Grid Control Theory and Resilient Control

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Power System Resiliency

- Historical reliability – predecessor to resiliency
  - Physical elements
    - Multiple generation stations with fuel source diversification
      - Various types of power plants
        - Fossil fuel, nuclear, hydropower, solar, wind, geothermal
      - Various types of fossil fuel burners at a plant
        - Coal, natural gas, heavy oil, diesel
      - Geographically distributed
    - Mesh-based transmission network topology
      - Multiple power flow pathways
      - Connections to multiple power plants
      - Tie-lines between utilities

Power System Resiliency

- Historical reliability
  - Control elements
    - Network protection – controls for abnormal operating conditions
      - Circuit-breaker isolation of faulted physical elements
      - Reclosing functions for rapid restoration of temporary or momentary faults
    - Power plant controls
      - Generation controls – voltage and power delivery to the grid
      - Remainder of plant controls – production of electric power from fuels
        - Local pumps, valves, conveyers, blowers and fans, etc.
    - Distributed regulation controls
      - Voltage control
        - OLTC transformers, voltage regulators, capacitor banks, SVC, StatCom, etc.
      - Power flow controls – phase shifting transformers,
    - Central controls
      - Balance of power and contingency preparation

Overview of Electric Grid Controls

- Electrical grid control points
  - Power plants
    - Generator controls
      - Output power
    - Power plant operations
  - Substations
    - Network / grid controls
      - Power flows
    - Network protection
  - Tie-lines
    - Interchange controls
      - Power flows
      - Regional stability

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Overview of Electric Grid Controls

- Operational periods
  - Normal operations
    - Power balancing: generation level and customer load consumption

$$0 = \sum_{\forall gen} P_{generators} + \sum_{\forall tie} P_{tie-lines} + \sum_{\forall ld} P_{loads} + P_{losses}$$

    - Contractual fulfillment to other utilities and region
      - Tie-line imports and exports between other utilities
    - Economical operation of the system
      - Low cost electrical production, maximize revenue
      - Optimal generation dispatch
    - Optimizing the control point to minimize the impact to the system by a major disturbance or perturbation
      - Minimize impact of $N-1$ and $N-2$ contingencies
      - Spinning reserves and equipment power margins

Overview of Electric Grid Controls

- Operational periods
  - Abnormal operations
    - Physical failures
      - Loss of a generator
        - Power plant issues, fuel supply
      - Loss of a transmission line or transformer
        - Faulted circuits, transformer failure, circuit breaker failure
      - Loss of ancillary equipment
        - Capacitor banks
    - Control failures
      - Mis-operation of network protection
      - Sensory measurement errors
      - Data errors in communication network
      - Loss of communications
      - Software errors in the energy management system or the SCADA system

Overview of Electric Grid Controls

- Operational periods
  - Recovery operations
    - System resource evaluation
      - What equipment is still functioning?
      - What parts can be restored quickly?
    - Stabilizing the current operating point
      - What equipment is operating near its limits?
      - What temporary actions must be made to move away from critical limits?
    - Recovery of generation
      - What standby generation can be brought online quickly?
      - How much intertie power can be imported?
    - Recovery of outage areas
      - Who are the critical customers that are without power?
    - Repairs and restoration
      - Where does the army of line workers need to go?

Overview of Electric Grid Controls

- Classical grid threats and events
  - Weather and other natural disasters
    - Lightning, high-speed wind, heat, ice and snow
    - Earthquakes, fires, floods, volcano eruptions
  - Animals and vegetation encroachment
    - Tree limbs, fast growing plants, diseased trees
    - Squirrels and rodents, bears, birds of prey
  - Human and equipment accidents
    - Automobile crashes, low-flying aircraft
    - UAV, balloons, etc.
    - Human errors by utility workers
  - Equipment failures
    - Device ageing, power overloads, dielectric breakdown, internal heating, etc.

Overview of Electric Grid Controls

- Malfeasant grid threats and events
  - Theft and vandalism
    - Substation attacks, copper theft, shooting at equipment, tower damage
  - Cyber attacks
    - Information theft, compromised database
    - Sensory data corruption, false data injection
    - Control signal corruption, false command injection
    - Overtaking equipment, denial of function
  - Other
    - Disgruntle employees or community members
    - Carelessness, senseless behavior, pranks, being obnoxious

