Power Grids
Normal Operation and Failures

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My talk...

- Power System
  - Structure, Operation and Control

- An example of a Power Grid: India

- An example of a Grid Failure
"Except for a few islands and some small isolated systems, the entire electric grid is really one big circuit. The humble wall outlet is actually a gateway to one of the largest and most complex objects ever built. The grid encompasses billions of individual components, tens of millions of miles of wire and thousands of individual generators."

Thomas Overbye, Re-engineering the Electric Grid, American Scientist, 2000, Vol. 88, Iss. 3.
Bulk Power Systems

Bulk power system network

Load centre
Distribution network

Auto Transformer

15 KV 220 KV

To a neighboring system

66 KV

Long HVDC line

220 KV

66 KV

400 KV 16 KV
Common Doubts for a non-specialist

- Why interconnect to form large grids?
- Why AC and not DC?
  Role of DC in modern power grids
- Why 50 Hz / 60 Hz?
- Why Three phase?
Synchronous Links

- **Synchronous Grid:**
  - Synchronous machines interconnected with AC lines

![Diagram of Synchronous Grid]

Induction Generators?
Synchronous Links

- **Synchronous Grid:**
  - Synchronous machines interconnected with AC lines
  - Power Flow in AC lines - function of Voltage phase Angle Difference (determined by the relative rotor position in synchronous machines)
  - Frequency throughout grid is the same in steady state (why ?)
Synchronous Links

- **Synchronous Grid:**
  - Synchronous machines interconnected with AC lines

Induction Generators?
Dynamics in a Synchronous Grid

Centre of Inertia motion
( depends on sum of forces : $F_{g1}+F_{g2}+F_{g3}-F_{L1}-F_{L2}-F_{L3}$ )

Relative motion (swing)
Dynamics in a Synchronous Grid

- Sudden Load Throw Off
  Stable Common and Relative Motion

- Sudden Generation Trip
  Stable Common and Relative Motion

- Large Disturbance Angular Instability: **Loss of Synchronism**

- Small Disturbance Angular Instability: Growing Oscillations (triggered by *any* disturbance: big or small)
Effect of Lack of Synchronism in AC ties

Not Acceptable!
Distance Relays trip

Uncontrolled
System Separation
Asynchronous Links

- Asynchronous Interconnects
  - HVDC links: Power flows not a function of Phase Angle Difference
  - Frequencies of connected regions could “happily” be different
Synchronous Links

\[(P_{\text{GEN1}} - P_{\text{LOAD1}}) - (P_{\text{GEN2}} - P_{\text{LOAD2}}) = P_1 + P_2\]

Frequency of Area 1 and 2 is the same (in steady state)
Asynchronous Link

Frequency of Area 1 and 2 need not be the same
Synchronous or Asynchronous?

\[(P_{GEN1} - P_{LOAD1}) - (P_{GEN2} - P_{LOAD2}) = P1 + P2\]

Frequency of Area 1 and 2 is the same (in steady state)
Issues in Interconnected Systems

- Ownership

- Monitoring & Control Hierarchy

- Cooperation and Coordination is necessary!
Subsystems: Generator Control

Valve / Gate control

Power Electronic Control

TURBINE + BOILER

EXCITER

ROTOR MECHANICAL EQUATIONS

MACHINE WINDING EQUATIONS

GENERATOR

δ, ω

V

Ψ

MECH POWER

FIELD VOLTAGE

Machine Winding Equations
Static Excitation: Voltage Control

Main Generator

Controlled Rectifier

DC

AC
AVR

Gate/ Valve (mech) Control by governor

TURBINE and/or BOILER

MECH POWER

GENERATOR

ROTOR (MECHANICAL EQUATIONS)

\[ \delta, \omega \]

\[ V \]

\[ \Psi \]

