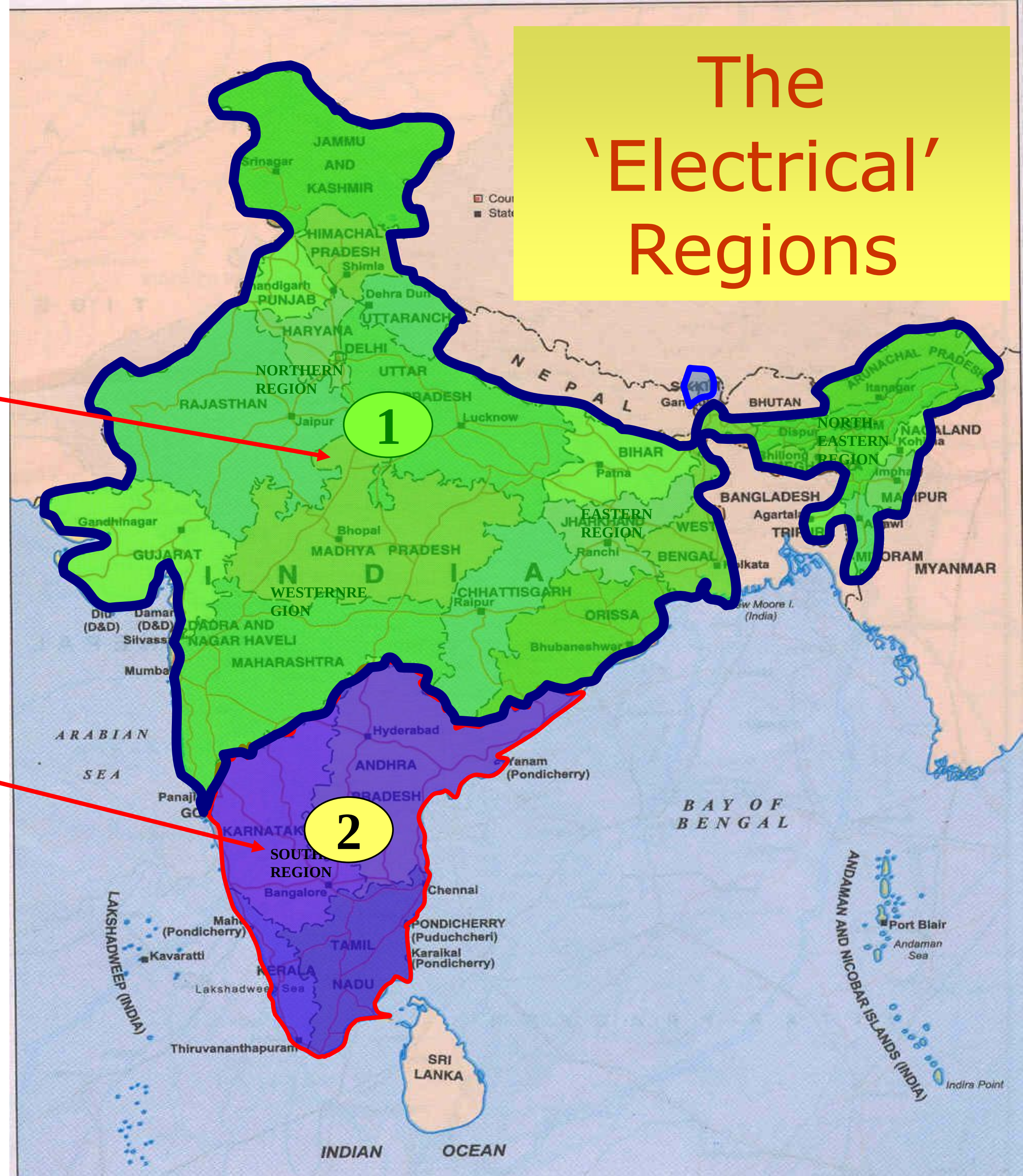
Options :
1. ±800kV HVDC : 8nos.
2. ±800kV HVDC : 5nos.; 765kV EHVAC : 6nos.
3. ±800kV HVDC : 4nos.; 1200kV UHVAC : 2nos.

- **Selection of Next Level Transmission Voltage i.e. 1200kV UHVAC in view of :**
  - Loading lines upto **Thermal Capacity(10000 MW)** compared to **SIL(6000 MW)**
  - Saving **Right of Way**

The 'Electrical' Regions

'N-E-W' Grid

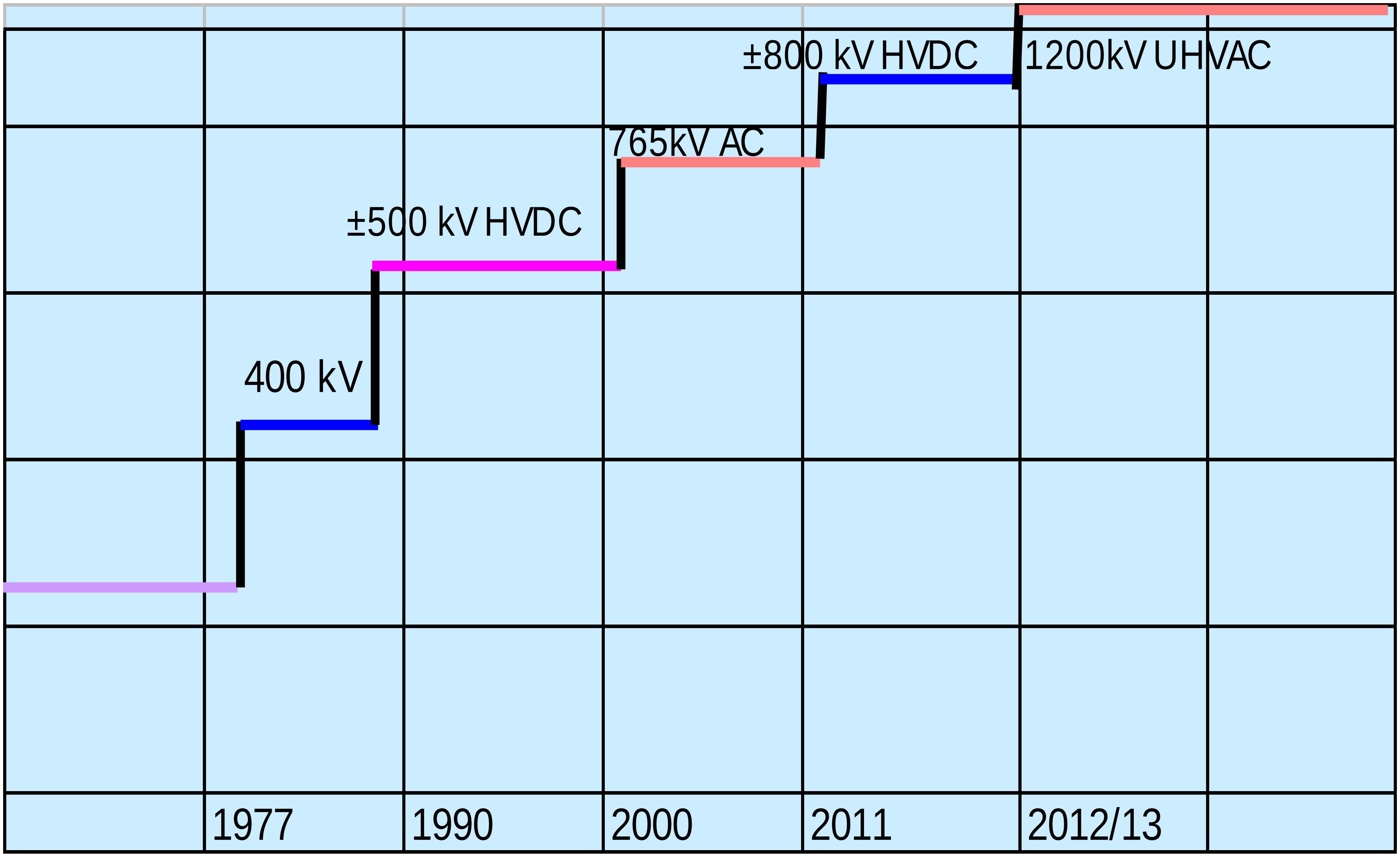
SOUTH Grid



Indian Power System - Present

- Transmission Grid Comprises:
  - 765kV/400kV Lines - 77,500 ckt. km
  - 220/132kV Lines - 114,600 ckt. km
  - HVDC bipoles - 3 nos.
  - HVDC back-to-back - 7 nos.
  - FSC – 18 nos.; TCSC – 6 nos.
- NER, ER, NR & WR operating as single grid of 90,000MW
- Inter-regional capacity : 14,600 MW

Pushing Technological Frontiers



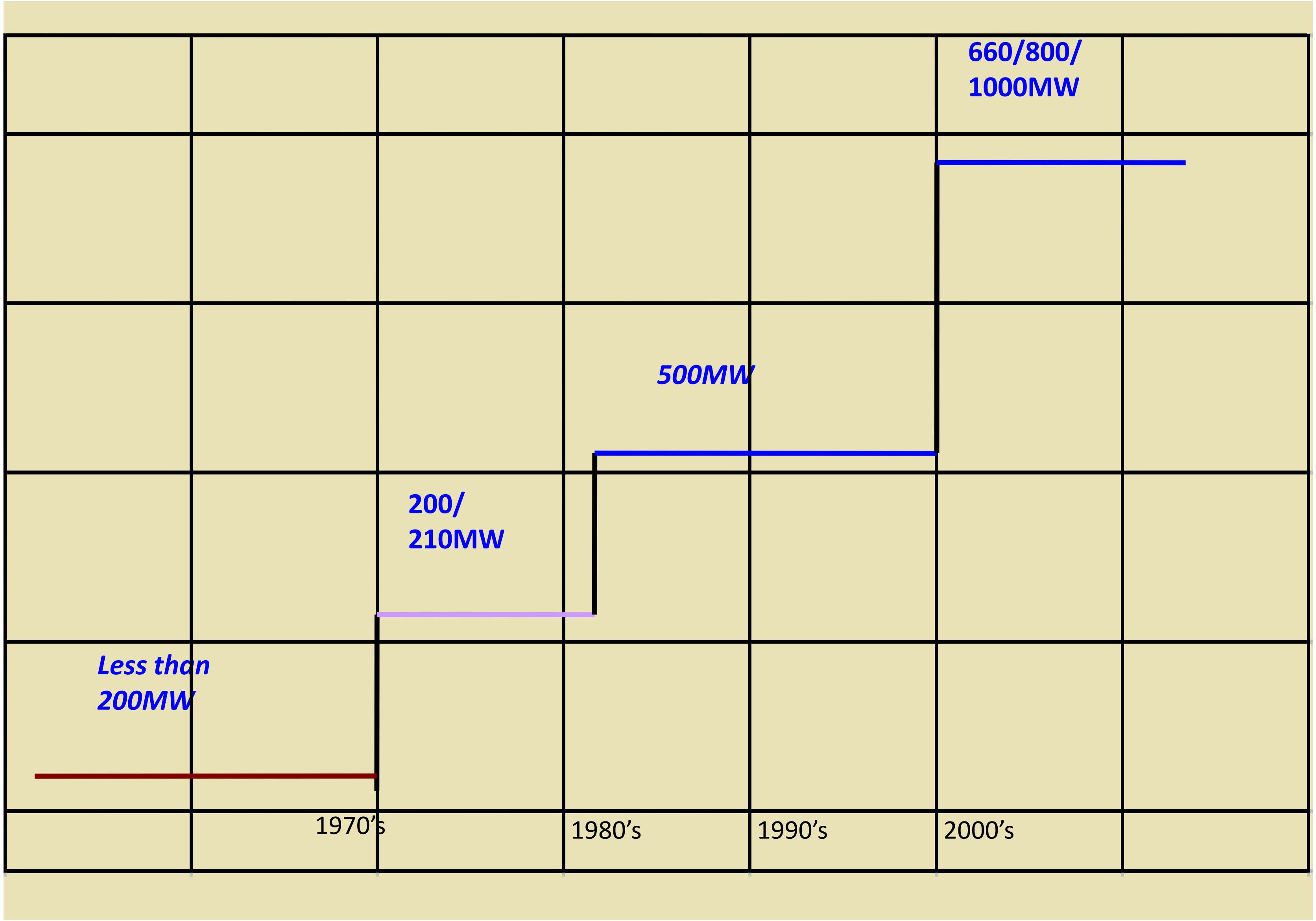
Line Parameters

- Line parameters of 1200kV/765kV/400kV Transmission System

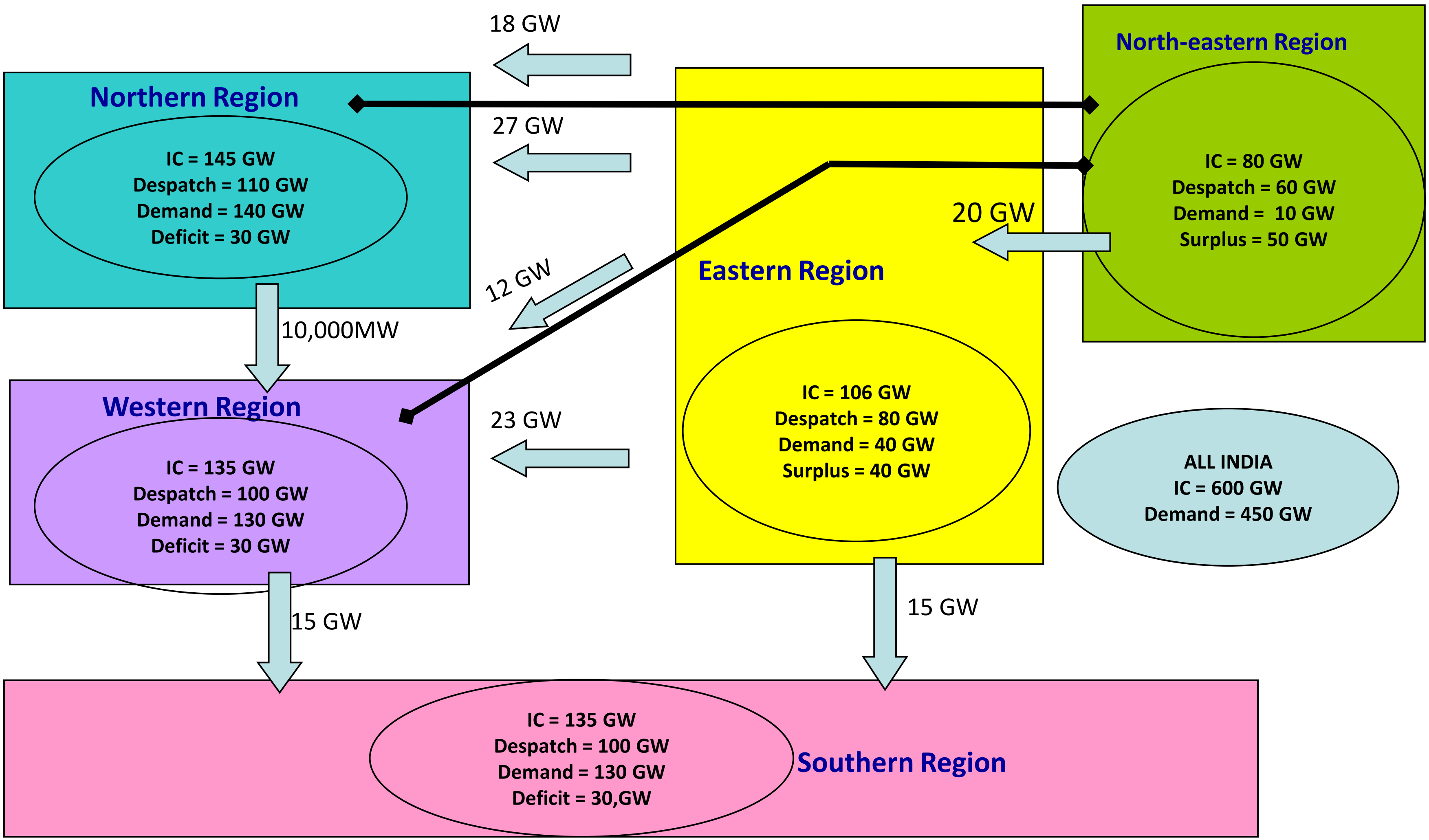
	1200 kV	765kV	400kV
Nominal Voltage (kV)	1150	765	400
Highest voltage(kV)	1200	800	420
Resistance (pu/km)	4.338×10^{-7}	1.951×10^{-6}	1.862×10^{-5}
Reactance (pu/km)	1.772×10^{-5}	4.475×10^{-5}	2.075×10^{-4}
Susceptance (pu/km)	6.447×10^{-2}	2.4×10^{-2}	5.55×10^{-3}
Surge Impedance Loading (MW)	6030	2315	515

Base kV :1200kV/765kV/400kV; *Base MVA :100 MVA*

Adoption of Generating unit size

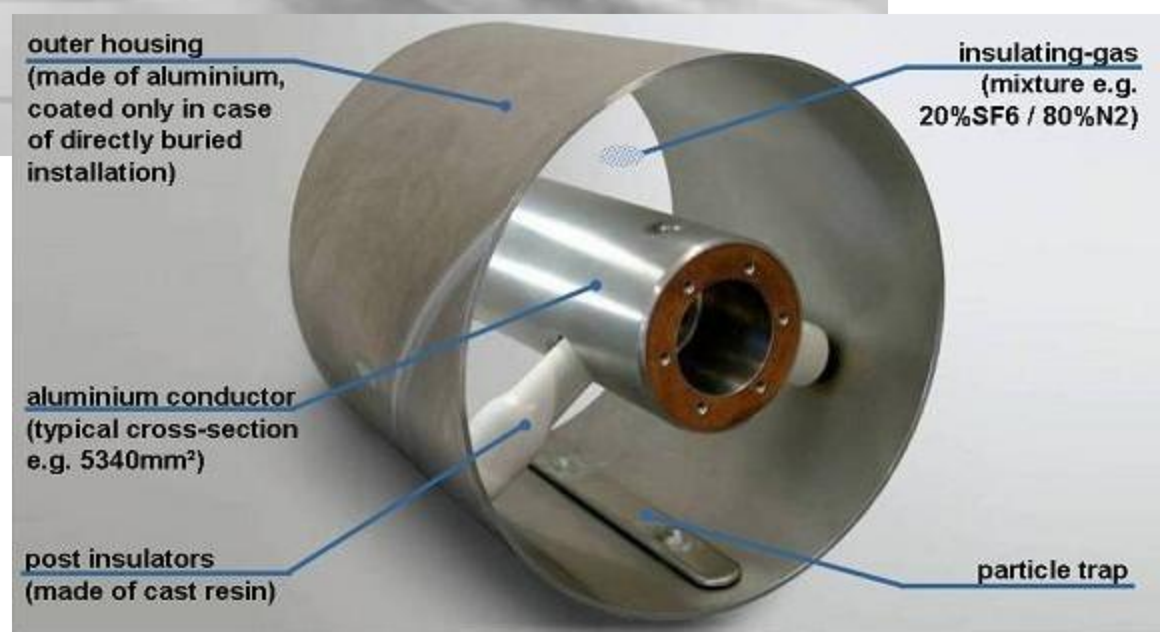


Likely power transfer requirement between various regions by 2022 & beyond



New Transmission Technologies

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



outer housing
(made of aluminium,
coated only in case
of directly buried
installation)
insulating-gas
(mixture e.g.
20%SF6 / 80%N2)
aluminium conductor
(typical cross-section
e.g. 5340mm²)
post insulators
(made of cast resin)
particle trap

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.
  - http://www.energy.siemens.com/hq/en/power-transmission/gas-insulated-transmission-lines.htm#content=Description

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

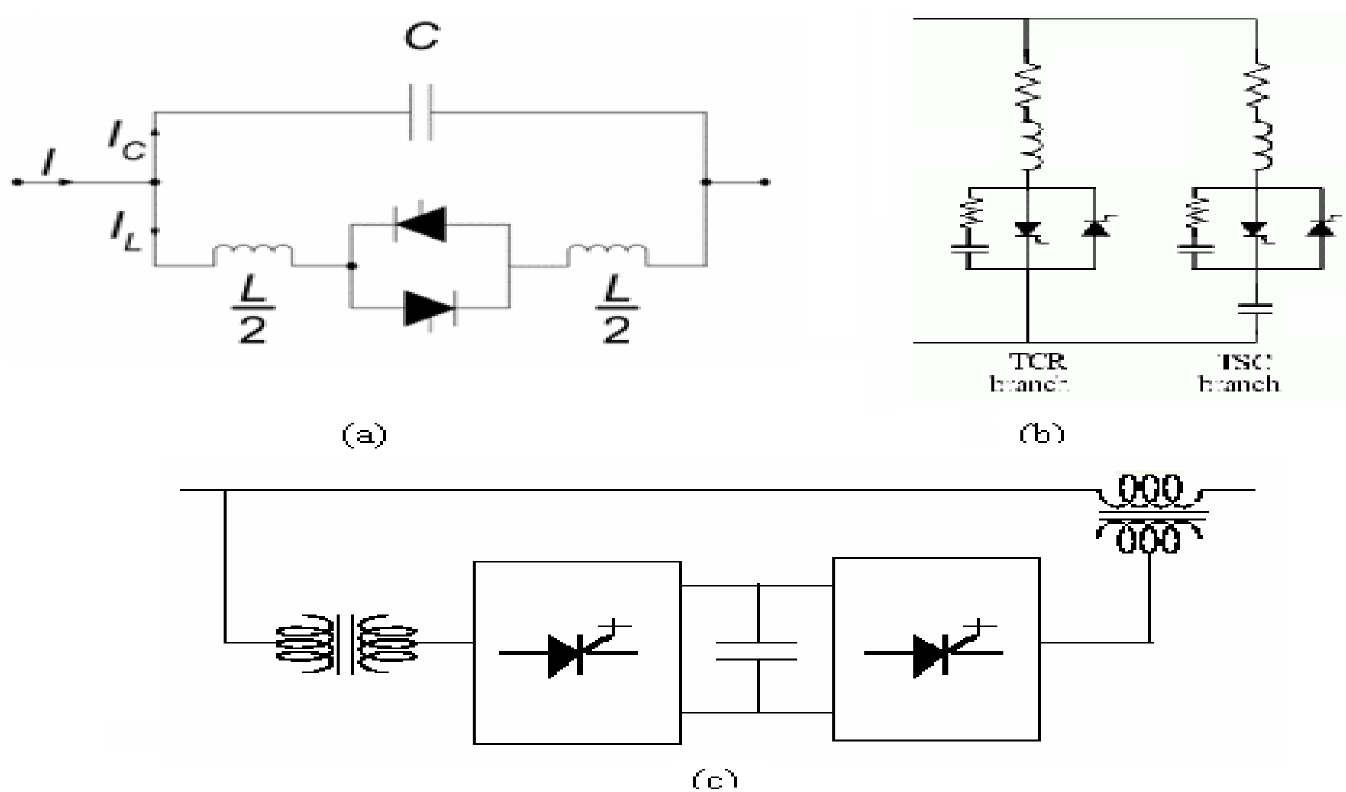
- Low complexity-thanks to fewer components
- Small and compact
- Useful in windmills
- Offers asynchronous operation.