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Power Plant Controls

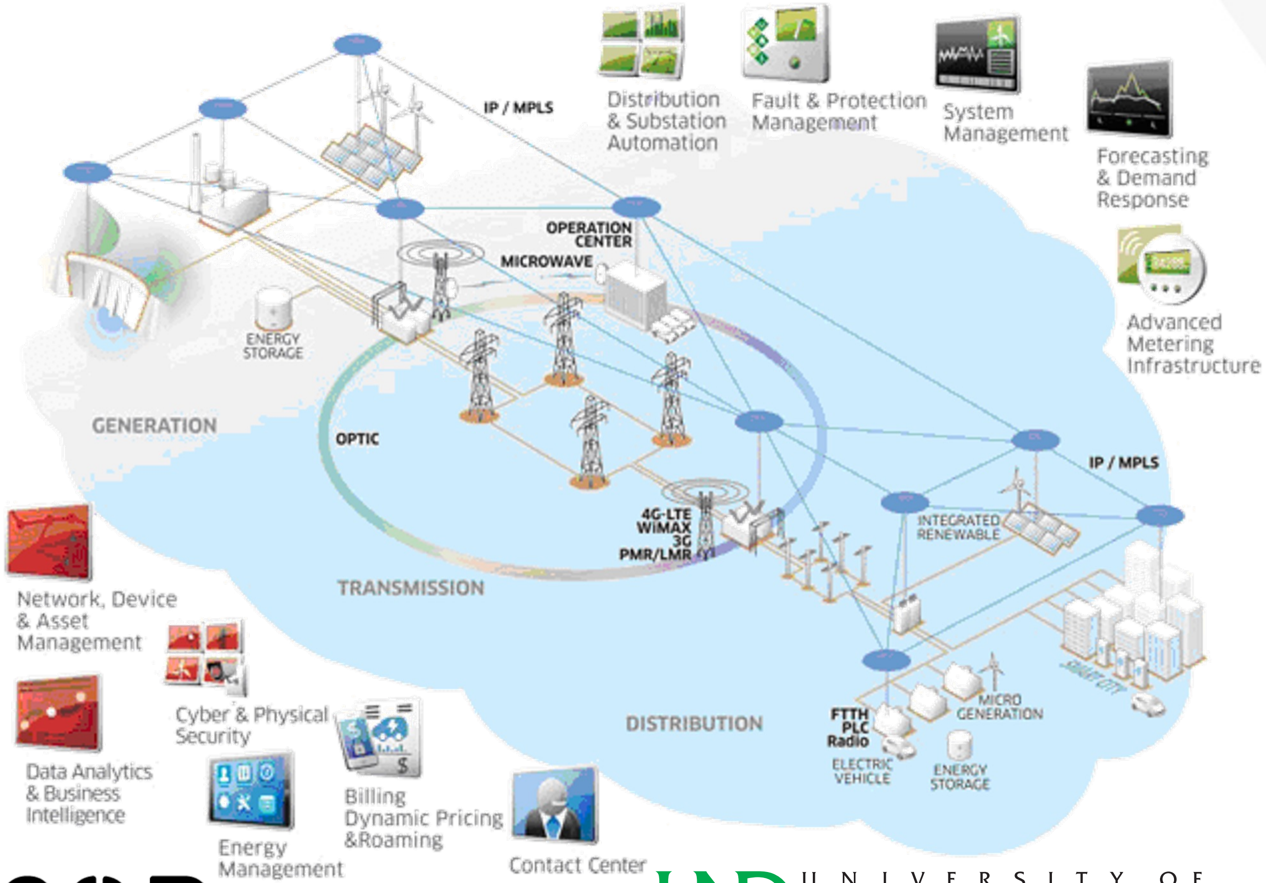
- Classical internal plant controls
  - Local control room with power plant operators
  - Systems of controllers for supporting the production of mechanical power to the generator
  - Supervisory and hierarchy control schemes with data collection
  - Alarms and warning systems associated with power plant operations
  - Conditional monitoring of the plant's equipment
- Classical interface controls with the grid
  - Governor / shaft speed control
    - Scheduled active power production and maintain system's electrical frequency at 60 Hz
  - Voltage regulator and excitation control
    - Scheduled reactive power production and maintain system's voltage profile

Substation Controls

- Classical substation controls
  - Most substations are automated and unmanned
    - A few critical and important substations have small crews for quick response times
  - Functions of substations
    - Primary: voltage transformation, transmission line interconnects, and fault protection
    - Secondary: reactive power supply and voltage regulation
  - Control points
    - Circuit breaker operations, local tap-changer controls, local reactive compensation controls
    - Protective relay (and other Intelligent Electronic Devices, IED) setpoints and parameters
  - Data gathering
    - Operational and non-operational measurements and performance data
      - Operational data includes power flows, voltages, circuit breaker status, and fault currents

Utility Control Center

- Centralized generation and grid control
  - Operator stations
  - Energy Management Systems (EMS) and System Control and Data Acquisition (SCADA)
    - State Estimation (SE)
    - Optimal Power Flow (OPF)
    - Performance indices and voltage stability
    - Contingency Analysis
    - Load flow and fault analysis
  - Event and data recordings
  - Regional energy market transactions
  - NERC region (balancing authority) interface



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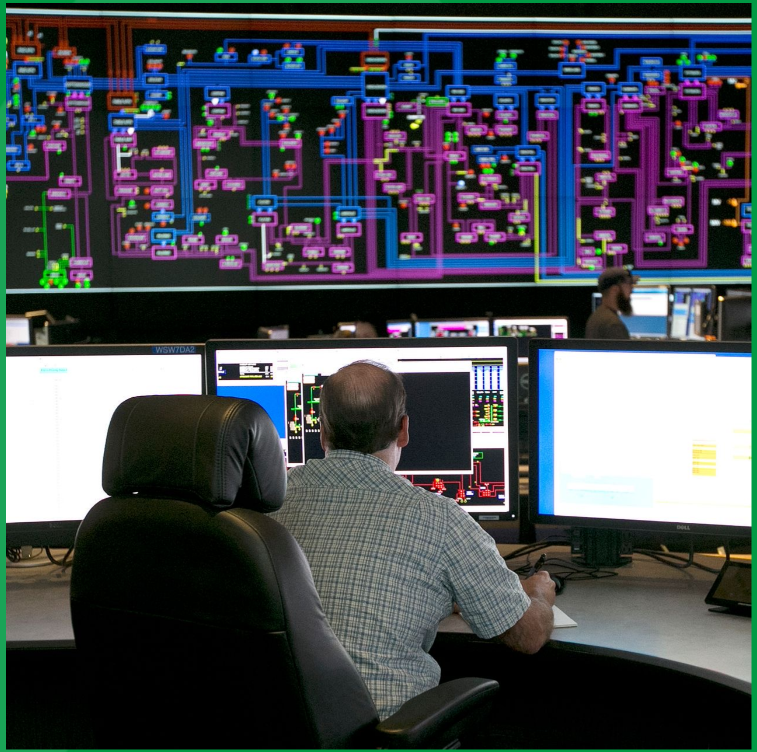
Power System Control Architecture