MACHINE WINDING EQUATIONS

POWER ELECTRONIC VALVE CONTROL

EXCITER

FIELD VOLTAGE

REFERENCE VOLTAGE

POWER ELECTRONIC VALVE CONTROL

AVR

Terminal Voltage of Generator

NETWORK
Frequency Control

- Frequency Depends on Cumulative Load-Gen Balance in a Synchronous Grid
- Load is Weakly Frequency Dependent
- Generation-Load Balance has to be Maintained.
- Generation Control or Load Shedding
Subsystems: Generator Control

- Valve / Gate control
- Power Electronic Control

TURBINE + BOILER → MECH POWER

EXCITER → FIELD VOLTAGE

GENERATOR

δ, ω, V, Ψ

ROTOR MECHANICAL EQUATIONS

MACHINE WINDING EQUATIONS

FIELD VOLTAGE
Primary Control
Speed Control (Governor)

Load Sharing by different generators: Droop Control
Power Flow (Synchronous Grids)

Line Flows Depend on Line Parameters
Power Flow (Synchronous Grids)
Power Flow Control in AC lines

Modulation also possible with these devices
Control Centre
Present SCADA/EMS – Multi way information Flow

Unified Load Despatch & Communication

5 Nos.

Region Level

31 Nos.

National Level

51 Nos.

State HQ Level

1649 Nos.

Group of District Level

Plant/Sub Station Level

NLDC

RLDC

SLDC

SUB LDC

RTU
Preventive Control

1. (STATIC) DATA ACQUISITION (executes every 2-4 seconds) → Remote Measurements
   - Voltage/Power "Raw" Measurements
   - Status of Circuit Breakers

2. STATIC STATE ESTIMATION (executes every 10s to 1 min)
   - Present Network/Load/Generation Configuration (Operating Condition)

3. STATIC / DYNAMIC SECURITY ANALYSIS (executes every 1 – 10 mins)
   - NORMAL STATE
   - OR
   - ALERT STATE

4. SECURITY CONSTRAINED OPTIMAL POWER FLOW (Executes every 10 – 30 mins)
   - REAL / REACTIVE POWER SCHEDULE CHANGES
Un-Synchronized Measurements

Magnitude of the two phasors can be determined independently but phase angle difference cannot be measured without synchronization of measurements.
Synchronized Measurements

Phase angular difference between the two can be determined if the two local clocks are synchronized. Synchronizing pulses obtained from GPS satellites.
The Indian Power Grid
Indian Power System: Among the Largest in the World

- National Grid (UK) 68GW
- PJM (USA) 165GW
- MidWest ISO (USA) 159GW
- RTE (France) 93GW
- Red Electrica (Spain) 93GW
- ONS (Brazil) 100GW
- Terna (Italy) 57GW
- Eskom (South Africa) 43.5GW
- SO - UPS (Russia) 146 GW
- PGIL (India) 163GW
- Tepco (Japan) 64GW
- KPX (South Korea) 70GW
- SGCC (China) 900GW

Source: VLPGO (~2011)
Some Typical Numbers (~2011)

- Generating Units :~ 1600
- 400kV & above Trans. Line :~ 700
- Transformers (High Voltage) :~ 2000
- Busses (Extra High Voltage) :~ 5000
- Control Areas :~ 100
- Inter-State Metering Points :~ 3000
- Open Access transactions typical daily :~ 100
- Captives participating in market :~ 125
The Indian Grid

Installed Capacity: ~ 180 GW
By 2027: ~575 GW

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Thermal</td>
<td>65%</td>
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<tr>
<td>Hydro</td>
<td>21%</td>
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<tr>
<td>Nuclear</td>
<td>3%</td>
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<tr>
<td>Renewable</td>
<td>11%</td>
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</table>

Renewables: Wind, Small Hydro, Biomass etc

Wind Energy: 14 GW (Fifth Largest)

Courtesy: Power Grid Corporation of India Ltd. / Ministry of Power
Five Regional Grids
Two Frequencies