- **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)

Flexible AC Transmission Systems (FACTS) are the name given to the application of power electronics devices to control the power flows and other quantities in power systems.



- **Benefits of FACTS Technology**
  - To increase the power transfer capability of transmission networks and
  - To provide direct control of power flow over designated transmission routes.
- **However it offers following opportunities**
  - Control of power flow as ordered so that it follows on the prescribed transmission corridors.
  - The use of control of the power flow may be to follow a contract, meet the utilities’ own needs, ensure optimum power flow, ride through emergency conditions, or a combination thereof.
  - Increase the loading capability of lines to their thermal capabilities, including short-term and seasonal.
  - Increase the system security through raising the transient stability limit, limiting short-circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.

- Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Allow secure loading of transmission line to a level closer to the thermal limits, while avoiding overloading and reduce the generation margin by having the ability to transfer more power between the controlled areas.
- Damping of power oscillation,
- Preventing cascading outages by limiting the impacts of faults and equipment failures.
- Provide greater flexibility in sitting new generation.
- Upgrade of lines.
- Reduce reactive power flows, thus allowing the lines to carry more active power.
- Reduce loop flows.
- Increase utilization of lowest cost generation.

- Whether HVDC or FACTS ?
  - Both are complementary technologies.
  - The role of HVDC is to interconnect ac systems where a reliable ac interconnection would be too expensive.
    - **Independent frequency and control**
    - **Lower line cost**
    - **Power control, voltage control and stability control possible.**
  - The large market potential for FACTS is within AC system on a value added basis where
    - **The existing steady-state phase angle between bus nodes is reasonable.**
    - **The cost of FACTS solution is lower than the HVDC cost and**
    - **The required FACTS controller capacity is lesser than the transmission rating.**

Throughput	HVDC 2 terminal	FACTS
200 MW	$ 40-50 M	$ 5-10 M
500 MW	75-100 M	10-20 M
1000 MW	120-170 M	20-30 M
2000 MW	200-300 M	30-50 M

- FACTS technology is concerned with development of following two areas
  - High rating Power electronic switching devices and Pulse Width Modulated converters.
  - Control methods using digital signal processing and Microprocessors.
  - Devices: IGBT→ Insulated gate bipolar transistors, GTO→ gate turn off thyristor, MCT→ Metal oxide thyristor (MOS) controlled transistor

Table: Comparison of power semiconductor devices

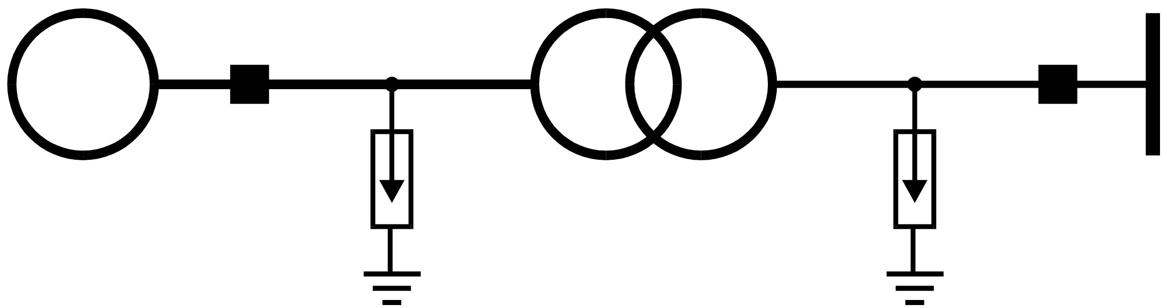
	Thyris-tor	GTO	IGBT	SI * thyristor	MCT	MOSFET
Max. voltage rating (V)	8000	6000	1700	2500	3000	1000
Max. current rating (A)	4000	6000	800	800	400	100
Voltage blocking	Sym./ Asym.	Sym./ Asym.	Asym.	Asym.	Sym./ Asym	Asym.
Gating	Pulse	Current	Voltage	Current	Voltage	Voltage
Conduction drop (V)	1.2	2.5	3	4	1.2	Resistive
Switching frequency (kHz)	1	5	20	20	20	100
Development target max. voltage rating (kV)	10	10	3.5	5	5	2
Development target max. current rating (kA)	8	8	2	2	2	0.2

* SI: Static induction thyristor, MOSFET: MOS field effect transistor

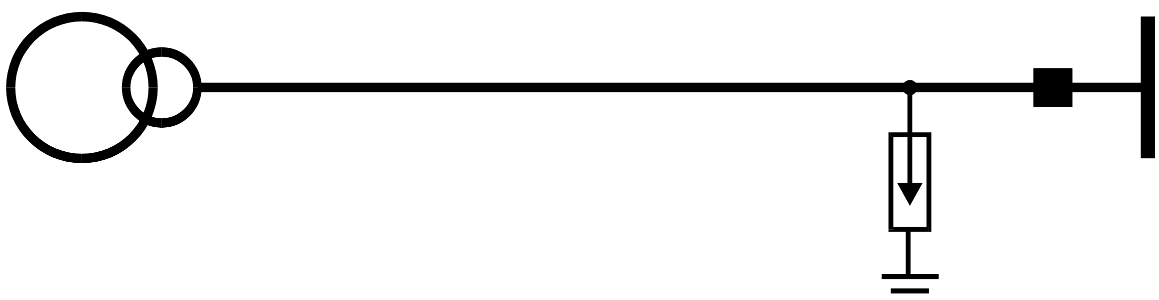
- **Developments in Generation side**
  - Powerformer Energy System
  - Distributed Generations
    - Wind Power
    - Fuel Cells
    - Biomass etc.
  - Combined Cycle Power Plants

Powerformer Energy System

Conventional



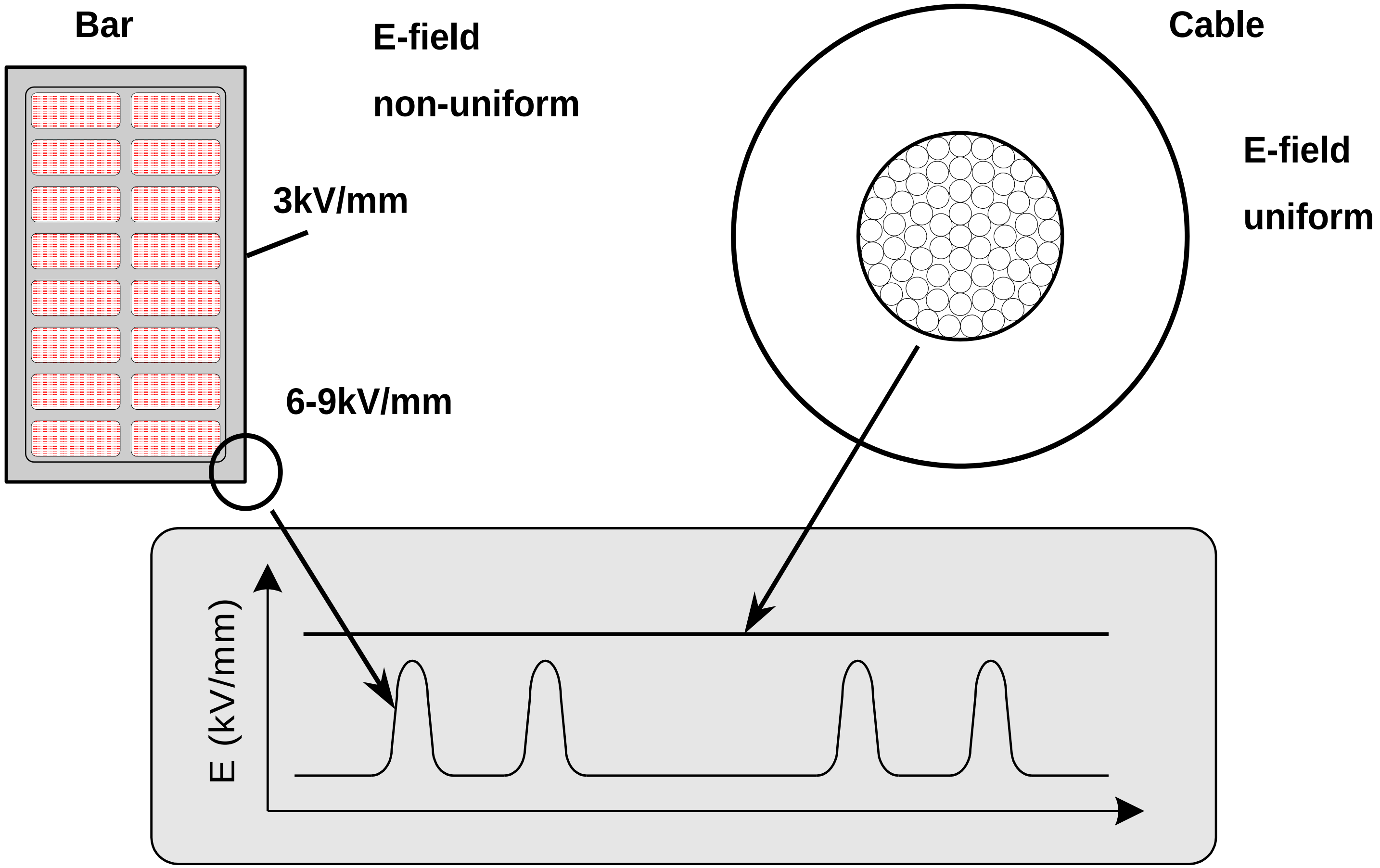
Powerformer™



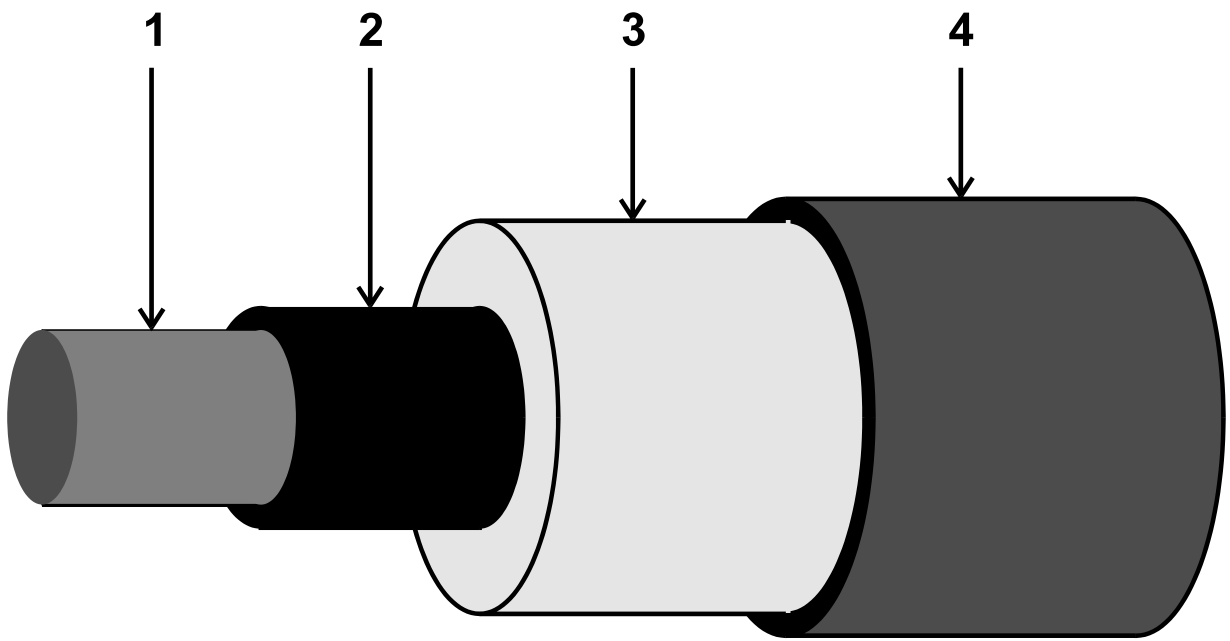
Powerformer^{TM} Benefits

- 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

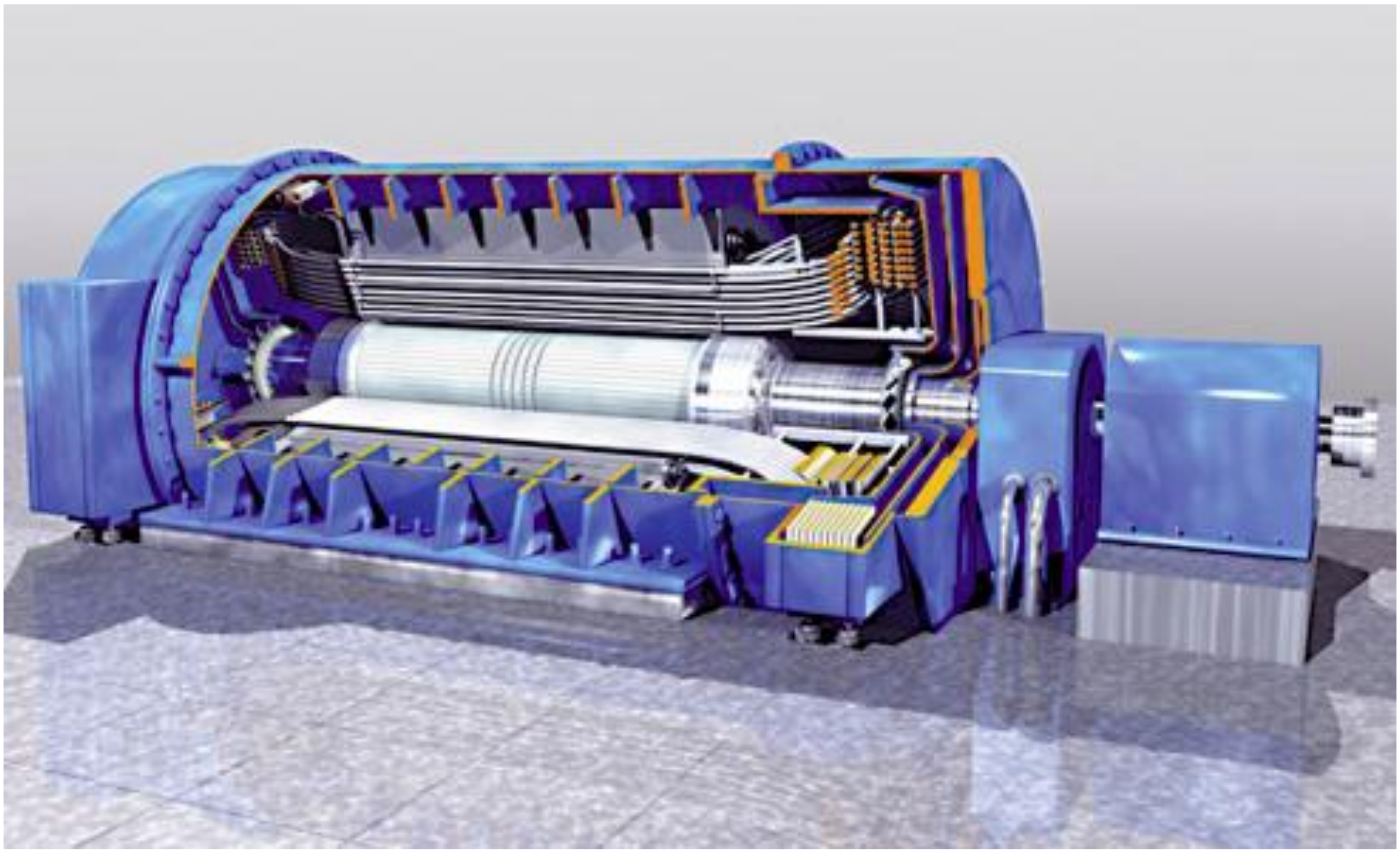


Stator winding



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

136 kV 42 MVA Powerformer from ABB



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%,** converting between 28 to 35% of the energy in their fuel into useful electric power.
- 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.