- Distributed Management System
- Energy Management System
- SCADA
- Data Bases
- Front-End Processors
- Communications
- Substation Remote Terminal Units
- Field Devices

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Power System Control Architecture

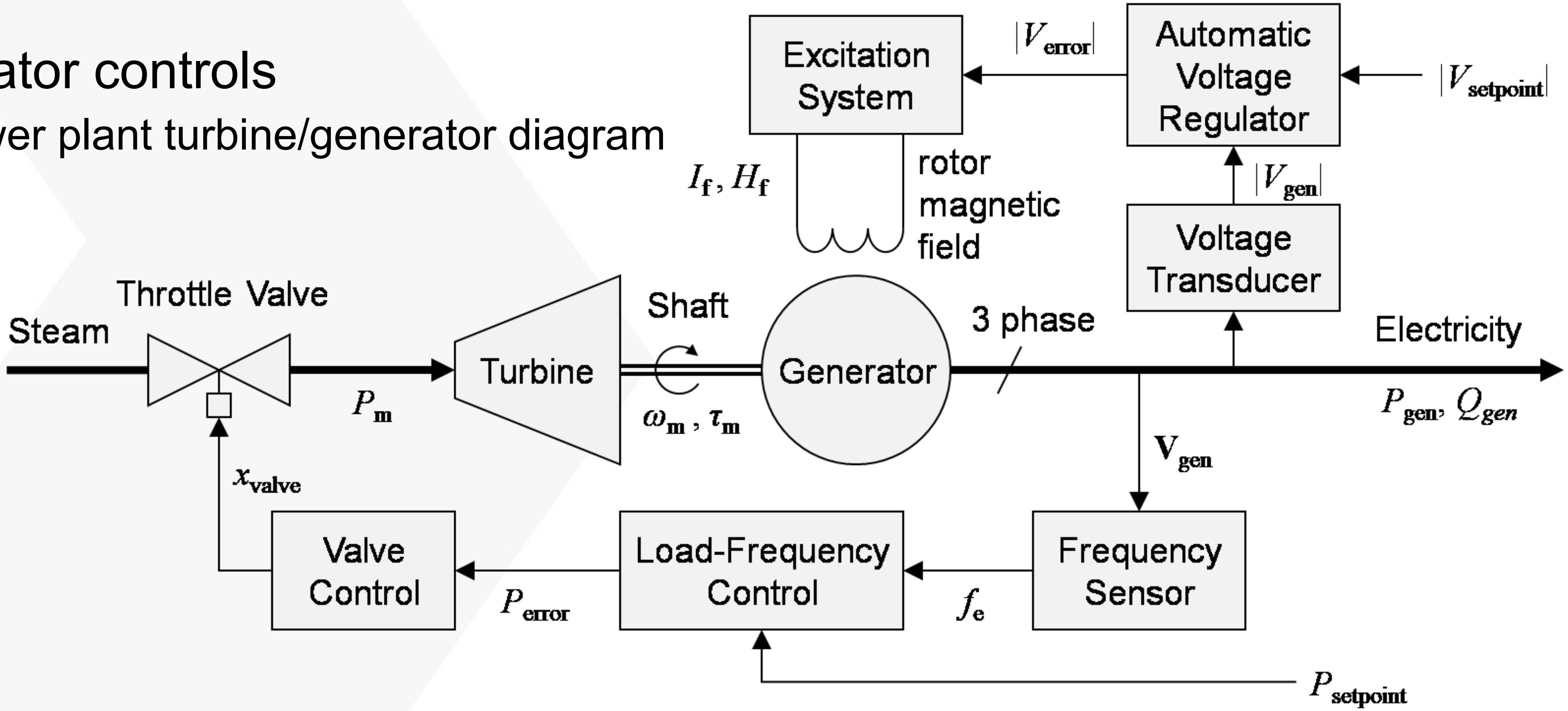
- Generator control
  - Control objectives
    - Produce electricity at the specified power
    - Maintain the shaft speed for 60 Hz operation
    - Maintain the specified terminal voltage
    - Drive the Area Control Error (ACE) to zero
  - Control laws
    - Over-frequency (OF) and positive ACE
      - Reduce the prime mover power
    - Under-frequency (UF) and negative ACE
      - Increase the prime mover power
    - OF and negative ACE or UF and positive ACE
      - Use weighted coefficients in the counterbalance between frequency and ACE for dominate error

Power System Control Architecture

- Generator control
  - Control setpoint and remote inputs
    - Output power level - from Economic Dispatch
    - Terminal voltage level - from Optimal Power Flow
    - Area Control Error signal - from SCADA
  - Feedback loops
    - Governor shaft speed control
      - Steam throttle valves or hydro penstock gates
    - Automatic voltage regulator, excitation control
      - Rotor magnet currents
  - Other controls and protection systems
    - Power system stabilizer
    - Loss of field/excitation, reverse power/motoring, out-of-step/loss of synchronization, over excitation, neg. sequence, voltage/frequency, off nom. frequency
    - Phase and ground fault protection, differential protection