October 1991
East and Northeast synchronized

March 2003
West synchronized with East & Northeast

August 2006
North synchronized with Central Grid

Central Grid

Inter – Regional Capacity: ~ 22 GW

Installed Capacity: ~ 180 GW

By 2027: ~575 GW

Courtesy: POSOCO

MERGING OF MARKETS

SR Synch By 2013-14

NEW Grid

Five Regional Grids
Five Frequencies

South Grid

By 2013 - 14
The Indian Grid: HVDC

HVDC (Long Distance)
1. Rihand – Dadri
2. Chandrapur – Padge
3. Talcher – Kolar
4. Balia - Bhiwadi

BACK To BACK
1. Vindhyachal
2. Bhadravati
3. Gazuwaka
4. Sasaram
The Indian Grid

Energy Resources

Major Load Centres

Hydro

Thermal

Courtesy: Power Grid Corporation of India Ltd. / Ministry of Power
Spatial Distribution of Load

Source:
Powerline, Oct-2006
765 KV RING MAIN SYSTEM
THE POWER ‘HIGHWAY’

Cheap Thermal

AND PIT HEAD THERMAL POWER FROM THE EAST ENTERS THE RING AND EXITS TO POWER STARVED REGIONS

Courtesy: POSOCO
The Grid Collapse of 30th July 2012

2:33:11:9 hours
Although sudden it's not inconceivable

From Geet Ramayana (G.D.Madgulkar)
MP antecedent trippings

- 00.20 hrs
  Hand tripped

- 00.05 hrs trip, 01.35 hrs
  revived Xmer

- 00.10 hrs
  overload

- ~02.34 hrs
  overload
Demand met > 70 GW in NEW grid

Scheduled vs Actual Flows
02:30 hours
Frequency: 49.68 Hz
Zone 3 tripping of Main-II
DR of Bina-Gwalior

Approx impedance seen: 110 ohm
“Distance Protection”

\[ V_1 \text{ is normally much greater than the impedance of the line } Z_L. \]
Distance Protection

Fault

Voltage at fault point is \( \sim \) zero

\[
V_1 \text{ will be equal to } Z
\]

Relay setting to detects fault on this line \( V_1 < Z_L \); immediate trip

Relay setting (back-up) for faults on neighbouring line \( V_1 < Z_L + Z_{L1} \) (Slow trip setting)
PMU data 30-7-2007, 2:33 hours
30-7-2007: WAFMS (NTP synchronized)
PMU data 30-7-2007, 2:33 hours

Events observed 2:33 hours onwards (30th July)

- Gwalior Bina Trip
- Load Encroachment
- Jamshedpur Rourkela I and II (Load Encroachment)
- Final Separation on Power Swing (ER-NR interface)
- Bhinmal Sanchore (NR-WR interface) on Power Swing (Zone 1)
First Conclusion

- The critical event leading to large angular separation was Gwalior-Bina 400 kV trip
- From DR, PMU, WAFMS : Tripping time is established to be 2:33:11:9
- Trip was NOT on fault.
- Zone3 tripping (back-up protection)
- “Load encroachment”
Zone-1 trippings at ~2:33:15, due to large angular separation ---- NR becomes an island

Balai-Biharsharif
Balai-Patna
Grkpr-Muzzpr.
Zone -1 tripping (Gorakhpur-Muzaffarpur)

Zone 1 implies $V_1/I < Z_L$
Birds-eye view (WAFMS)

System separation at this point.

Most generators will trip at 47.5 Hz
Issues

- Extreme Insecure Operation due to multiple line outages (forced/planned).
- Tripping on overload (220 kV) -
- Tripping on load-encroachment (Zone 3) – Audit of settings. Technological solution – use of PMUs
- Reactive Power Absorption: Lines opened on HV (eg Barh Balia) – reduced security
Issues

- NR : U/f relaying – very little
- WR-ER-NER : Inadequate governor response
- HVDC/TCSC power boost (angular stability controllers) ?
Restoration

Hydro-units require very little startup power
Restoration

Two islands

Synchronize generator

Disconnect from neighbouring system

Islands are synchronized

RESTORATION COMPLETE
Concluding Thoughts about the Blackout

- Back to Basics
- Technology:
  - Wide Area Measurement Systems
  - Power Electronics based interconnects
- The excitement of observing system-wide dynamic phenomena!