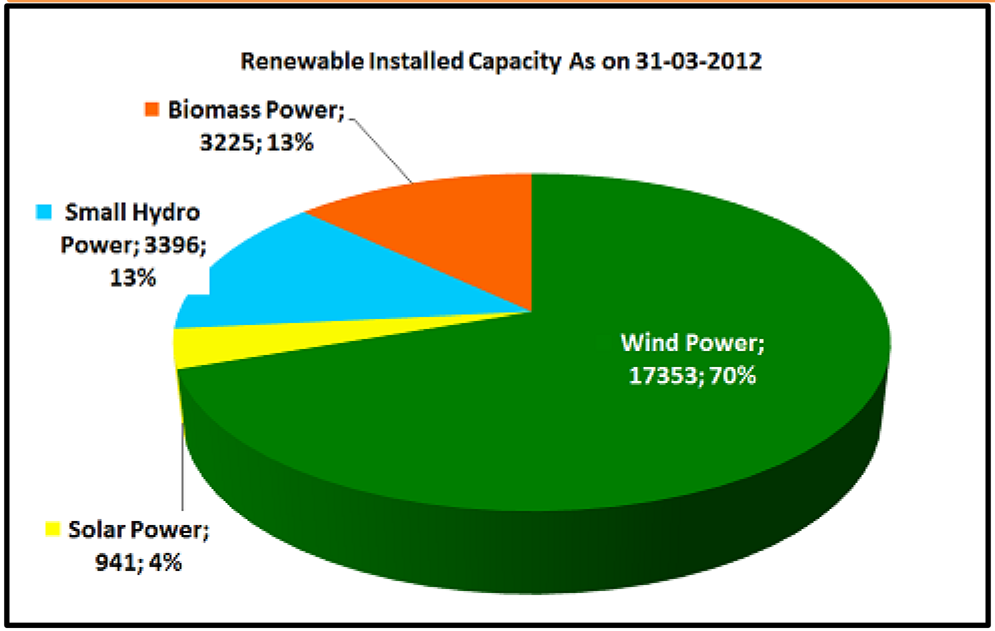
DG "Wins" Not Because It is Efficient, But Because It Avoids T&D Costs

Proximity is often more important than efficiency

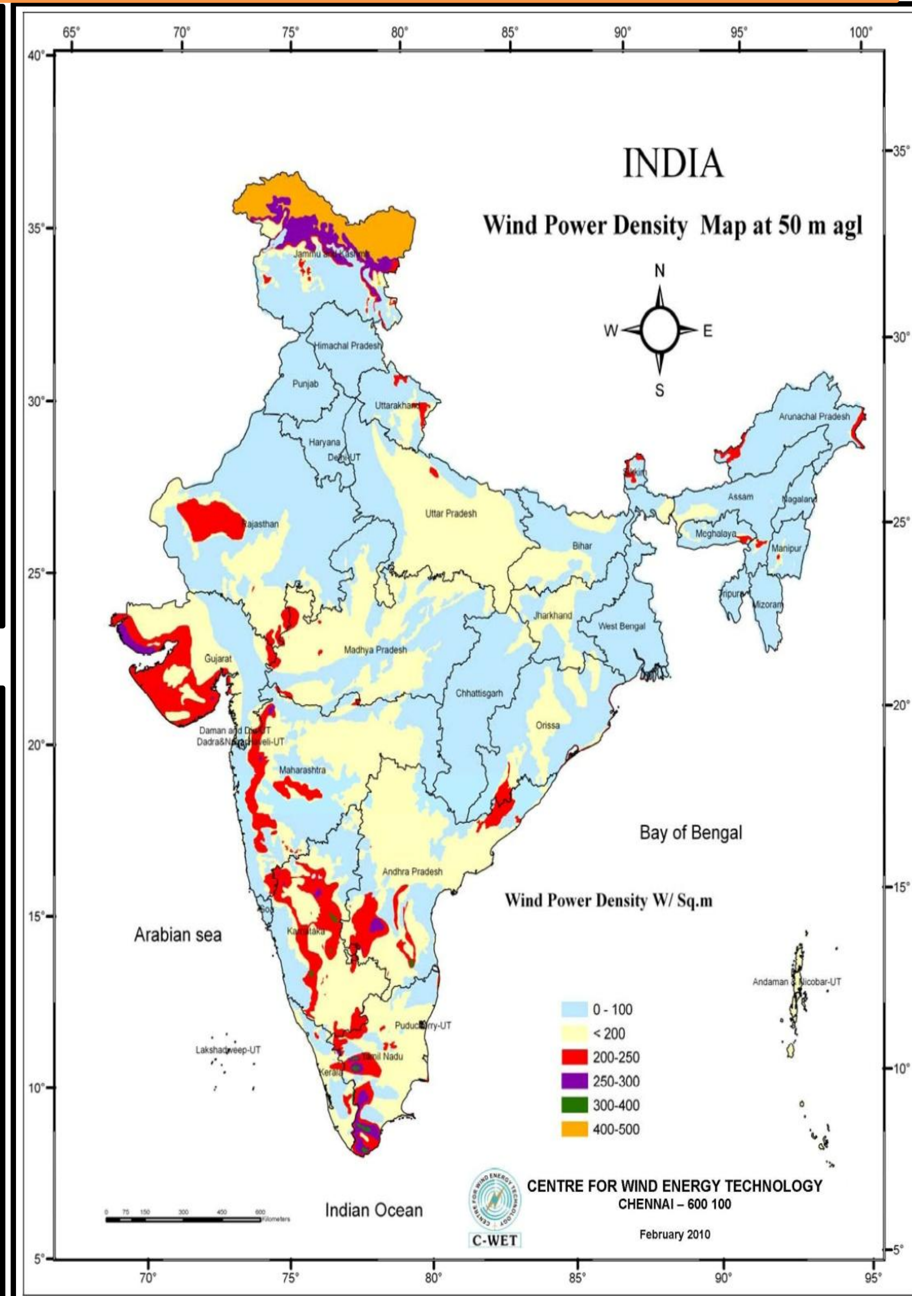
- Why use DG units, if they are not most efficient or the lowest cost?
  - The reason is that **they are closer to the customer**. They only have to be more economical than the central station generation and its associated T&D system. A **T&D** system represents **a significant cost** in **initial capital** and **continuing O&M**.
  - By avoiding T&D costs and those reliability problems, DG can provide **better service at lower cost**, at least in some cases. For example, in situations where an existing distribution system is near capacity, so that it must be reinforced in order to serve new or additional electrical demand, the capital cost/kW for T&D expansion alone can exceed that for DG units.

Renewable Energy Scenario in India

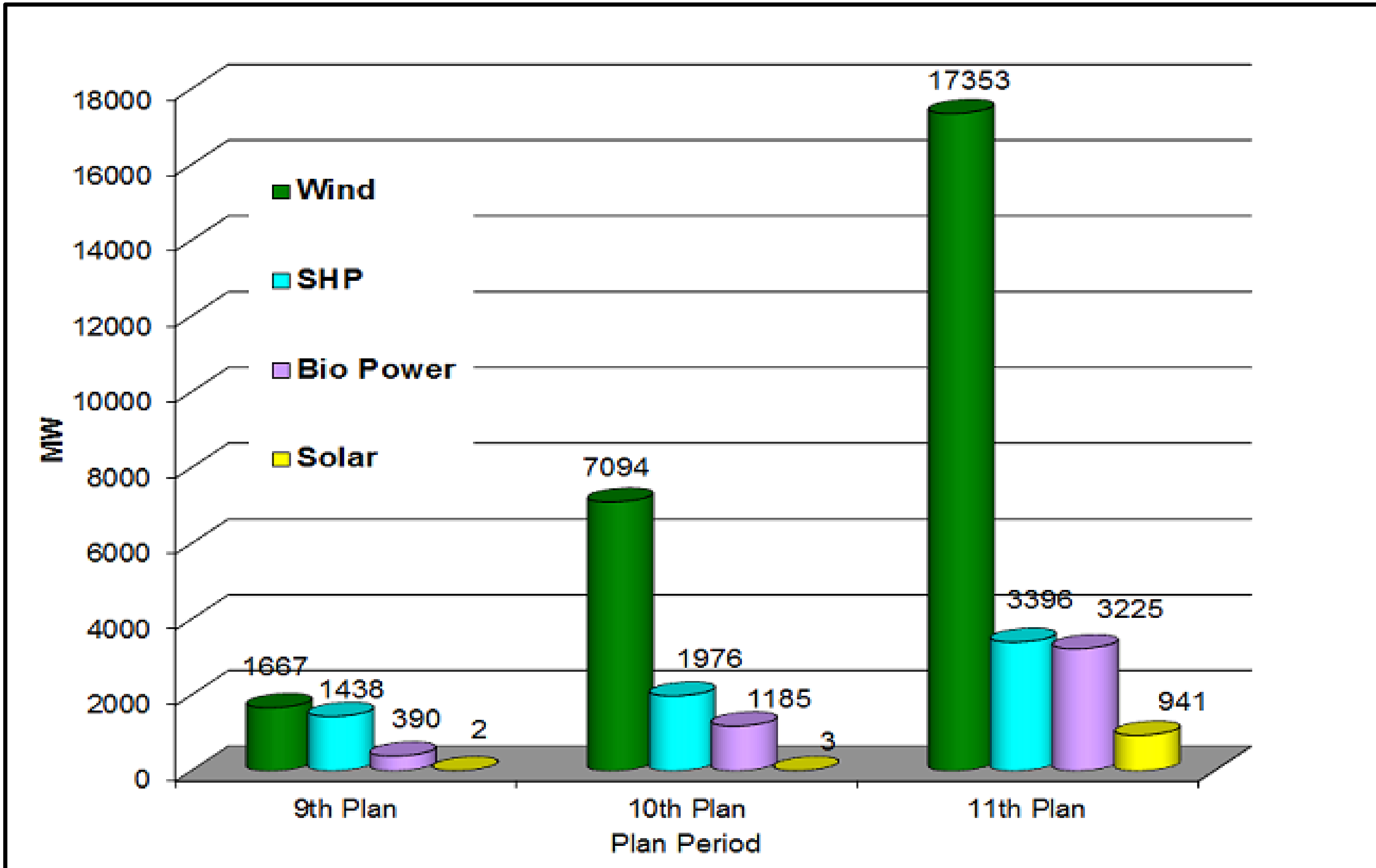
Renewable Installed Capacity



Resources	Grid-Interactive Capacity (MW) up to 31.03.2012
Wind Power	17353
Small Hydro Power	3396
Biomass Power / Bagasse Cogeneration	3225
Solar Power	941
Total	**24915**



Growth pattern of RE addition in different five year plans



(Source-MNRE)

Opportunities/Challenges

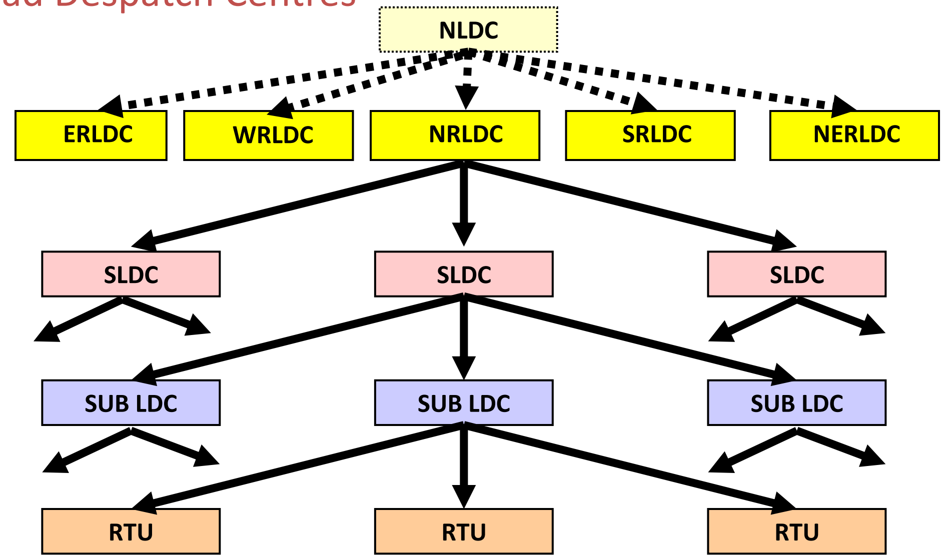
- Transmision of power
- Renewable Energy/Distributed Generation
- DC Distribution System
- Smart grid

Operational Changes in Power Systems

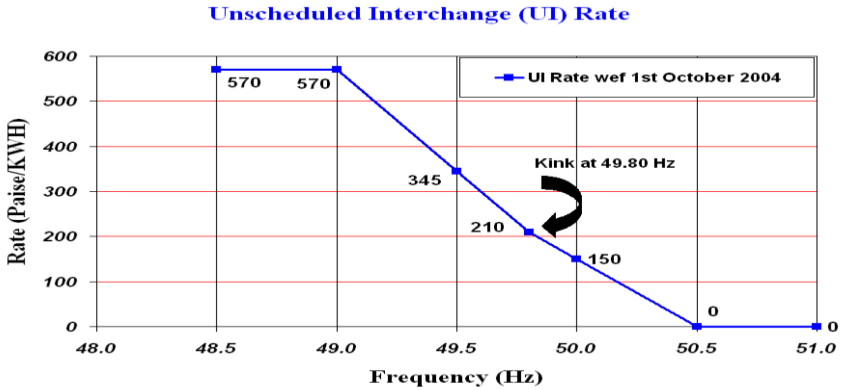
Grid Management

Initiatives

- Modernisation of Load Despatch Centres



- Implementation of Grid Code
- Manning of Load Despatch Centres with trained personnel
- Adoption of Availability Based Tariff (ABT)



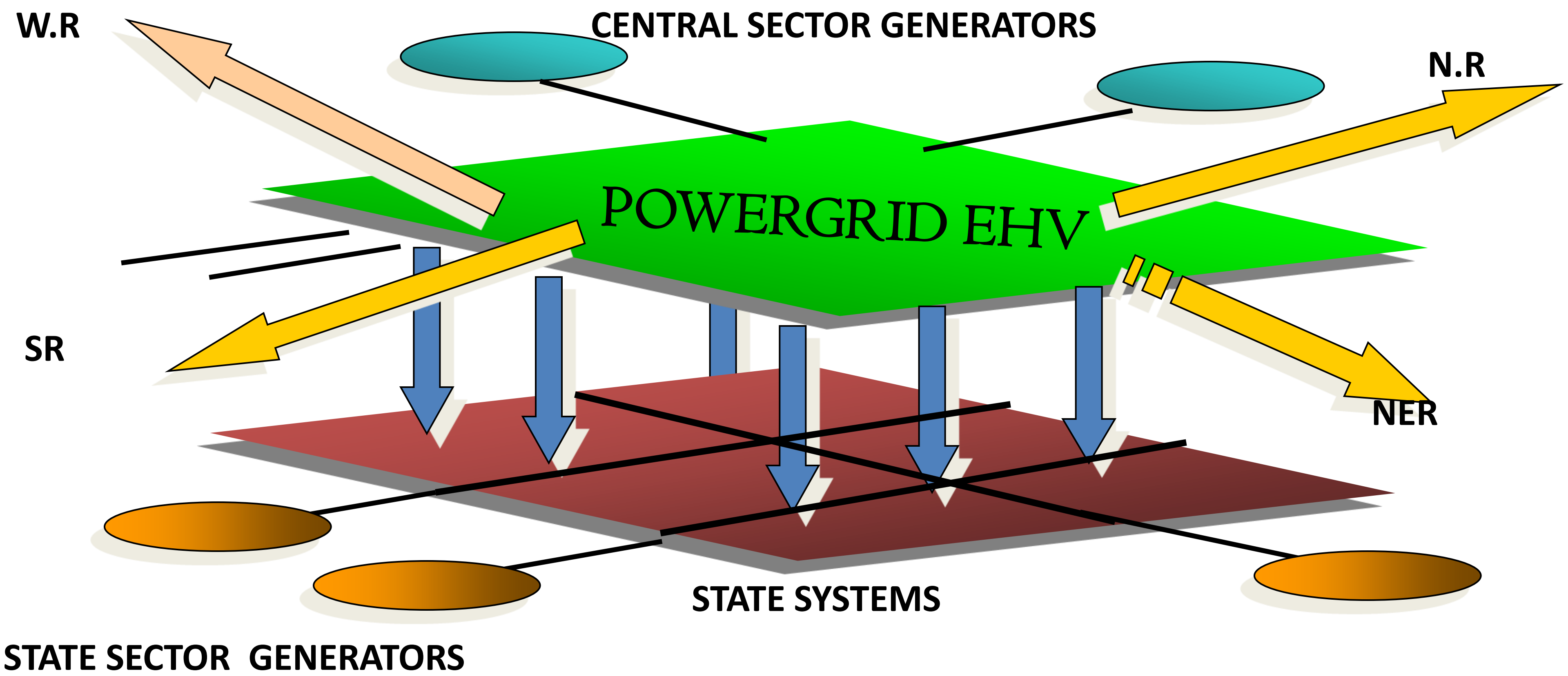
Future Prospective-

❖ Intelligent Grid -Smart Power Delivery System

- Wide area monitoring system
- Adaptive islanding schemes
- Self healing capability
- Voltage Security Assessment, Dynamic Security Assessment

Availability Based Tariff Mechanism In India

BULK POWER TRANSACTION
Example: NR, Rajasthan, BBMB



Availability Based Tariff

Capacity Ch. + Energy Ch. ± UI

A + B ± C

Pre ABT Settlement System

- **The payment to Central Generating Station by a constituent - proportion to total energy drawls**

– Recommendation of K.P.Rao Committee Report.

- **Both *Fixed and Variable charge* was payable as per energy drawls**
- **Based on Monthly Regional Energy Account- REA**
- **Conventional Meter Readings**
- **Fixed cost recoverable with deemed generation**
- **Incentive payable after accounting for deemed generation**

Although a two part tariff- Single part for constituent

Components of Availability Tariff

(a) Capacity Charge: for payment of fixed cost

-Proportionate to entitlements (not actual drawls)

-is a function of ex-bus MW capability of the power plant for the day declared in advance, paid by beneficiaries @ their respective % share in the plant

(b) Energy Charge: for payment of variable cost

-Payable for schedules (not as per actual drawls)

= MWh for the day as per ex-bus drawl schedule for the beneficiary finalized in advance x Energy charge rate for the Plant

(c) Unscheduled Interchange : Payable for deviations from schedules

= Σ [(Actual energy interchange in a 15- minutes time block – scheduled interchange for the time block) x UI rate for the time block]

Total Payment for the day = (a) + (b) ± (c)

BACKGROUND (situation upto early 2002)

Deplorable state of regional grid operation

- Uncontrolled frequency fluctuations, from below 48.0 Hz to above 52.0 Hz.
- Voltages beyond permissible limits
- Frequent grid disturbances
- Lack of optimization in generation (merit – order compromised)
- Unchecked deviations from schedules
- Perpetual operational and commercial disputes between utilities

MAIN REASONS :

- Shortage and poor availability of generating capacity → extensive (but inadequate) load curtailment, particularly during peak load hours.
- Reluctance to back down generation during off-peak hours, due to faulty bulk power tariff structure (single-part, constant paise / kWh)
- Inadequate reactive compensation at load end
- Blocked governors
- Gaps in understanding of the subject, and a lack of consensus on how to tackle the problem.

- Federal democracy : Tussle between Central Government organisations and State Government-owned vertically integrated utilities

- Lack of load dispatch and communication facilities to apply conventional load-frequency control, tie-line bias, control area concepts, etc.

A structured study in 1993-94 by M/s. ECC of USA, sponsored by World Bank/Asian Development Bank

→ AVAILABILITY TARIFF

Implementation started in 2002

Inherent Disadvantage

- **No incentives for generators /utilities to respond to dispatch orders for issues like frequency control**
  - **No Incentive for helping the grid**
  - **No disincentive for hurting the grid**
- **No signal to generators to match availability with system needs**
- **Did not promote Grid Discipline**
- **No signal for trading of power.**

Overall economy was lost.