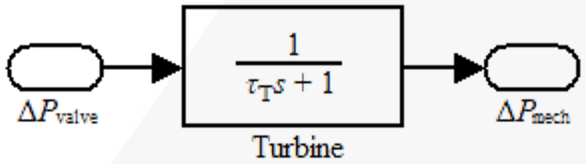
Power System Control Architecture

- Generator controls
  - Power plant turbine/generator diagram

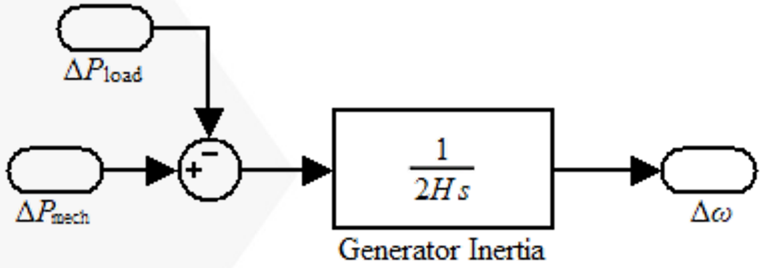


Power System Control Architecture

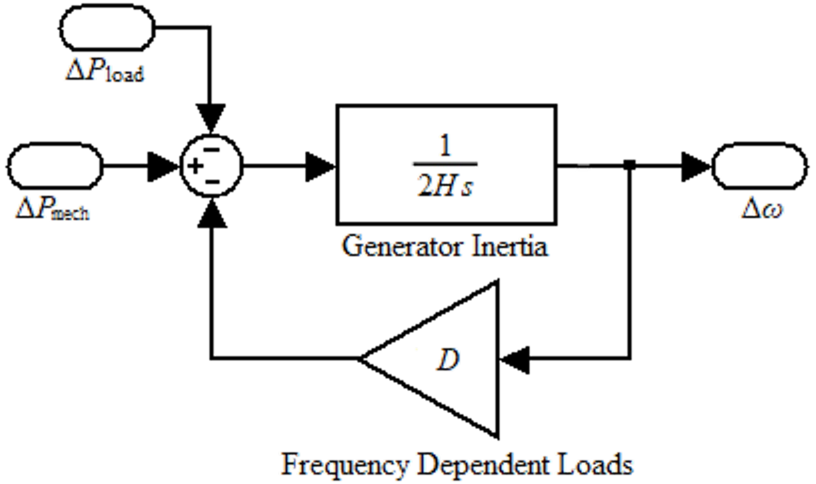
- Generator controls
  - Power plant component modeling