Ultimate Effect

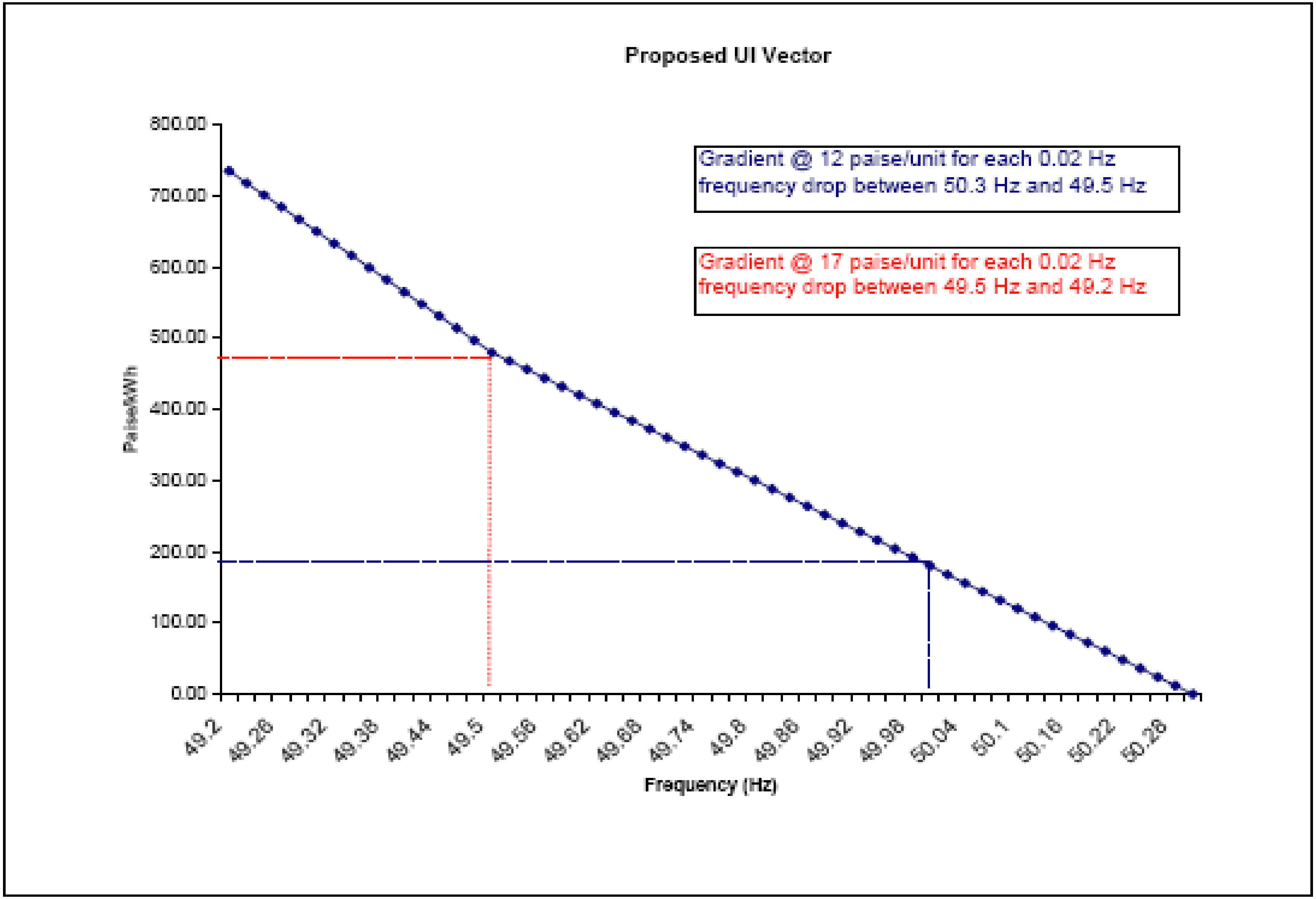
- **Grid Indiscipline-**
  - **Low Frequency during peak**
  - **High Frequency during off peak**
- **Control Instructions**
  - **Subjective decisions**
  - **Not based on overall economy**
- **Perpetual Operational & Commercial Dispute amongst Utilities/Central Generators**
- **Poor Supply quality to consumers/industries**
  - **Damage to equipments**
  - **Shifting of Industries/Investments**

Unscheduled Interchange Regulations 2009 (and subsequent amendments)

Unscheduled Interchange

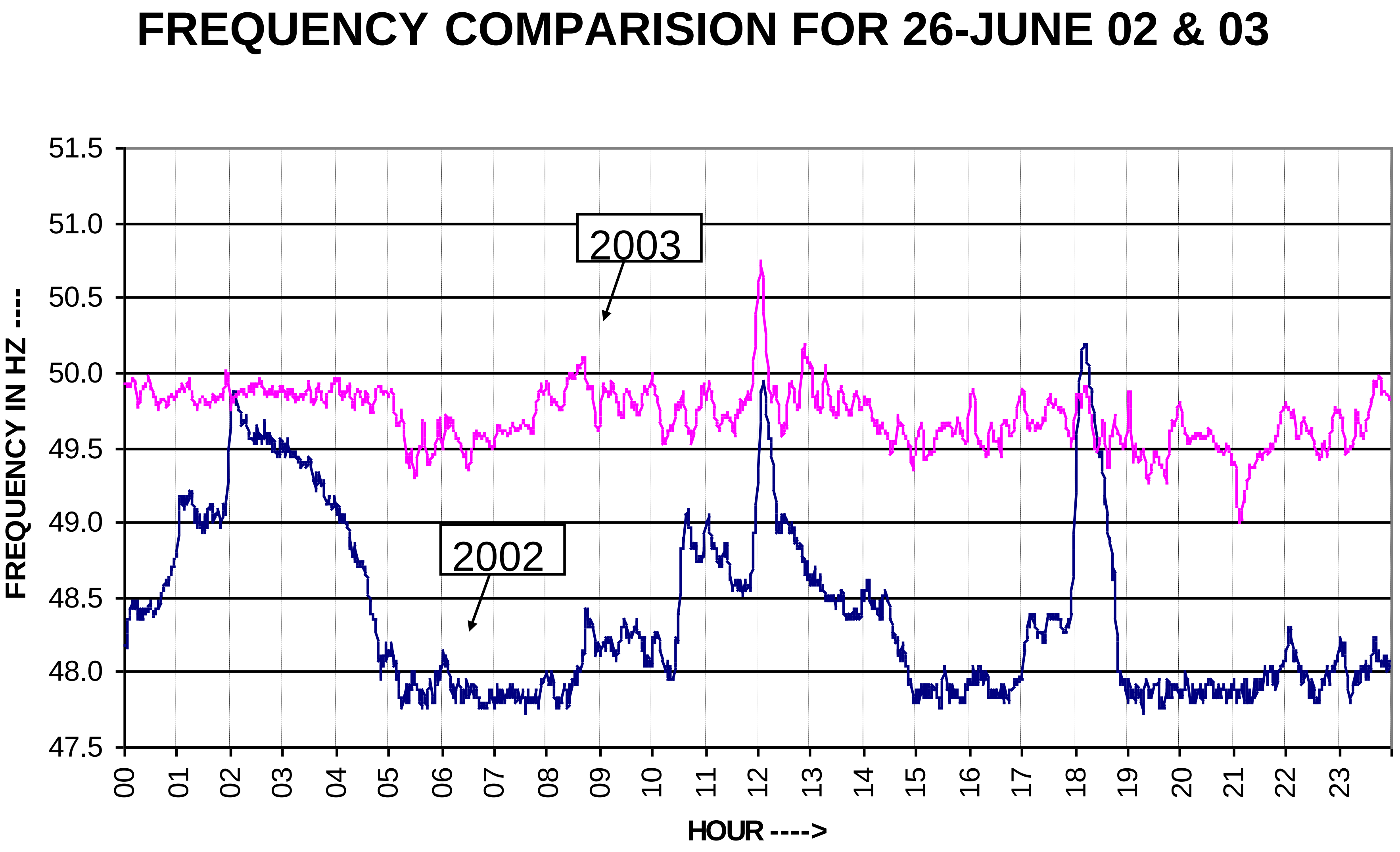
- ‘Unscheduled Interchange’ in a time-block for a generating station or a seller means its total actual generation minus its total scheduled generation, and,
- for a beneficiary or buyer means its total actual drawal minus its total scheduled drawal.

Unscheduled Interchange

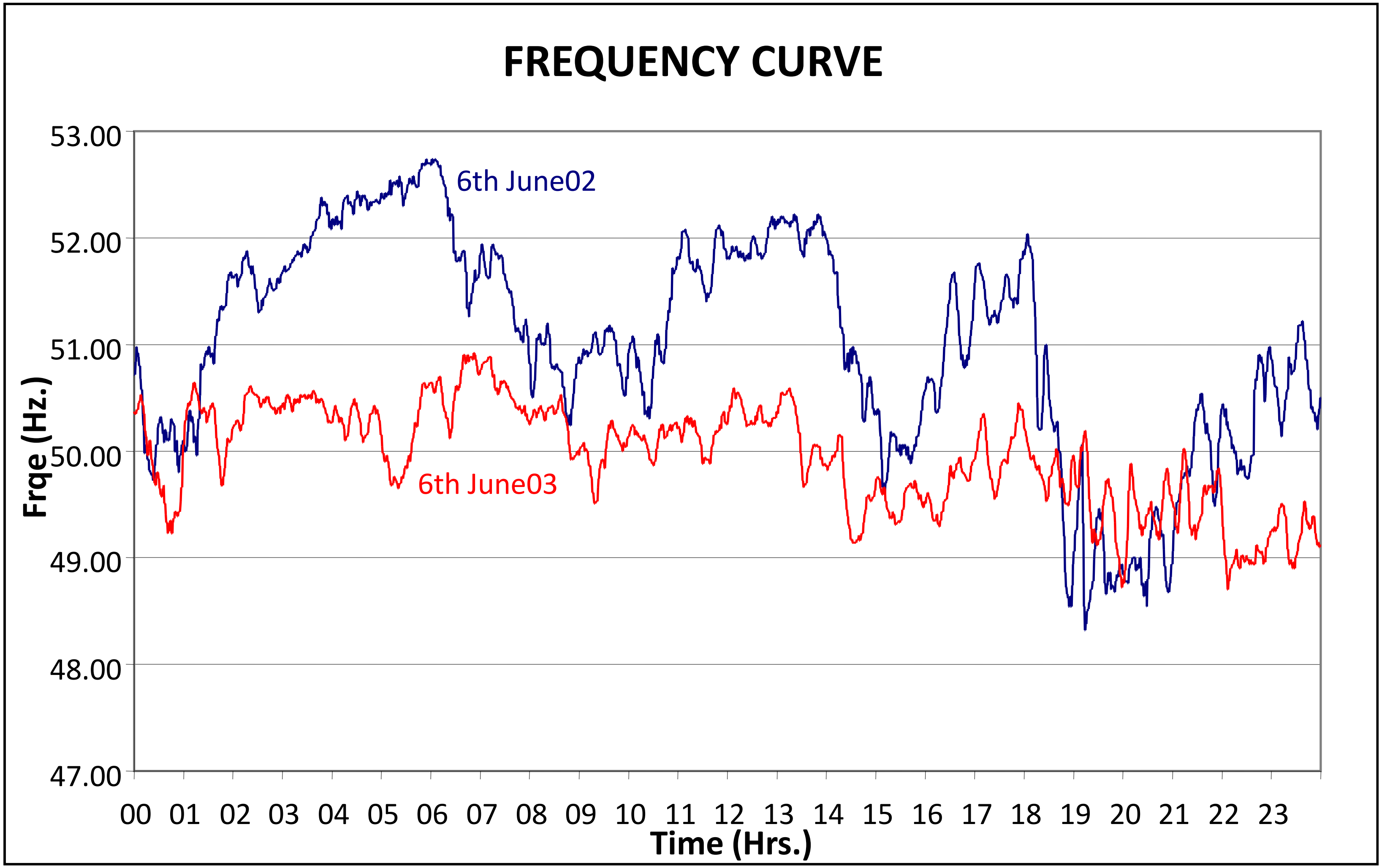


Advantages due to implementation of ABT

Frequency Profile of SR



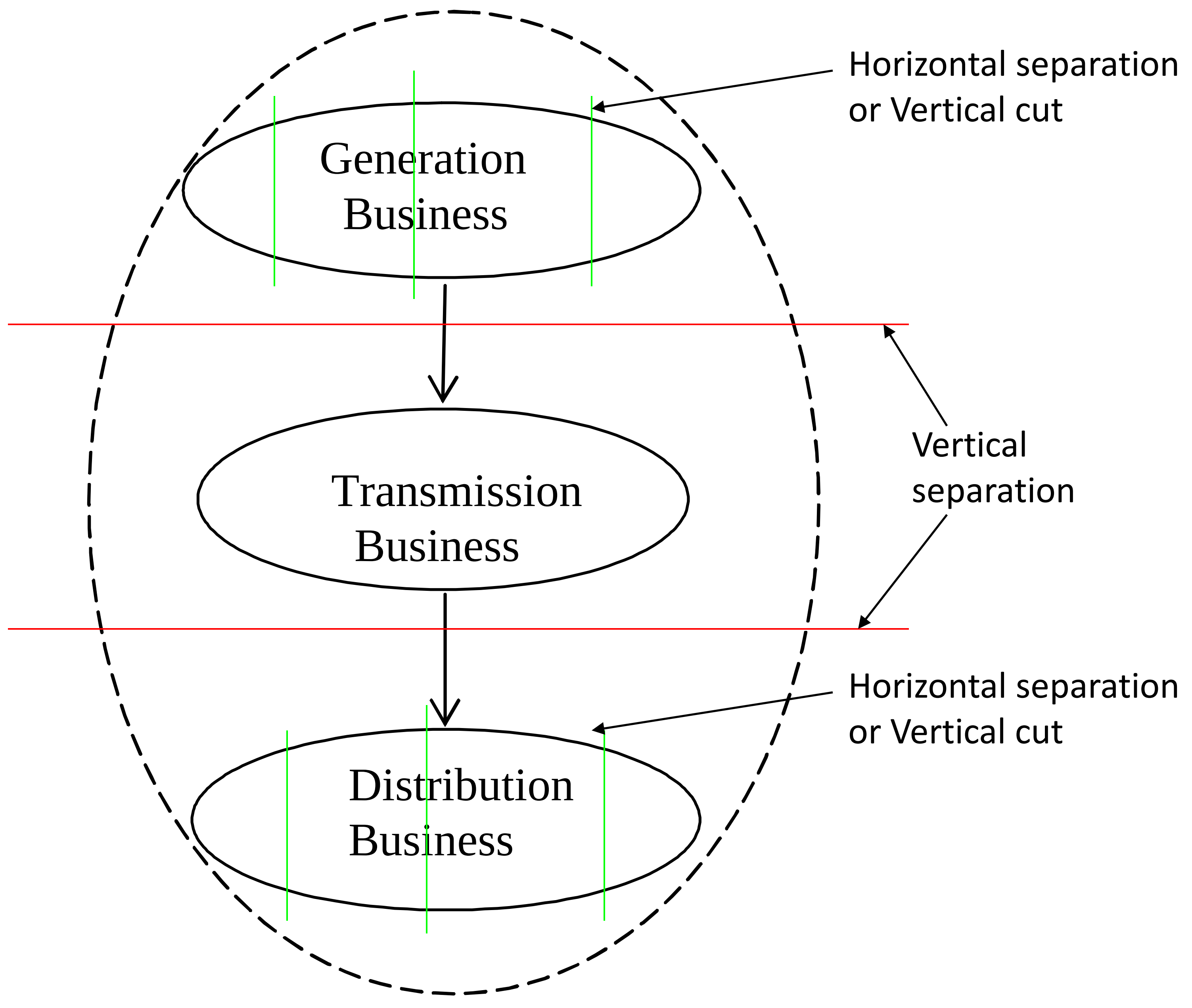
Frequency Profile of ER



- 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


Horizontal separation or Vertical cut
Generation Business
Vertical separation
Transmission Business
Horizontal separation or Vertical cut
Distribution Business

- **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.

- **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**

No longer necessary	The primary reason for regulation, to foster the development of ESI infrastructure, had been achieved.
Electricity Price may drop	Expected to drop due to innovation and competition.
Customer focus will improve	Expected to result in wider customer choice and more attention to improve service
Encourage innovation	Rewards to risk takers and encourage new technology and business approaches,
Augments privatization	In the countries where Govt. wishes to sell state -owned utilities, deregulation may provide potential buyers and new producers.

- **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

- **What will be the Potential Problems ?**
  - Congestion and Market power
  - Obligation to serve
  - Some suppliers at disadvantages
  - Price volatility
  - Non-performance obligation
  - Loss operating flexibility
  - Pricing of energy and transmission services
  - ATC calculations
  - Ancillary services Management
    - Reserves
    - Black start capability
    - Voltage and frequency control
    - System security and stability
    - Transmission reserves
  - Market Settlements and disputes

Milestones of Restructuring

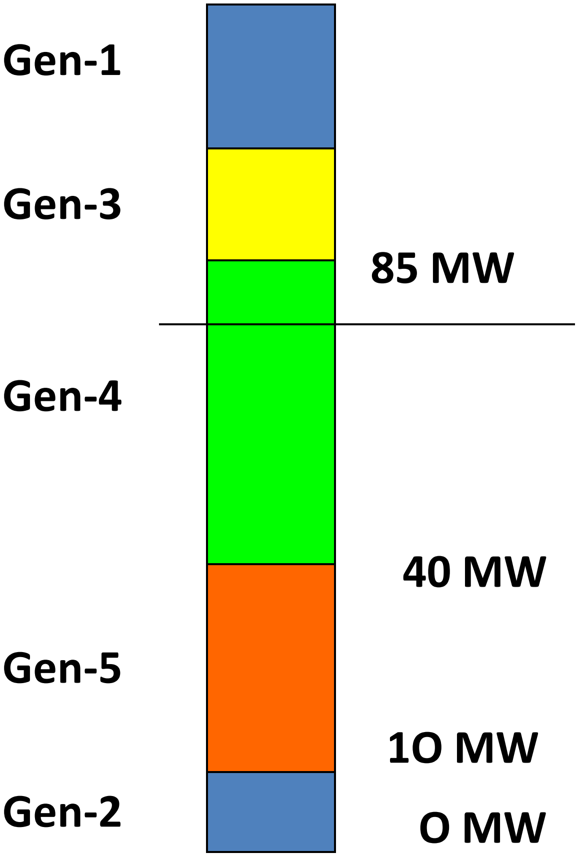
- **1982 Chile**
- **1990 UK**
- **1992 Argentina, Sweden & Norway**
- **1993 Bolivia & Colombia**
- **1994 Australia**
- **1996 New Zeeland**
- **1997 Panama, El Salvador, Guatemala, Nicaragua, Costa Rica and Honduras**
- **1998 California, USA and several others.**
- **2000 Several EU and American States**

- Markets are defined by the commodity traded
  - Energy
  - Transmission system
  - Ancillary services
- Markets defined by the time-frame of trade
  - Day-ahead
  - Hour-ahead
  - Real-time
- Based on auction - single-sided or double sided
- Based on type of bids --> block or linear bid
- Based on generation settlement - uniform price (MCP) or pay-as-bid

Market Clearing Price

Gen.	Price ($)	MW
Gen-1	2.5	20
Gen-2	2.0	10
Gen-3	2.4	15
Gen-4	2.3	45
Gen-5	2.2	30

Demand = 80 MW



- **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.

Intelligent Grid - WAMS

Leader not a follower

- What is Smart Grid?
- Is the present grid not smart?
- Why Smart Grid?
- Smart or Intelligent ???

What is Smart Grid?

- The electric industry is poised to make the transformation from a *centralized,* producer- controlled network to one that is *less centralized and more consumer-interactive.*
- The move to a smarter grid *promises* to change the industry's entire business model and its relationship with all stakeholders.
- A smarter grid makes this transformation possible by bringing the philosophies, concepts and technologies that enabled the internet to the utility and the electric grid.

- What is Smart Grid?
- Is the present grid not smart?
- Why Smart Grid?
- Smart or Intelligent ???

Is the present grid not smart?

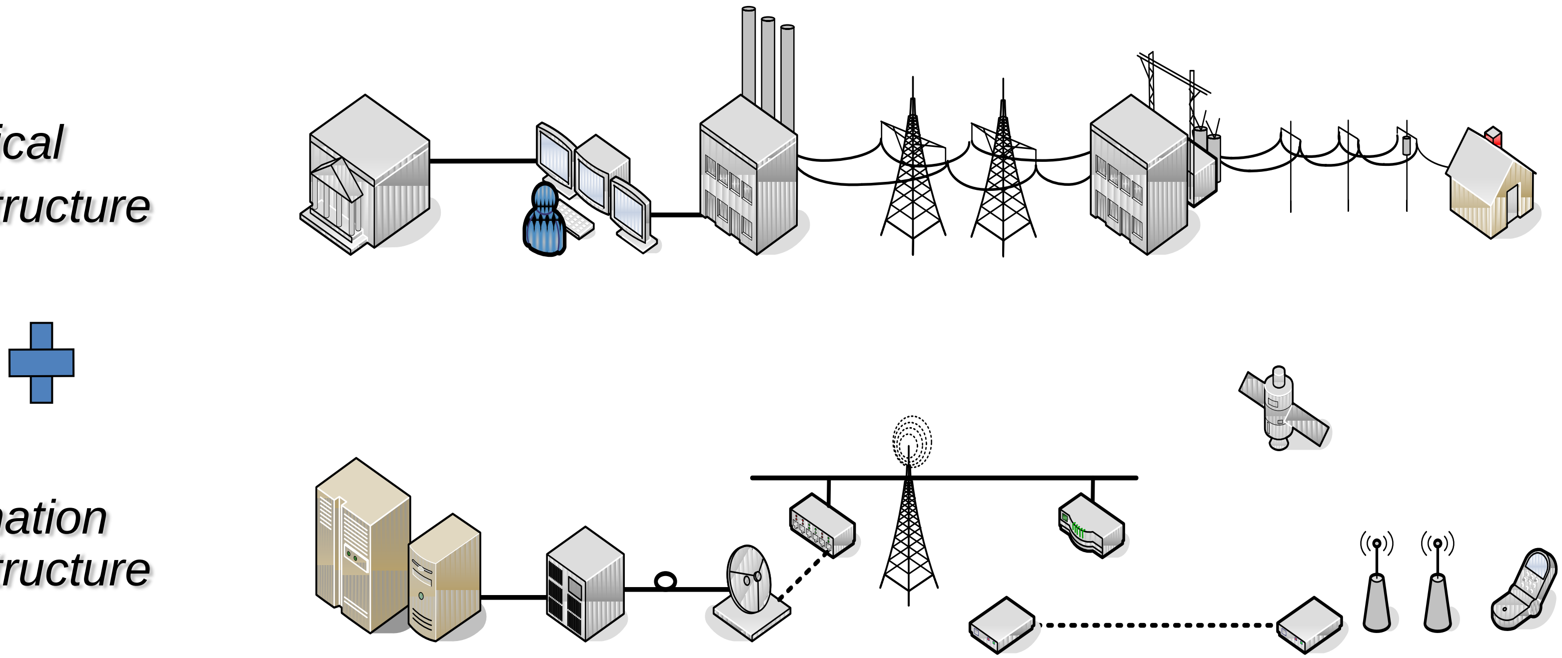
- It may surprise you to know that many of these ideas are already in operation.
- Yet it is only when they are empowered by means of the two-way digital communication and plug-and-play capabilities that exemplify a smarter grid that genuine breakthroughs begin to multiply.