Turbine



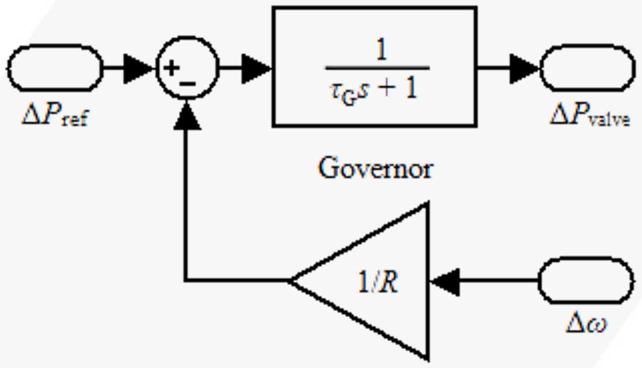
Generator with Static Load

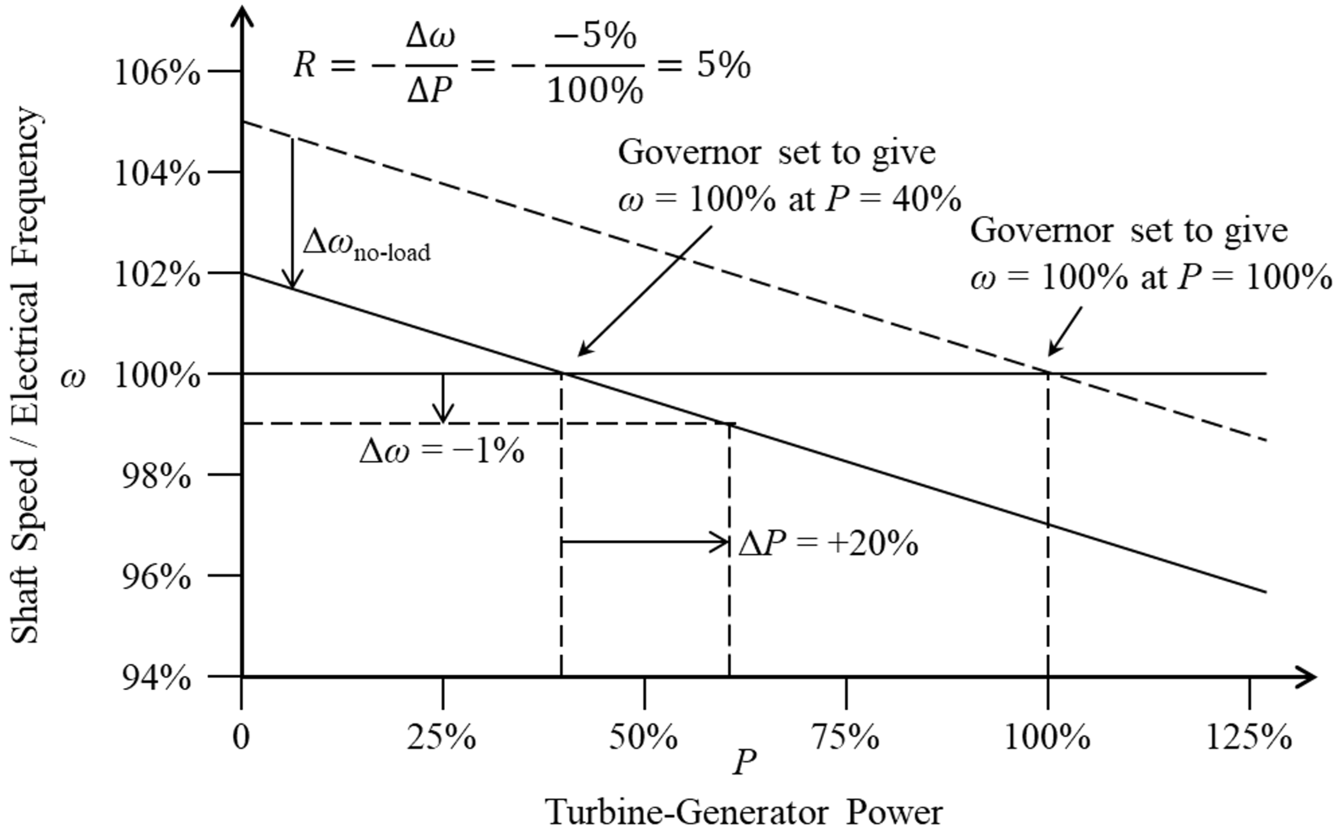


Generator Supplying Induction Motors

Power System Control Architecture

- Generator controls
  - Power plant component modeling
    - Governor speed control with droop control





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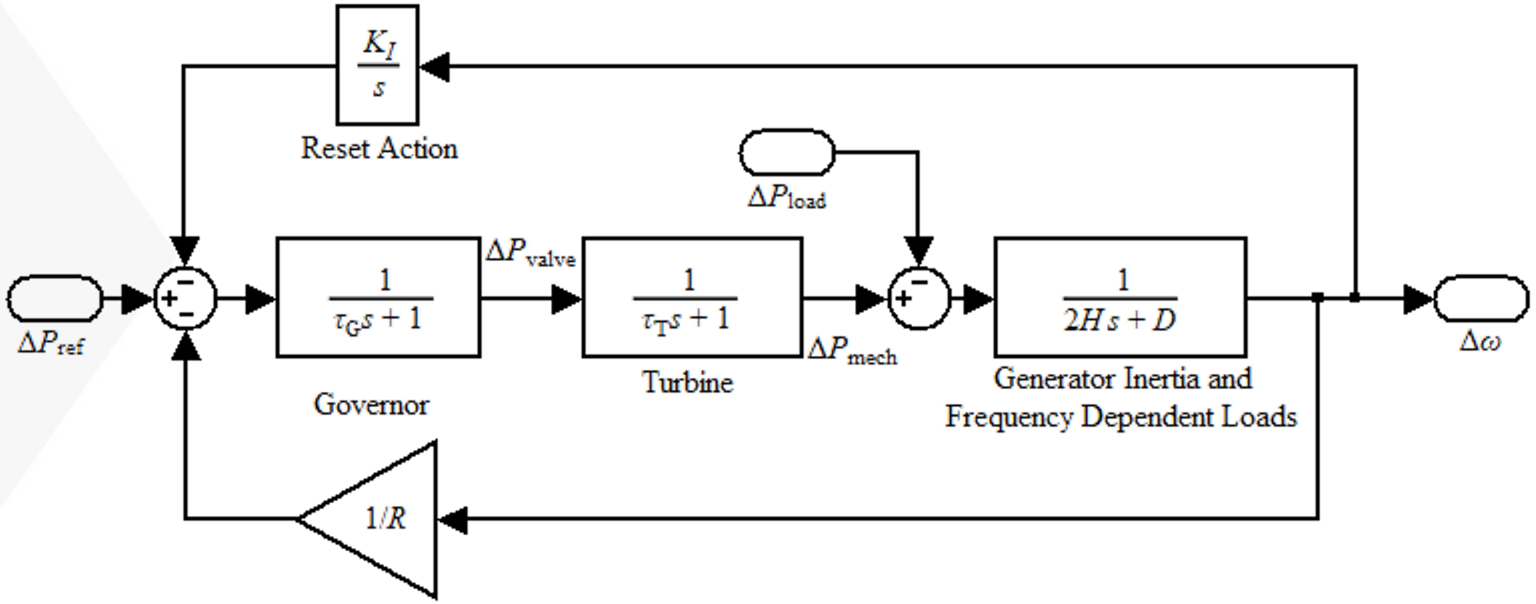
Power System Control Architecture

- Generator controls
  - Basic generator control loops
    - Single generator system