Merging Two Technologies

The integration of two infrastructures… securely…

Electrical Infrastructure

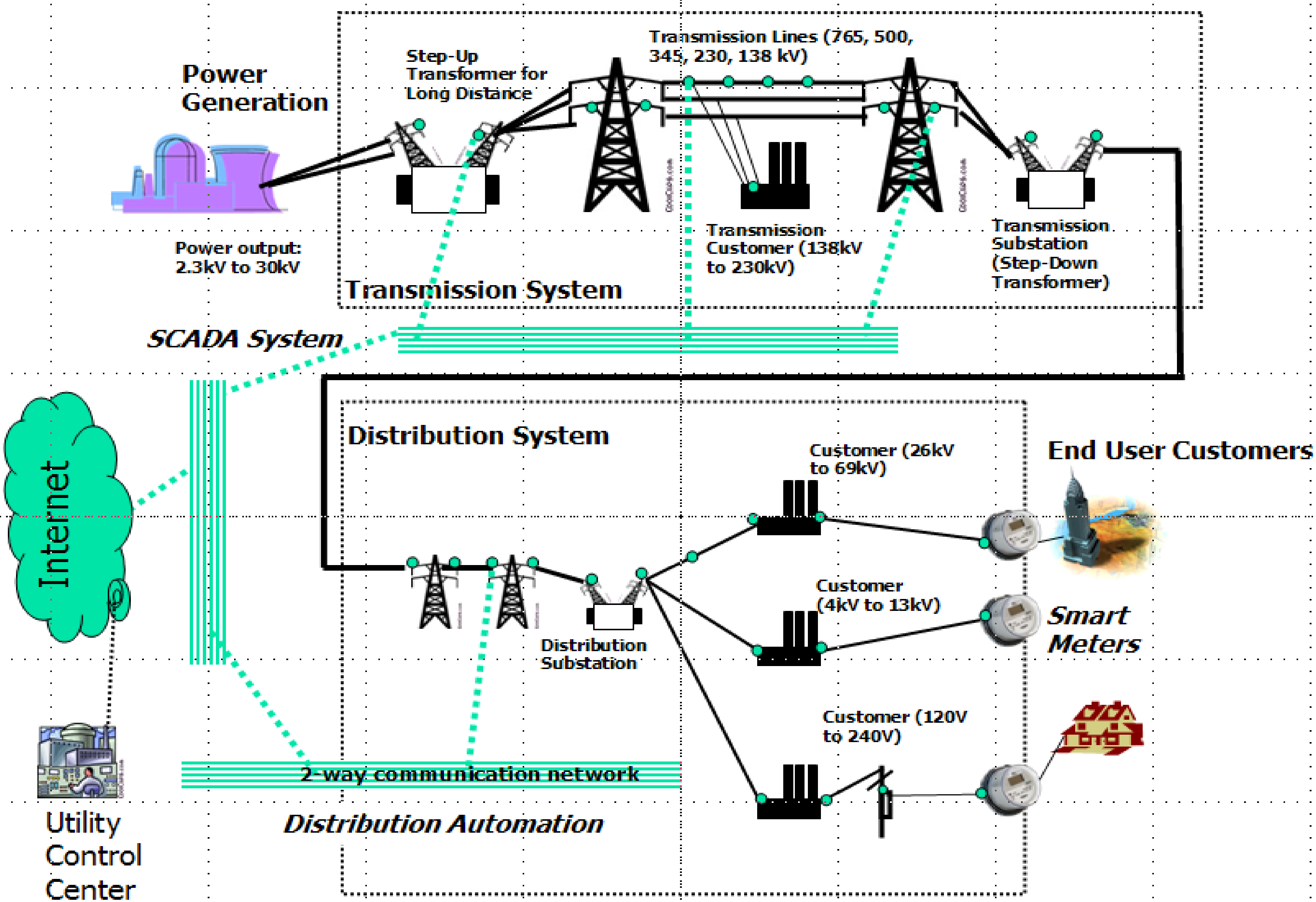
Information Infrastructure



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

What a Smart Grid would look like?

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

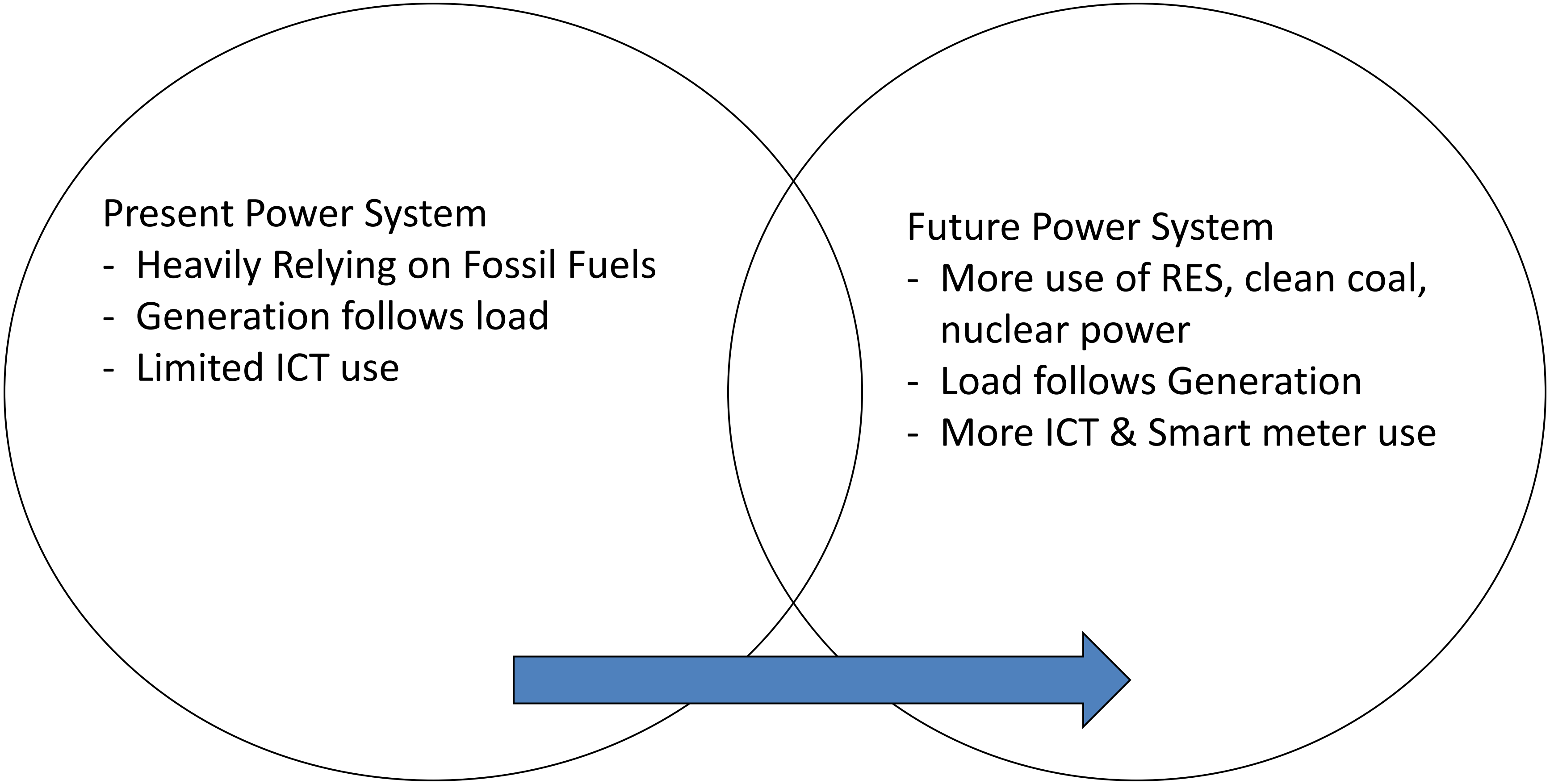


- What is Smart Grid?
- Is the present grid not smart?
- Why Smart Grid?
- Smart or Intelligent ???

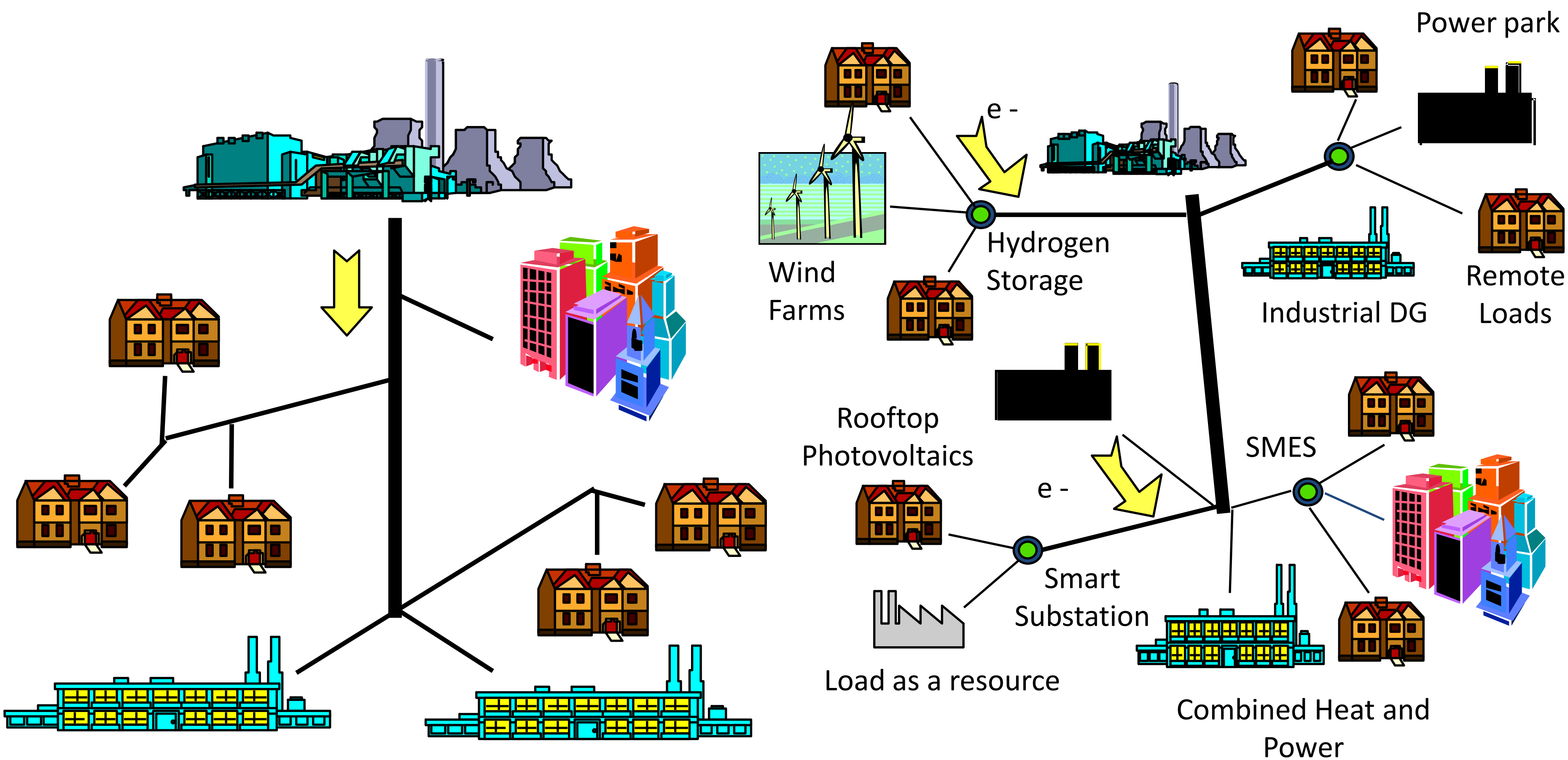
Some of the Recent Concerns

- Limited expansion of transmission network as compared to the generation addition.
  - Most of the generation, T&D systems have become old.
- Efficiency: Increased transmission and distribution losses.
- Lack of dynamic data for health monitoring and control.
- Reliability & Security: Increased concern towards vulnerability and resilience of the system under natural and man made disasters.
- Growing *environmental* concerns including the global warming.
- *Poor power quality*, limited customer focus and their participation in energy Management.
- Meeting the ever increasing electricity demand.
- Affordability:

Present and Future Power System

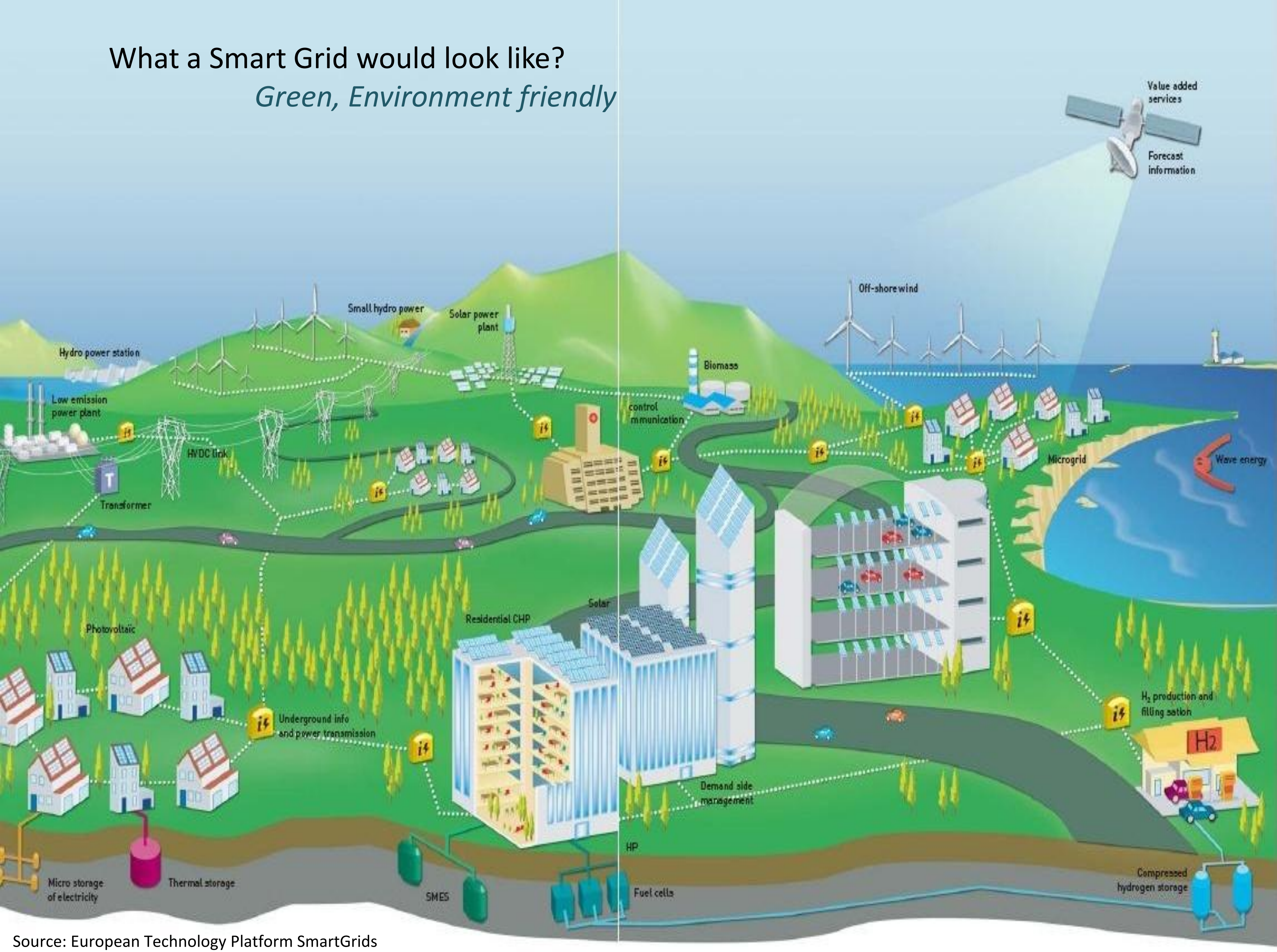


Today's Electricity … → *Tomorrow's Choices …*



What a Smart Grid would look like?

Green, Environment friendly

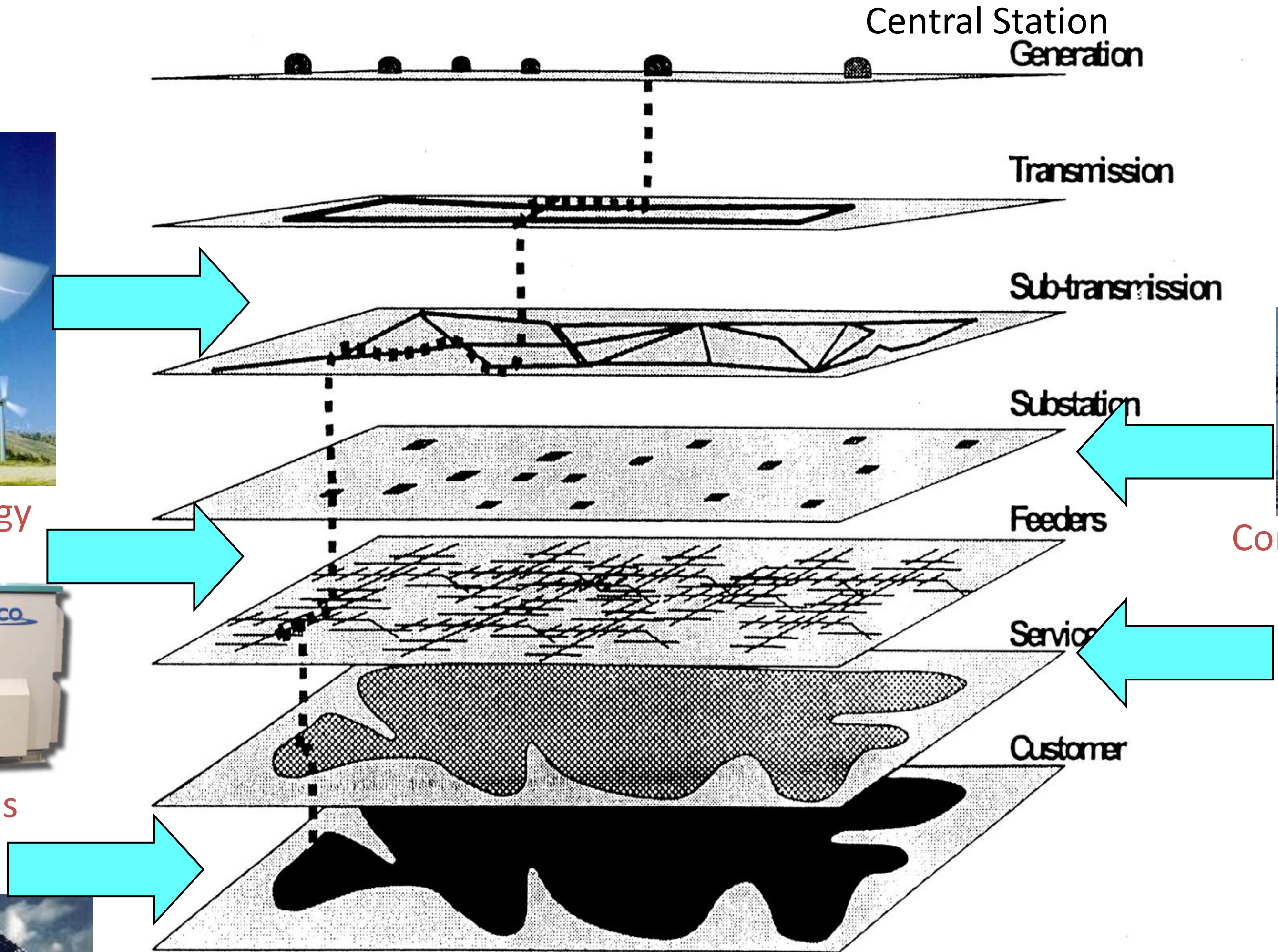


Source: European Technology Platform SmartGrids

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

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.

Smart Grid Initiatives

- US Dept. of Energy
  - GridWise & GridWorks
- Modern Grid Initiative (NETL: National Energy Technology Lab)
- GridWise Alliance (US industry group)
- IntelliGrid (EPRI)
- CERTS – Consortium for Electric Reliability Technology Solutions (USA)
- SmartGrids (European Union)
- Integration of Decentralized Energy Resources Program (NRCan Canada)
- NIST Special Publication 1108, NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0 , January 2010
- Smart Grid Forum launched in India on 27 May 2010.
- The Smart Grid Vision for India's Power Sector: A White Paper, under USAID DRUM project, prepared by PA Government Services, Inc., India

Smart Grid: Challenges and Opportunities

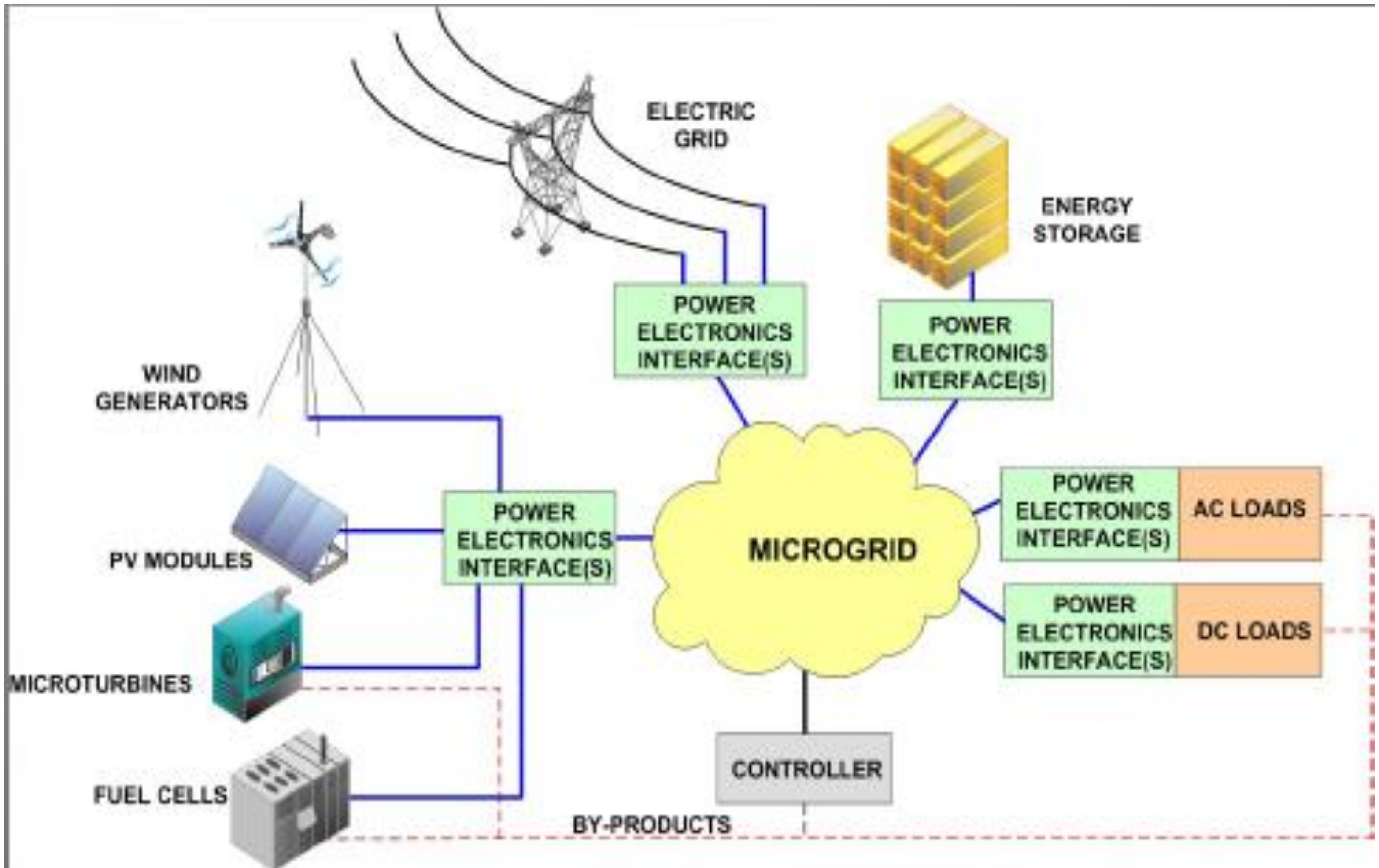
- The concept of a smart grid has its origins in the development of advanced metering infrastructure for
  - better demand-side management;
  - greater energy efficiency; and
  - improved supply reliability.
- Other developments have expanded the scope of smart grids:
  - renewable energy generation (wind and solar, among others);
  - maximizing the utilisation of generating assets; and
  - increased customer choice.
- New technologies will continue to expand the scope:
  - electric vehicles;
  - energy storage (batteries); and
  - smart appliances.

Challenges of the New Energy Economy

- The Smart-Grid
  - Automating the Grid
  - Return on Asset (ROA)
  - Dynamic Pricing
- Dealing with Evolutionary Change
  - Greater 30% Renewable, Distributed
    - Photovoltaic, Solar/Thermal, Wind, Biofuels
    - Climate Modelling & Prediction
    - Distribution becomes Transmission
  - Electric Vehicles
  - Transmission Capacity and Location

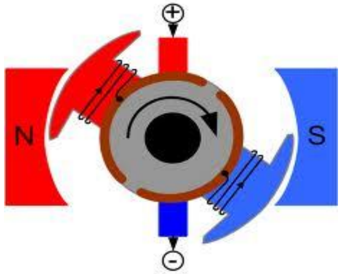
Micro Grid (DC or AC ?)

- Micro-grids are independently controlled (small) electric networks, powered by local units (distributed generation).



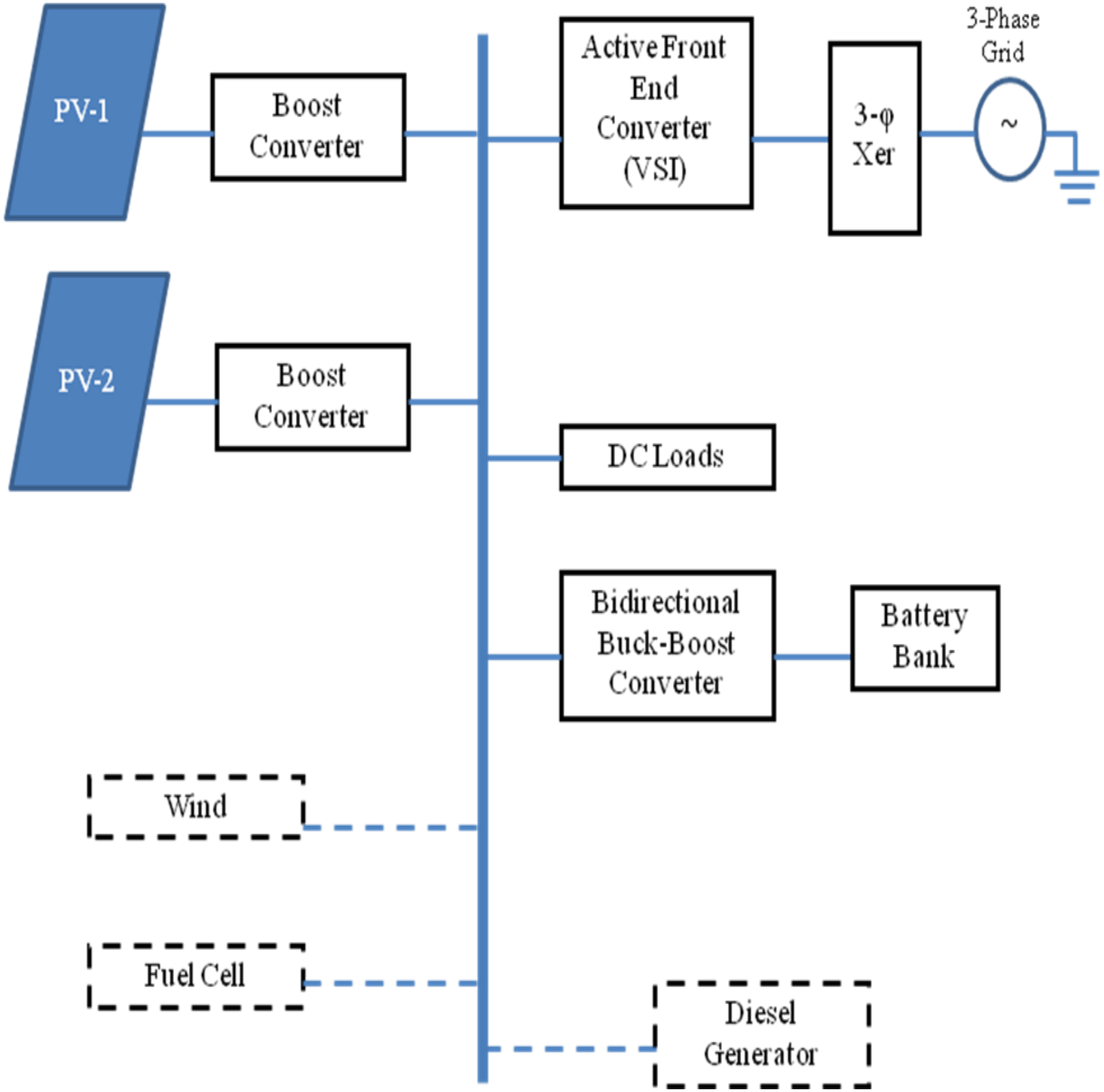
Why continue to use AC appliances?

- Lighting
  - LEDs, 10 to 100 times more efficient as compared to tungsten bulb, use only DC power
  - CFL is neutral to AC or DC power



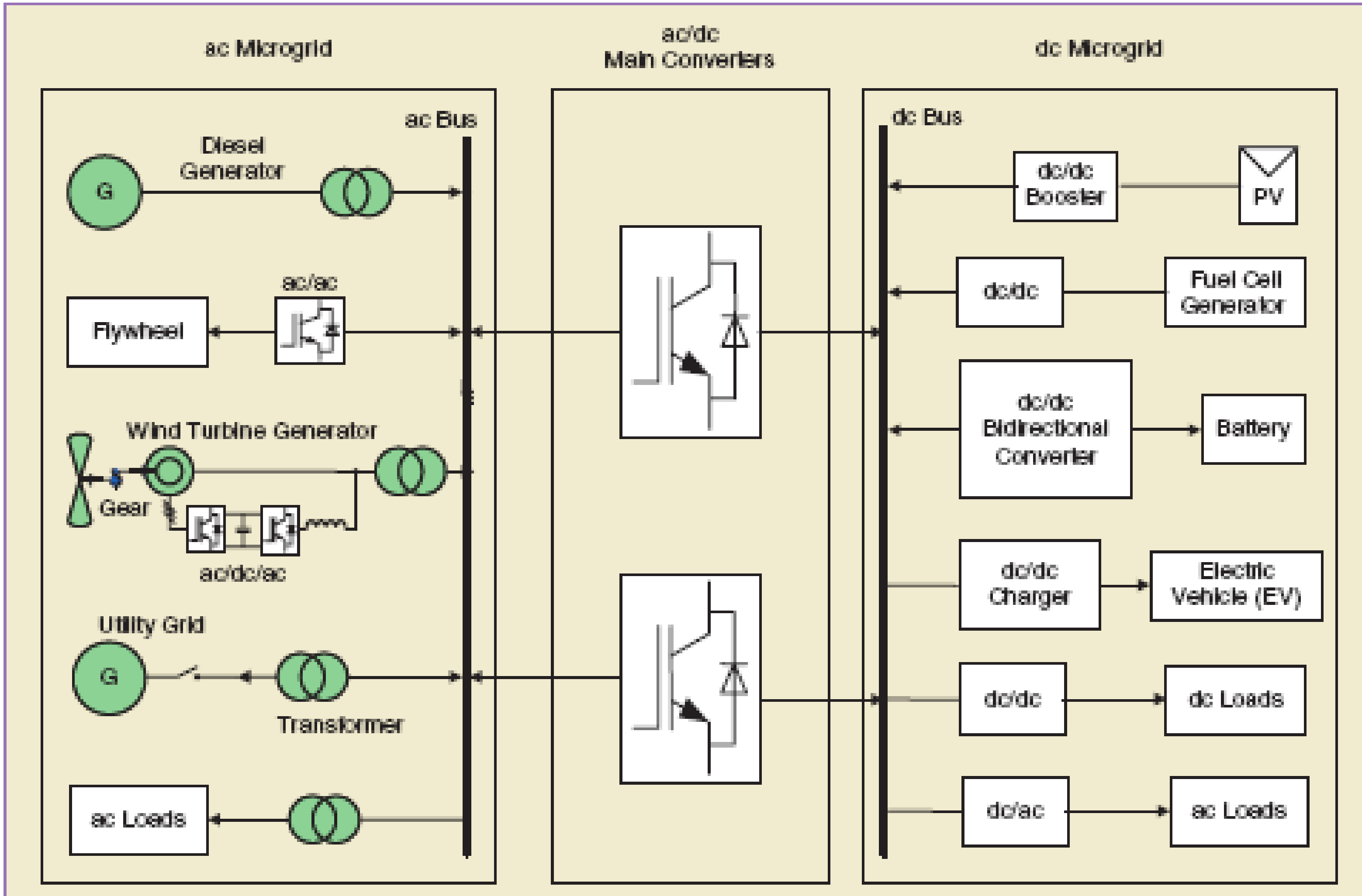
- Motor: a small DC motor can be 2.5 tomes more energy efficient as compared to a AC motor
  - Historically brush replacement needed – but not anymore
  - A fan is primarily a motor – a dc fan also allows better speed control
  - A refrigerator is essentially a motor
  - An air-conditioner is primarily a motor
  - A washing-machine / grinder is a motor

- Electronics: all electronics (mobiles/TV/Computers) use low voltage DC
  - Need a ac/dc power adaptor to charge
- World switched to AC primarily for transmission of power
  - Any ac / dc conversion or vice-versa implies 7 to 15% losses



DC Micro-grid System.

Hybrid AC/DC Microgrid



AC vs. DC Micro Grid

- Some of the issues with Edison's dc system:
  - Voltage-transformation complexities
  - Incompatibility with induction (AC) motors

- Power electronics help to overcome difficulties
  - Also introduces other benefits – DC micro-grids

- DC micro-grids
  - Help eliminate long AC transmission and distribution paths
  - Most modern loads are DC – modernized conventional loads too!
  - No need for frequency and phase control – stability issues?

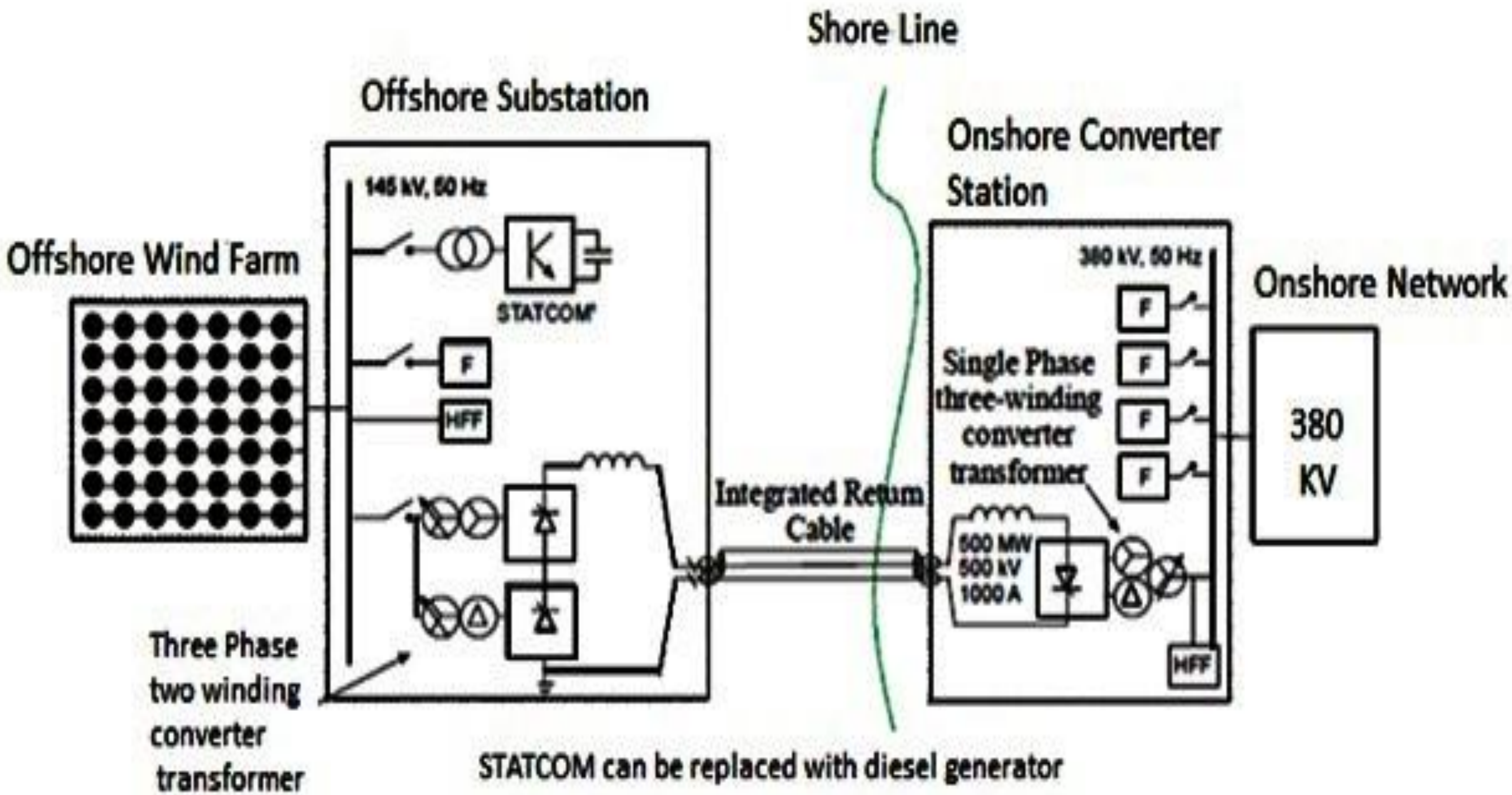
AC vs. DC Micro Grid

- **Cabling in DC distribution**
  - Greater current carrying capacity with DC system over AC
  - Therefore smaller and cheaper distribution cables for a given power
- **Interconnection into HVDC schemes**
  - Lower reacatance as large transformers & filters AC can be removed at offshore platform
  - Less components provides higher availability and less maintenance
- **DC transformer less, & filter less generation can provide efficiency improvements**

Challenges to DC systems

- ❖ **Technology**
  - ➢ Lack of DC on-load circuit breakers.
    - – Converteam’s Foldback Technology provides a solution
  - ➢ Can we generate in DC effectively?
- ❖ **Standards**
  - ➢ Real need for open standards if ideas such as Multi-terminal HVDC schemes, i.e. Supergrid, are to be realised
    - – Best achieved at pre-competitive stage
- ❖ **Supply chain partnering**
  - ➢ To be ready and on time
- ❖ **Fantastic opportunities for innovation**
  - ➢ Great challenges for Universities and R&D teams

Voltage Stability Assessment of Grid Connected Offshore Wind Farms


Shore Line
Offshore Substation
Onshore Converter Station
145 kV, 50 Hz
Offshore Wind Farm
STATCOM
F
HFF
Three Phase two winding converter transformer
Integrated Return Cable
Single Phase three-winding converter transformer
380 kV, 50 Hz
Onshore Network
380 KV
500 MW
500 kV
1000 A
STATCOM can be replaced with diesel generator