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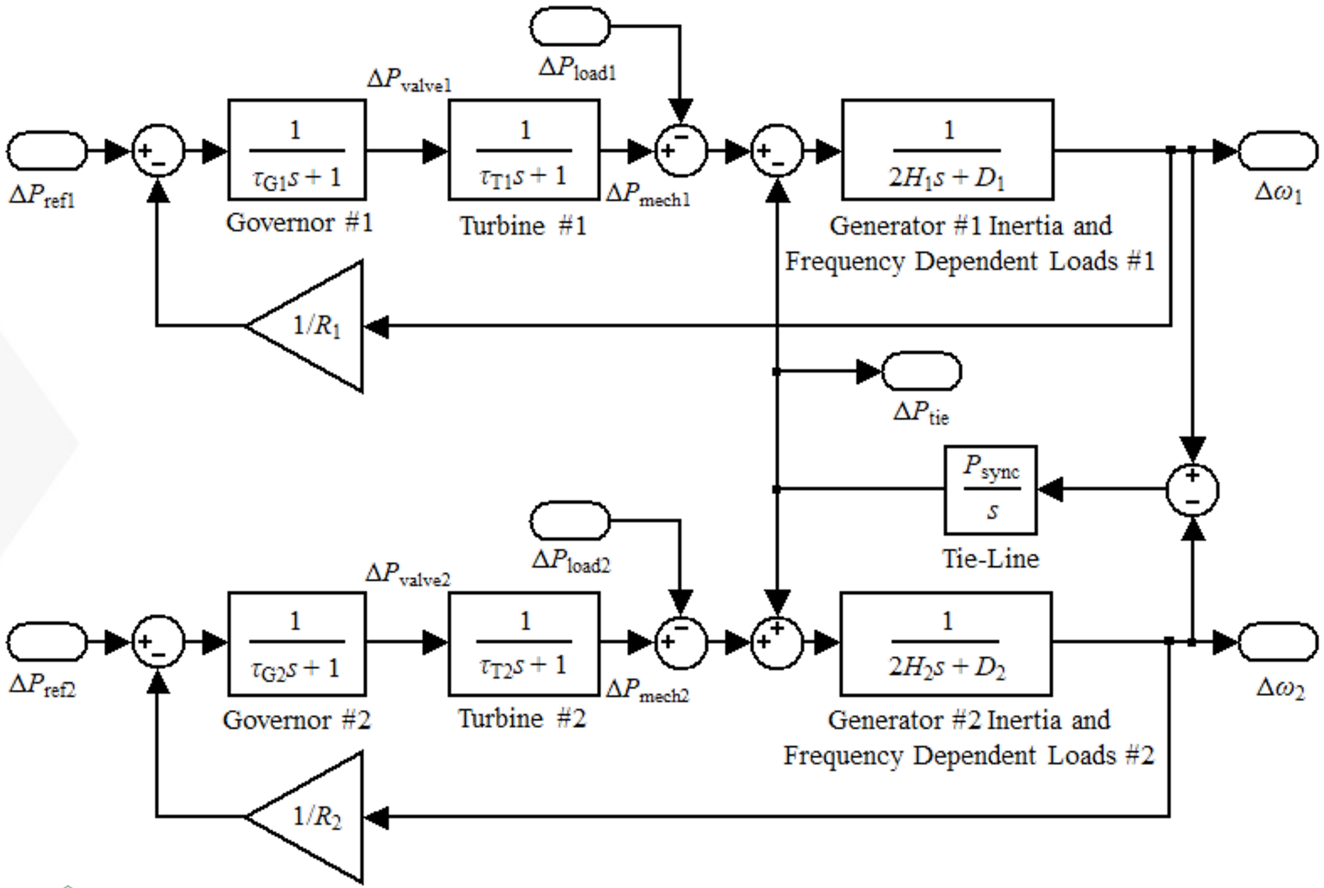
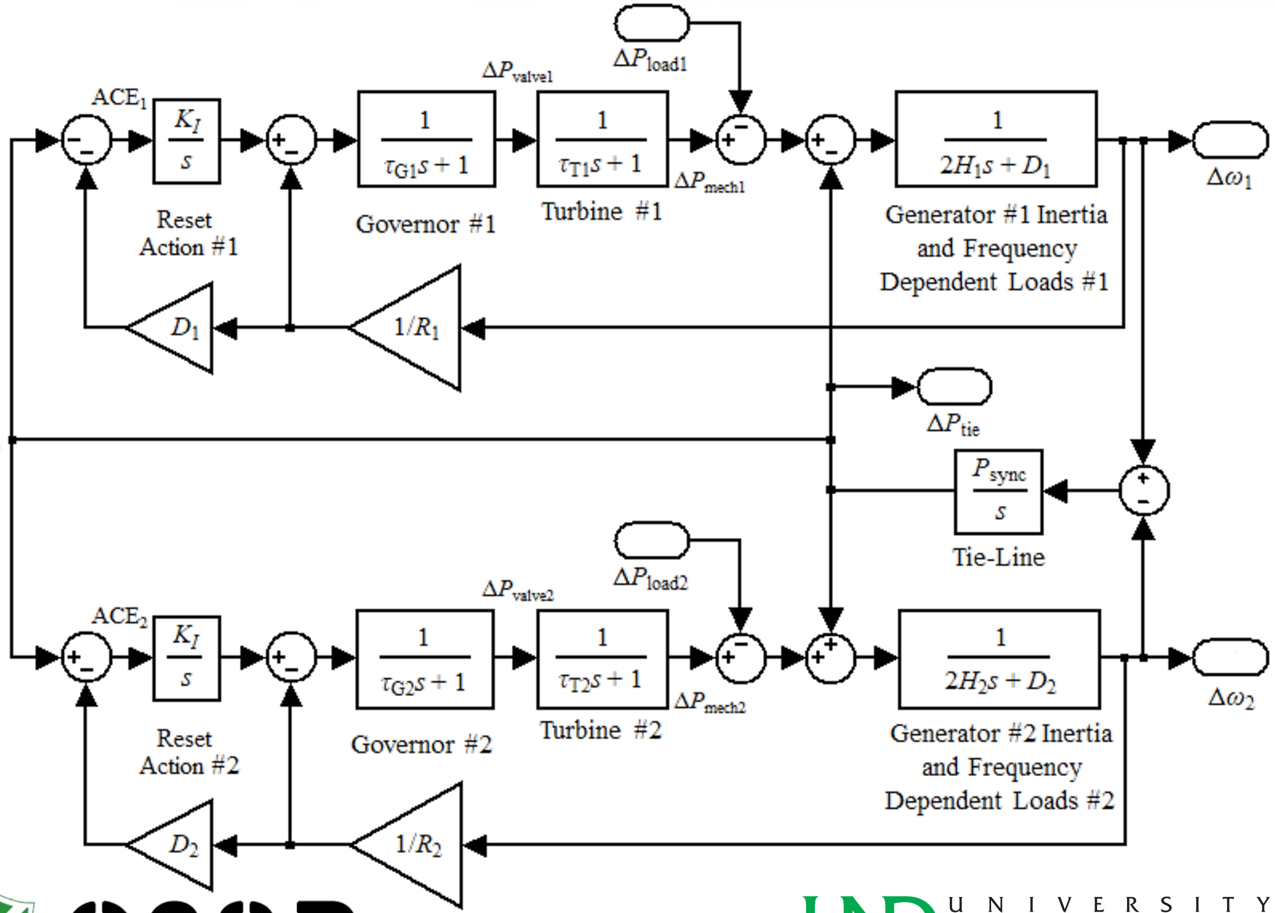
Power System Control Architecture