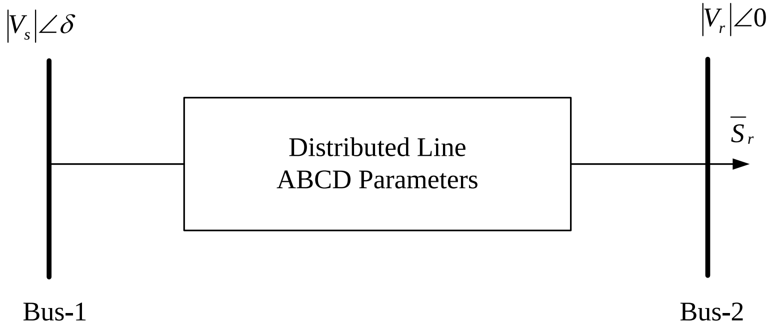
Comparison of Bulk Power Transmission

	HVAC	LCC based HVDC	VSC based HVDC
Maximum voltage Level	150 kV installed 245 kV claimed	Nor Ned: ±450 kV	± 150 kV installed ± 300 kV claimed
Substation volume	Smallest size	Biggest size	Medium size
Cable installation	Complex	Simple	Simple
Substation Installation Cost	Low	High	Highest
Compensation needed	Yes	Yes	No
Active power control	No	Yes	Yes
Reactive power control	No	No	Yes
Grid interconnections	Synchronous	Any	Any
Black start capability	Yes	No	Yes
Installation cost of cables	High	Low	Low

- **Offshore wind farms are connected to the grid through a long offshore/onshore cable having *substantial capacitive impedance* .**
- ***Voltage stability* and *reactive power management* are the concern.**
- **The *fluctuations* in mechanical input and *gusts* of wind will result in output-power spikes at the generator terminals. This causes poor voltage regulation and may lead to *voltage collapse* .**
- **A generalized dynamic voltage collapse index (*GDVCI*) suitable for long radial long transmission network has been proposed.**
- ***GDVCI* represents the distance to voltage collapse in terms of loading margin to maximum loading .**

Generalized Dynamic Voltage Collapse Index

$$S_r = V_r I_r^*$$



Let, $A = |A|\angle\alpha$ and $B = |B|\angle\beta$

where, *A*, *B*, *C* and *D* are generalized circuit constant and can be given as, $A = D = \cosh(\gamma l)$ $B = Z_C \sinh(\gamma l)$ $C = \dfrac{\sinh(\gamma l)}{Z_C}$

where,

z , y = Series & shunt impedance per unit length, respectively,

l = Length of line

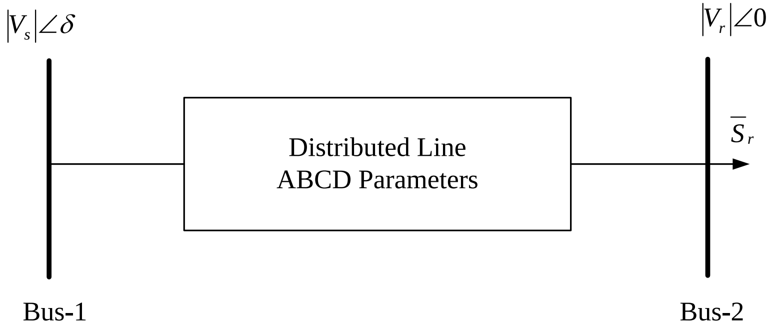
Z (=zl), Y (=yl)= Total series & shunt impedance, respectively

Z_C = *sqrt (z/y)* = characteristic impedance

γ = *sqrt (zy)* = propagation constant

$$S_r = \frac{|V_s||V_r|}{|B|}\angle(\beta-\delta) - \frac{|A||V_r|^2}{|B|}\angle(\beta-\alpha)$$

Generalized Dynamic Voltage Collapse Index



The active power (P_r) and reactive power (Q_r) at receiving end (Bus-2) i.e. at the PCC can be written as

$$P_r = \frac{|V_s||V_r|}{|B|}\cos(\beta-\delta) - \frac{|A||V_r|^2}{|B|}\cos(\beta-\alpha)$$

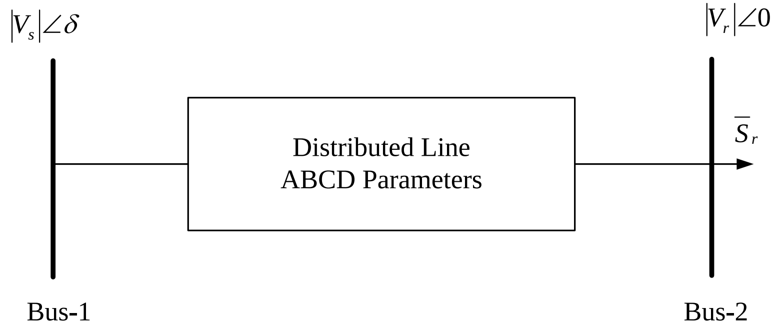
$$Q_r = \frac{|V_s||V_r|}{|B|}\sin(\beta-\delta) - \frac{|A||V_r|^2}{|B|}\sin(\beta-\alpha)$$

Squaring and adding equations , we get

$$P_r^2 + Q_r^2 + \frac{|A|^2|V_r|^4}{|B|^2} + 2\frac{|A||V_r|^2}{|B|}\left(P_r\cos(\beta-\alpha) + Q_r\sin(\beta-\alpha)\right) = \frac{|V_s|^2}{|B|}$$

$$|V_r|^4\left(\frac{|A|^2}{|B|^2}\right) + |V_r|^2\left[\left(2\frac{|A|}{|B|}\begin{pmatrix} P_r\cos(\beta-\alpha)+ \\ Q_r\sin(\beta-\alpha) \end{pmatrix}\right) - \frac{|V_s|^2}{|B|}\right] + P_r^2 + Q_r^2 = 0$$

Generalized Dynamic Voltage Collapse Index



$$|V_r|^2 = \frac{-b \pm \sqrt{\left(b^2 - 4ac\right)}}{2a}$$

$$a = \left(\frac{|A|^2}{|B|^2}\right) \quad , \qquad c = \left(P_r^2 + Q_r^2\right)$$

$$b = \left[\left(2\frac{|A|}{|B|}\left(P_r\cos(\beta-\alpha) + Q_r\sin(\beta-\alpha)\right)\right) - \frac{|V_s|^2}{|B|}\right]$$

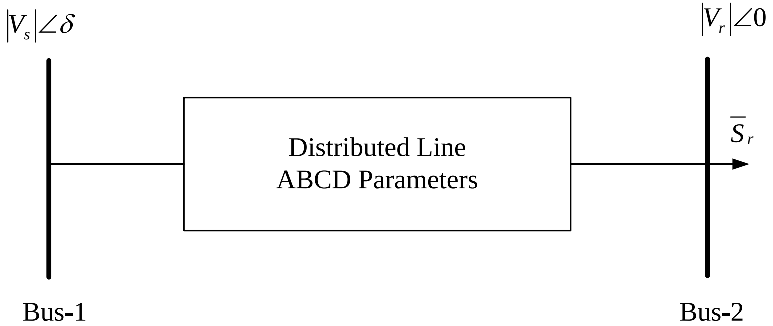
Solution of equation will exist only if,

$\left(b^2 - 4ac\right) \geq 0$ i.e.

$$\left[\left(2\frac{|A|}{|B|}\left(\begin{matrix}P_r\cos(\beta-\alpha)+ \\ Q_r\sin(\beta-\alpha)\end{matrix}\right)\right) - \frac{|V_s|^2}{|B|}\right]^2 - 4\left(\frac{|A|^2}{|B|^2}\right)\left(P_r^2 + Q_r^2\right) \geq 0$$

Generalized Dynamic Voltage Collapse Index

At maximum loadability point $(P_r + j\,Q_r)$ is replaced by $GDVCI * (P_r + j\,Q_r)$



$$\left[\left(2\frac{|A|}{|B|}\left((GDVCI)P_r\cos(\beta-\alpha)+(GDVCI)Q_r\sin(\beta-\alpha)\right)\right)-\frac{|V_s|^2}{|B|}\right]^2-4\left(\frac{|A|^2}{|B|^2}\right)(GDVCI)^2\left(P_r^2+Q_r^2\right)=0$$

$$(GDVCI)^2\left(\left(P_r\sin(\beta-\alpha)+Q_r\cos(\beta-\alpha)\right)^2\right)+(GDVCI)\left(\frac{|V_s|^2}{|A||B|}\left(P_r\cos(\beta-\alpha)+Q_r\sin(\beta-\alpha)\right)\right)-\frac{|V_s|^4}{4|A|^2|B|^2}=0$$

$$GDVCI=\frac{-b_1\pm\sqrt{\left(b_1^2-4a_1c_1\right)}}{2a_1}$$

$$a_1=\left(P_r\sin(\beta-\alpha)+Q_r\cos(\beta-\alpha)\right)^2$$

$$b_1=\frac{|V_s|^2}{|A||B|}\left(P_r\cos(\beta-\alpha)+Q_r\sin(\beta-\alpha)\right)$$

$$c_1=-\frac{|V_s|^4}{4|A|^2|B|^2}$$

Generalized Dynamic Voltage Collapse Index

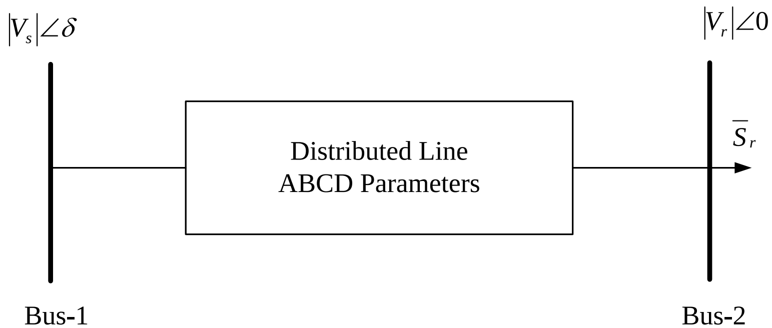
- **The *GDVCI* is expressed in terms of active and reactive power at Bus-2, voltage at Bus-1 and ABCD parameters of transmission Line/cable**

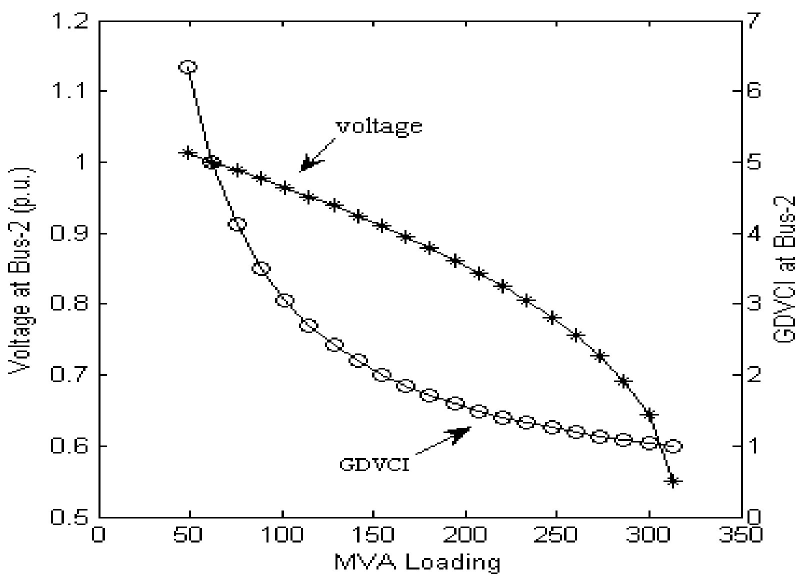
- **The index, *GDVCI*, when multiplied with a complex power at Bus-2 will give the maximum power that can be delivered at Bus-2 for given Bus-1 voltage.**

- ***GDVCI* represents the additional power (maximum loading – existing loading) that may be increased /decreased at Bus-2 before reaching collapse point .**

- **If *GDVCI* approaches to unity, it infers that transmission line is at its maximum loading and on the proximity to voltage collapse. For voltage stability, *GDVCI* must be higher than 1.**

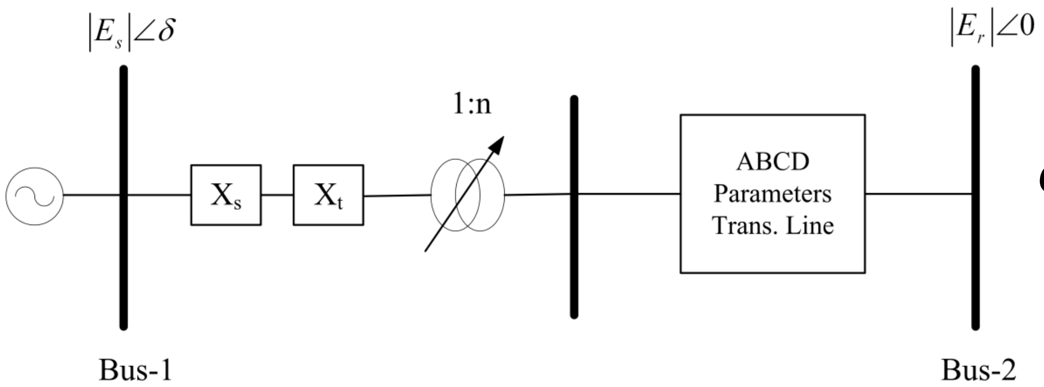
Simulation Results



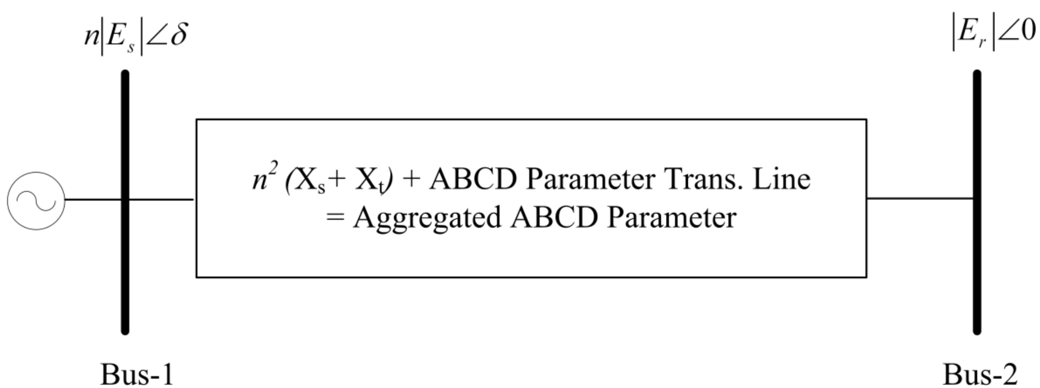


MVA loading at Bus-2	Voltage at bus-2 (p.u.)	*GDVCI* at Bus-2	Loading margin to reach maximum loading point MVA*(GDVCI-1)	*L-index* at Bus-2
48.84	1.0121	6.3418	260.8959	0.0429
62.04	1.0008	4.9925	247.6959	0.0538
75.24	0.9891	4.1166	234.4959	0.0657
88.44	0.9771	3.5022	221.2959	0.0784
101.64	0.9646	3.0474	208.0959	0.0920
114.84	0.9517	2.6971	194.8959	0.1066
128.04	0.9384	2.4191	181.6959	0.1221
141.24	0.9244	2.193	168.4959	0.1388
154.44	0.9099	2.0055	155.2959	0.1568
167.64	0.8948	1.8476	142.0959	0.1763
180.84	0.8788	1.7128	128.8959	0.1975
194.04	0.862	1.5962	115.6959	0.2208
207.24	0.8441	1.4946	102.4959	0.2466
220.44	0.8249	1.4051	89.2959	0.2755
233.64	0.8042	1.3257	76.0959	0.3083
246.84	0.7815	1.2548	62.8959	0.3462
260.04	0.7562	1.1911	49.6959	0.3912
273.24	0.7271	1.1336	36.4959	0.4469
286.44	0.6917	1.0813	23.2959	0.5207
299.64	**0.6435**	**1.0337**	**10.0959**	**0.6347**
312.84	**No Sol.**	**0.9901**	**-3.1041**	**0.9141**

GDVCI Index with OLTC operation



$$GDVCI_o = \frac{-b_2 \pm \sqrt{\left(b_2{}^2 - 4a_2c_2\right)}}{2a_2}$$

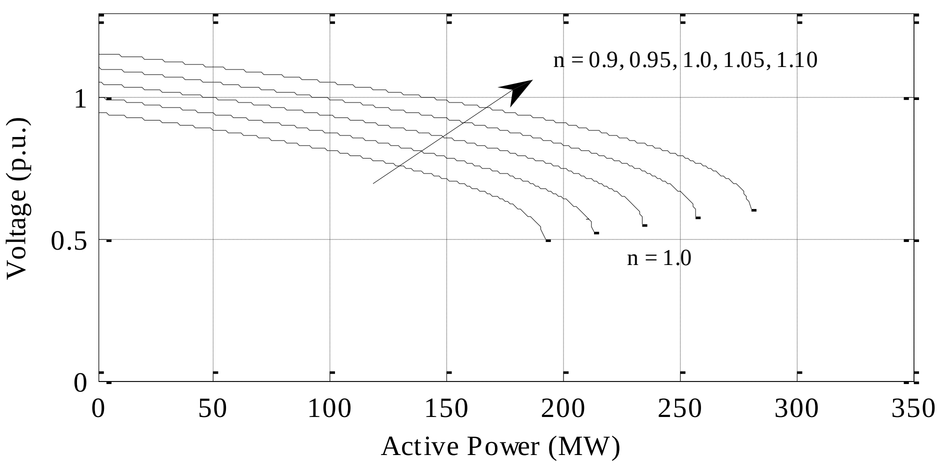


$$a_2 = \left(P_r \sin(\beta_o - \alpha_o) + Q_r \cos(\beta_o - \alpha_o)\right)^2$$

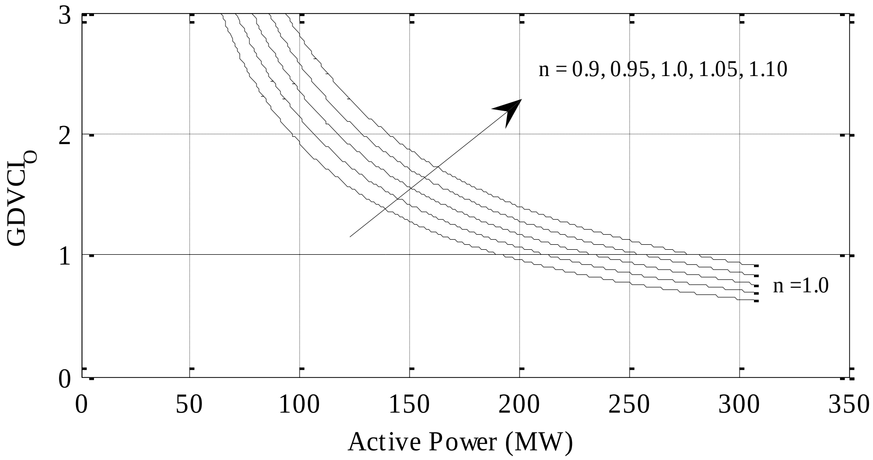
$$b_2 = \frac{n^2|E_s|^2}{|A_o||B_o|}\left(P_r \cos(\beta_o - \alpha_o) + Q_r \sin(\beta_o - \alpha_o)\right)$$

$$c_2 = -\frac{n^4|E_s|^4}{4|A_o|^2|B_o|^2}$$

Effects of OLTC Operation



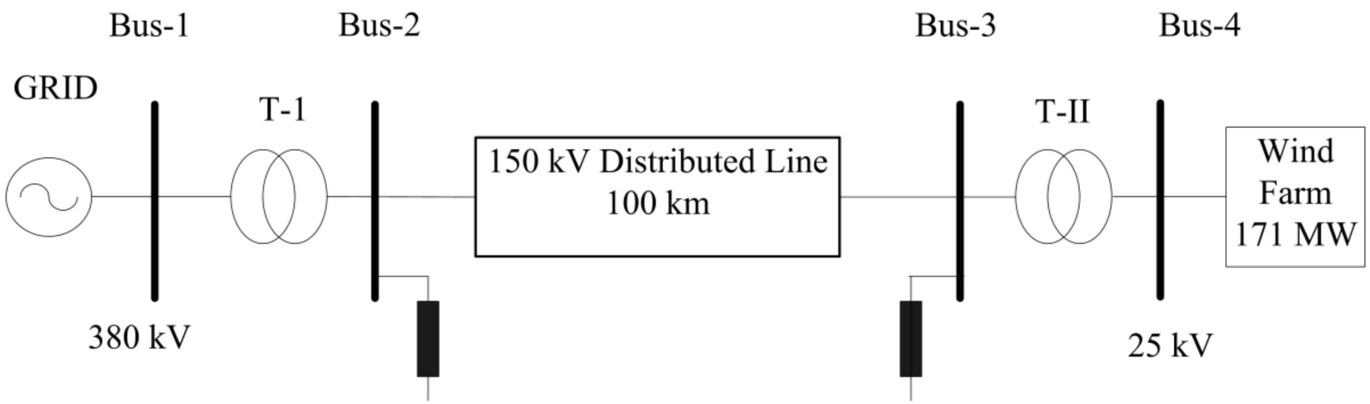
(a) P-V curves

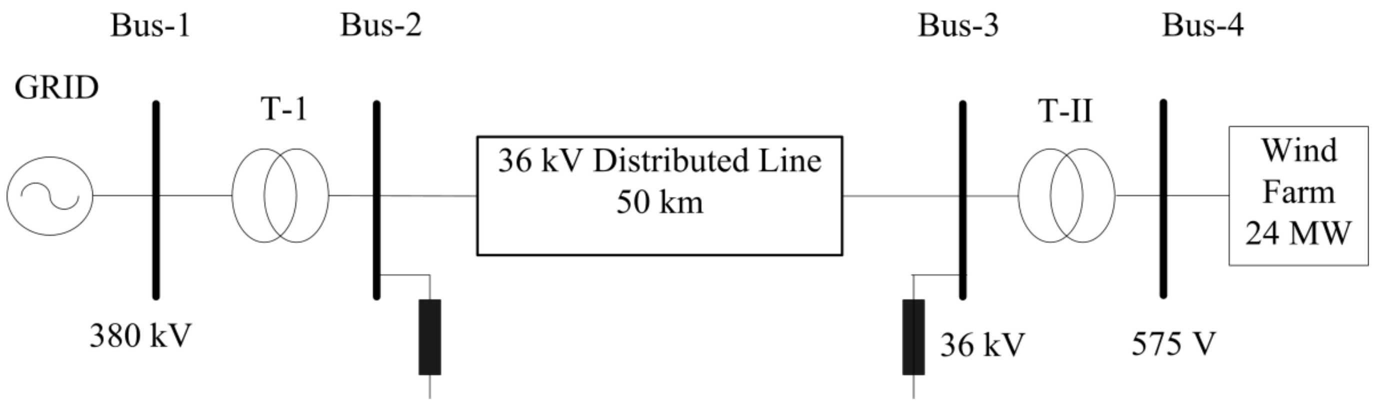


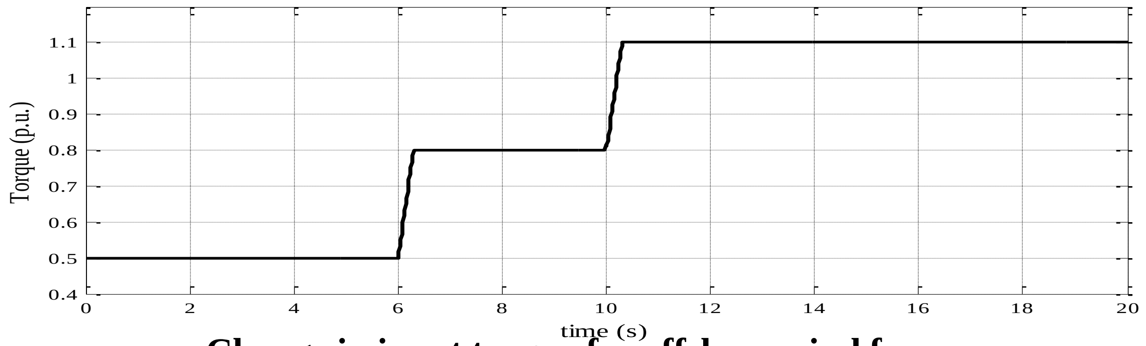
(b) Voltage Collapse Index

There is increase in the maximum power transfer limit and $GDVCI_0$ with increase in tap setting (*n*)

Case Studies: Offshore Wind Farms

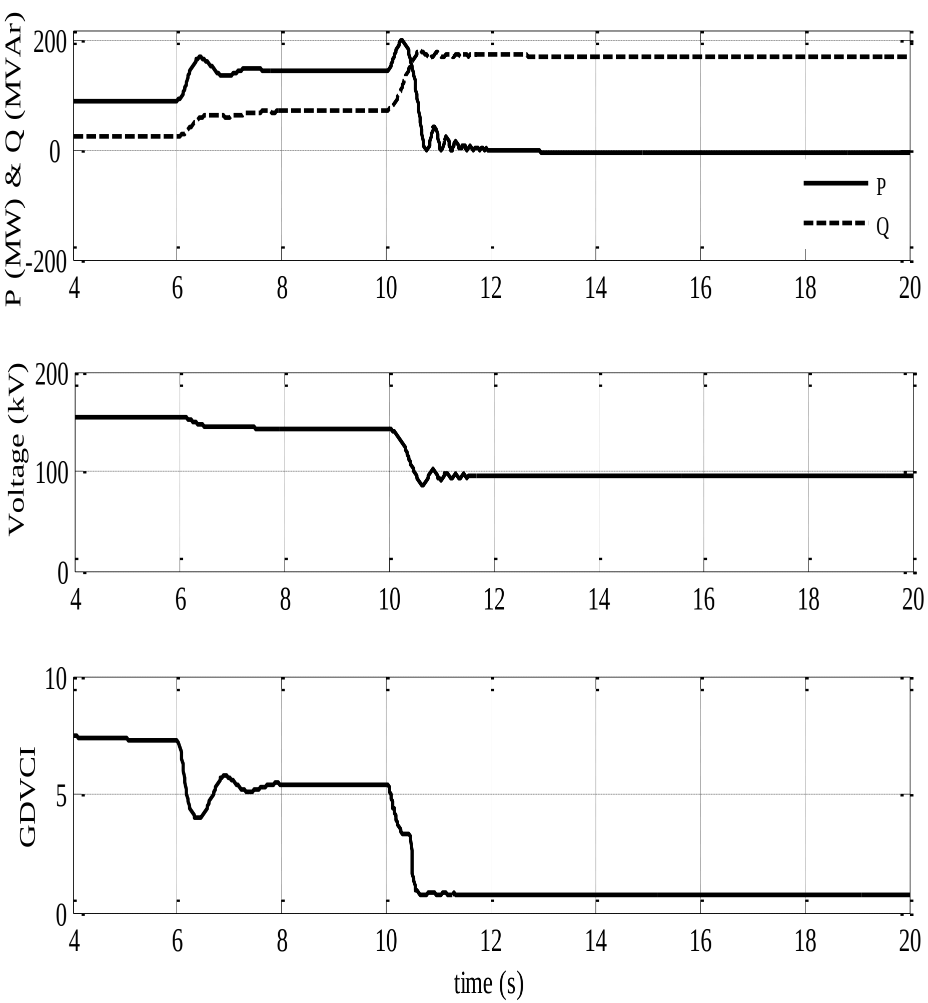




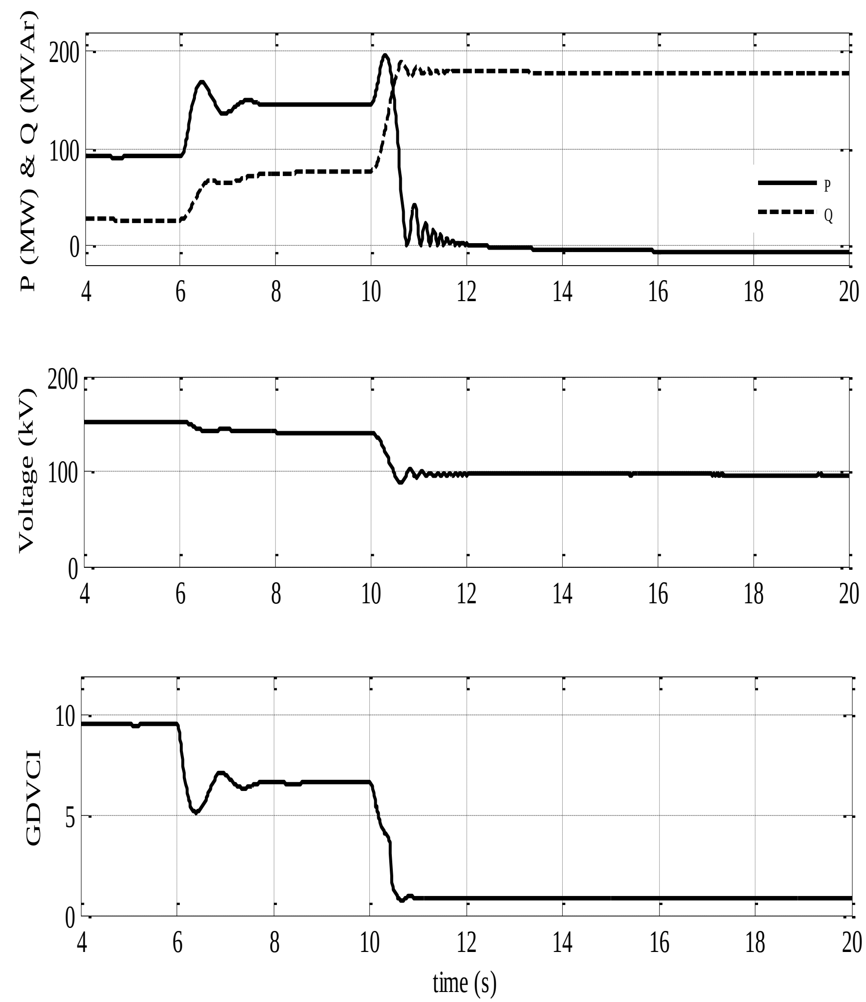


Change in input torque for offshore wind farms

Dynamic Response of the 171 MW Offshore Wind Farm

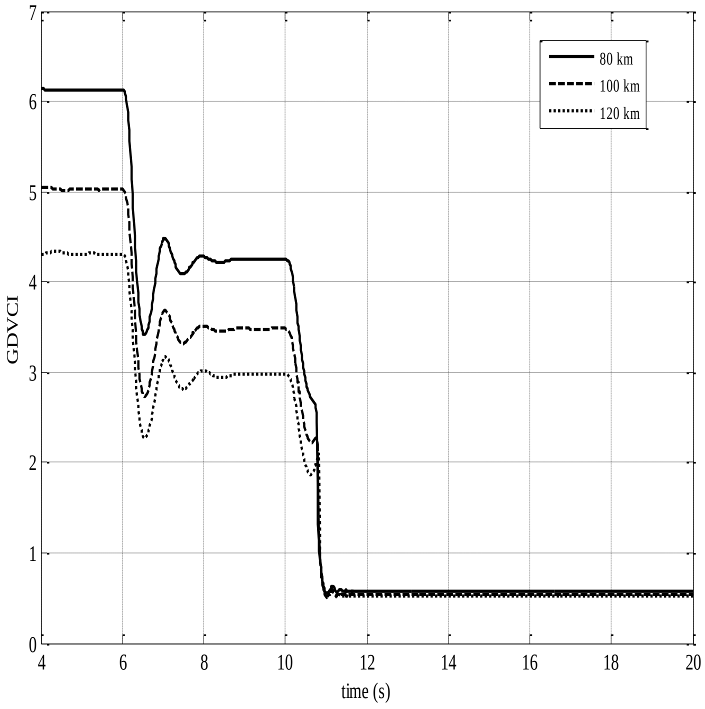


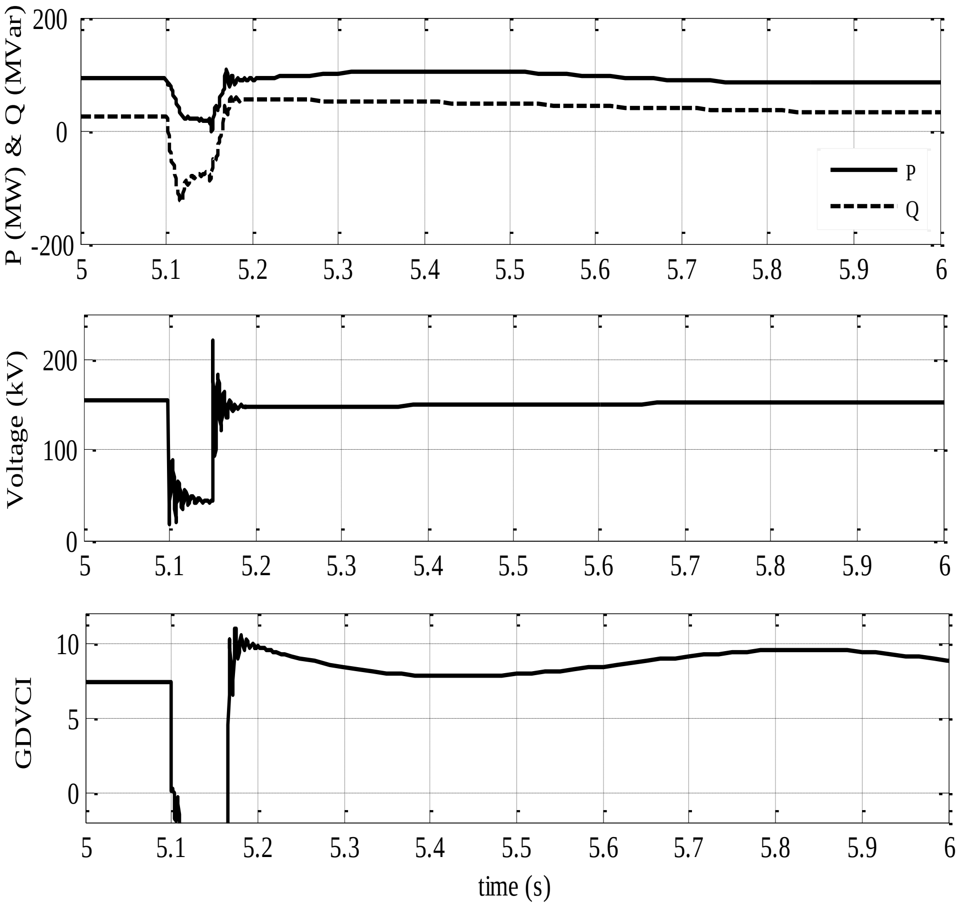
Transmission line length of 100 km



Two transmission lines (50 km each) of different parameters connected in cascading

Dynamic Response of the 171 MW Offshore Wind Farm

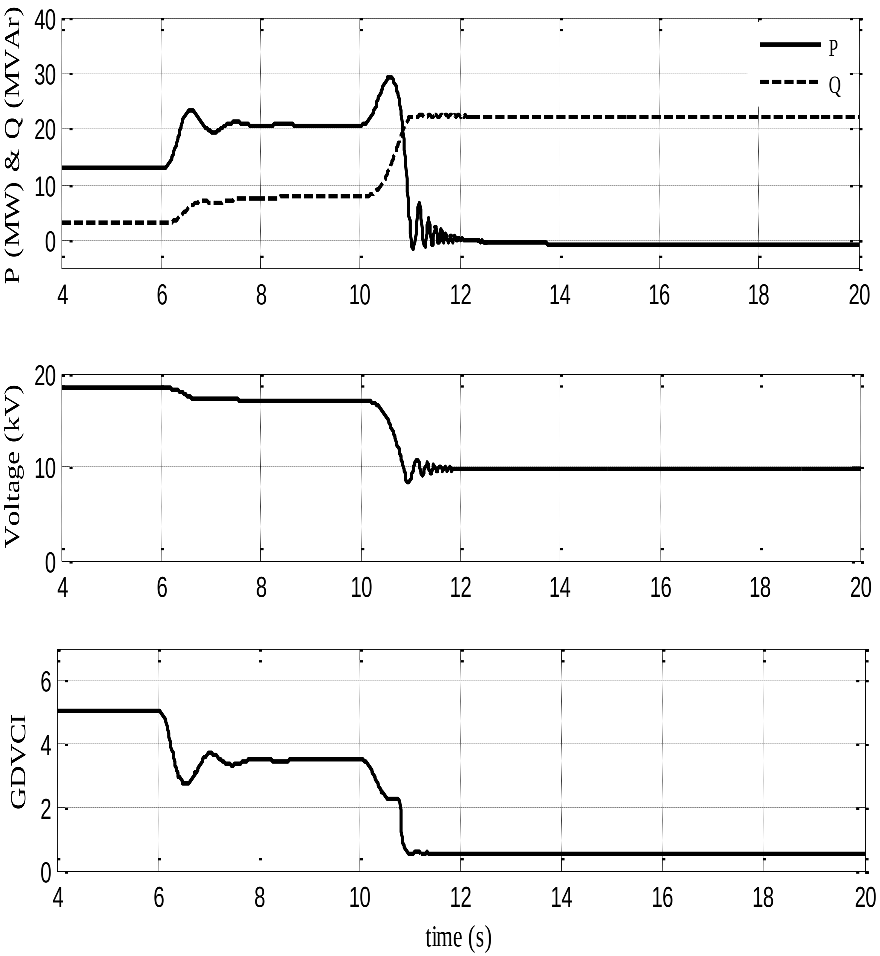




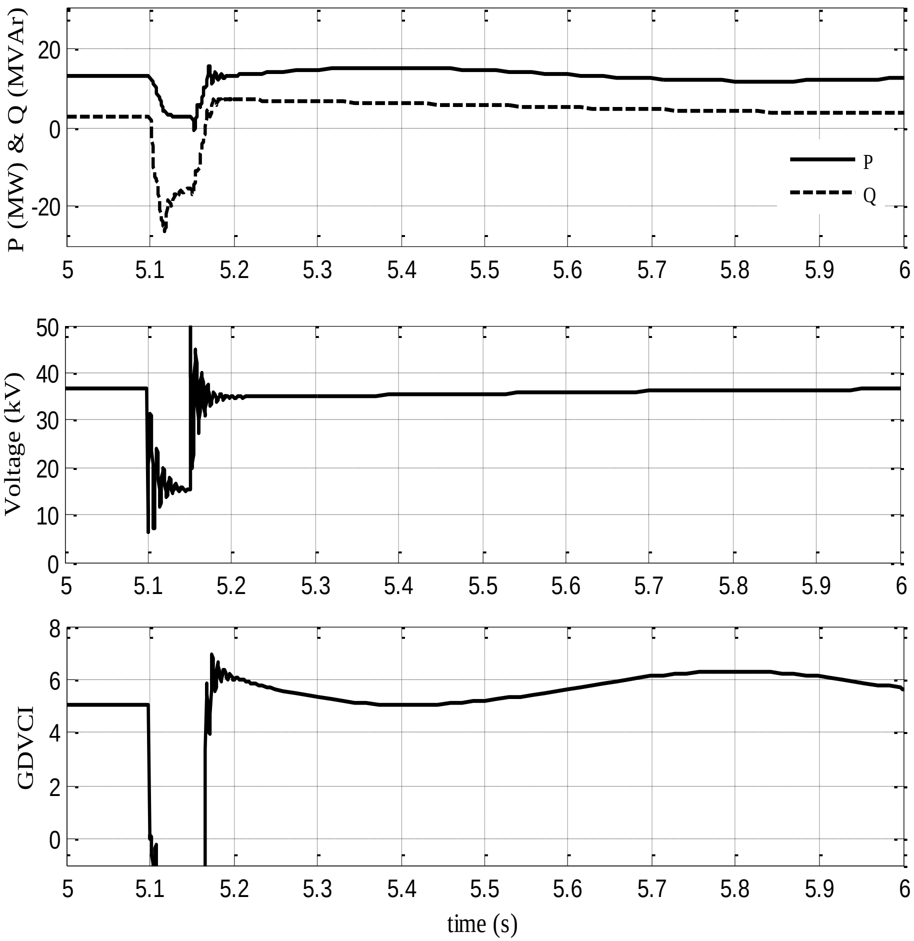
Three different transmission line length (80,100,120 km) on *GDVCI*

Three-phase gird short circuit fault

Dynamic Response of the 24 MW Offshore Wind Farm



Transmission line length of 50 km



Three-phase gird short circuit fault

Conclusions

- **Formulation of the *GDVCI* is very general and can be easily extended to incorporate power system elements in between two buses of radial system.**

- **Implementation of *GDVCI* does not involve iterations and hence gives instantaneous values.**

- ***GDVCI* performs better than *L-index*.**

- **The dynamic performance of *GDVCI* for a fault condition on offshore wind farms shows *effective* performance in estimating voltage collapse (i.e. loading margins) and can be used as a protective measure as voltage collapse indicator.**

Thank You
and Questions