- Generator controls
  - Basic generator control loops
    - Two generator system
    - Simple tie-line between the two generator
    - Manual set of generation dispatching ratio



Power System Control Architecture

- Generator controls
  - Basic generator control loops
    - Two generator system
    - Simple tie-line between the two generator
    - Area Control Error (ACE) used to coordinate generation
      - Tie-line bias control



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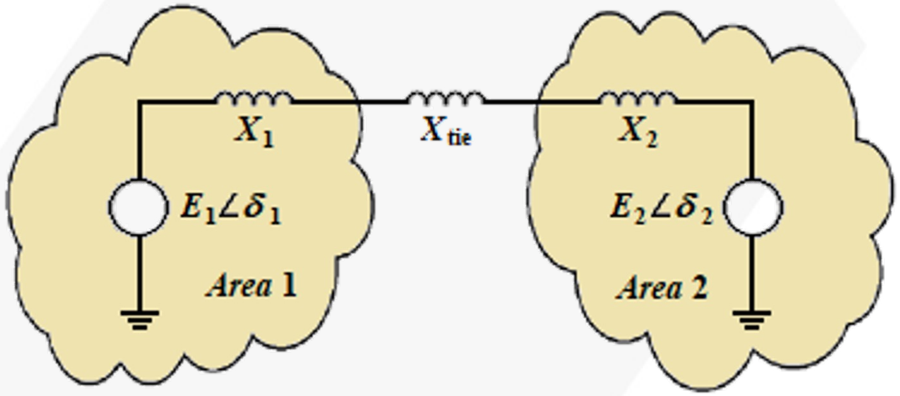
Power System Control Architecture

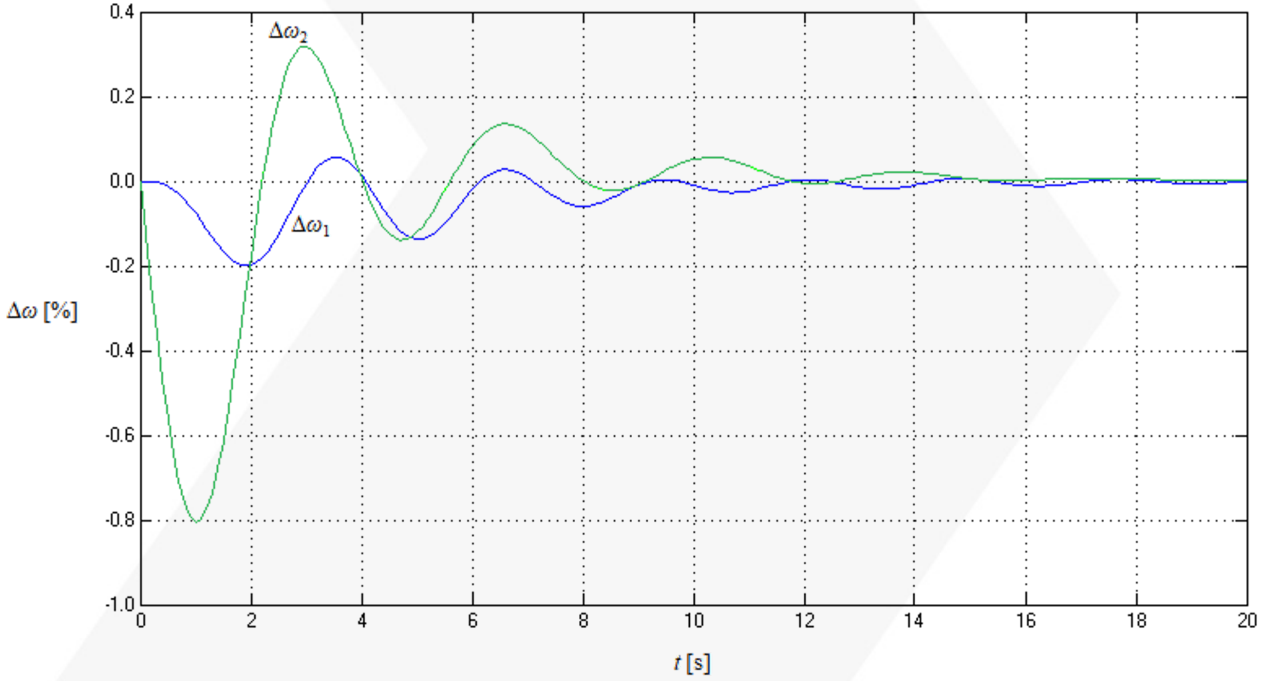
- Example
  - Two systems, each with a generator and load center, tied together with a tie-line
  - Event: 10 MW load change in area 1

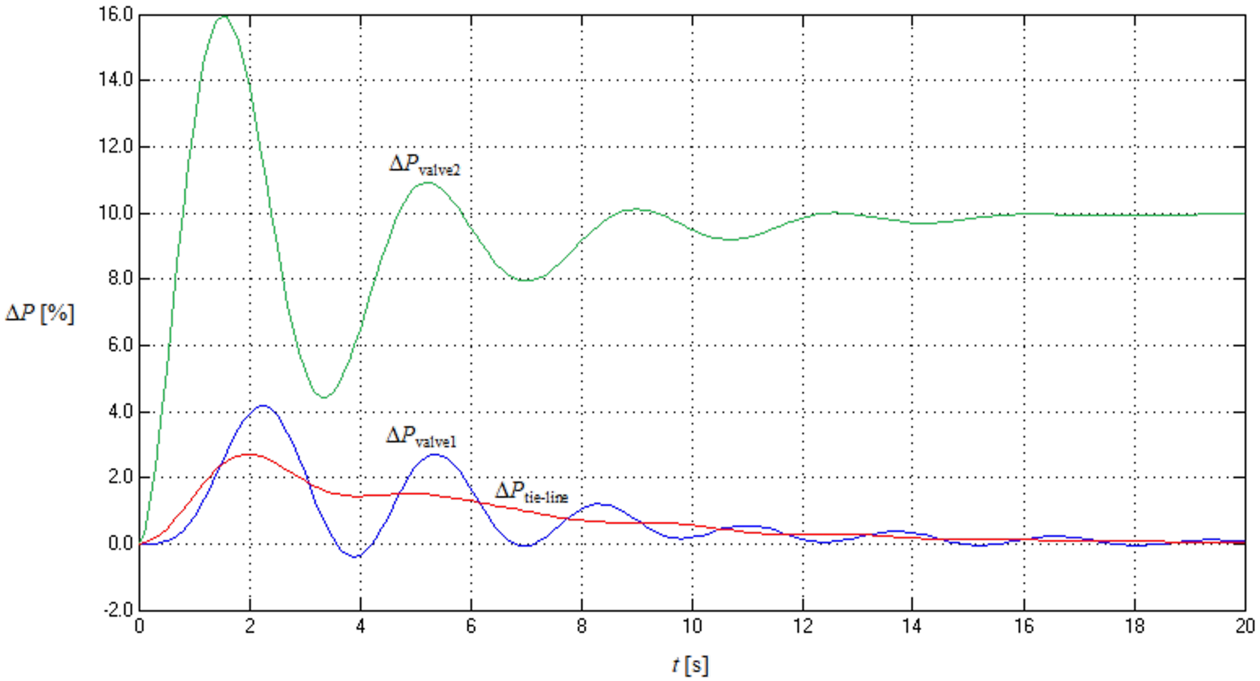


Parameter (Base Power = 1000 MVA)	Gen 1	Gen 2
Generator inertia constant, H [J/W]	3.0	4.0
Freq. sensitive load coeff., D [%P/%ω]	1.5	1.2
Governor Speed regul., $1/R$ [%P / %ω]	18.0	15.0
Governor time constant, τ_G [sec]	0.22	0.27
Turbine time constant, τ_T [sec]	0.47	0.43

Power System Control Architecture

- Simulation results

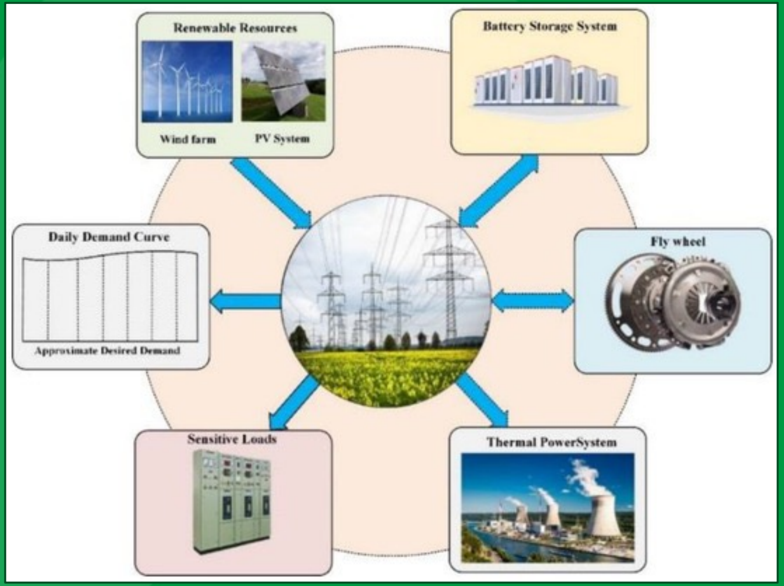




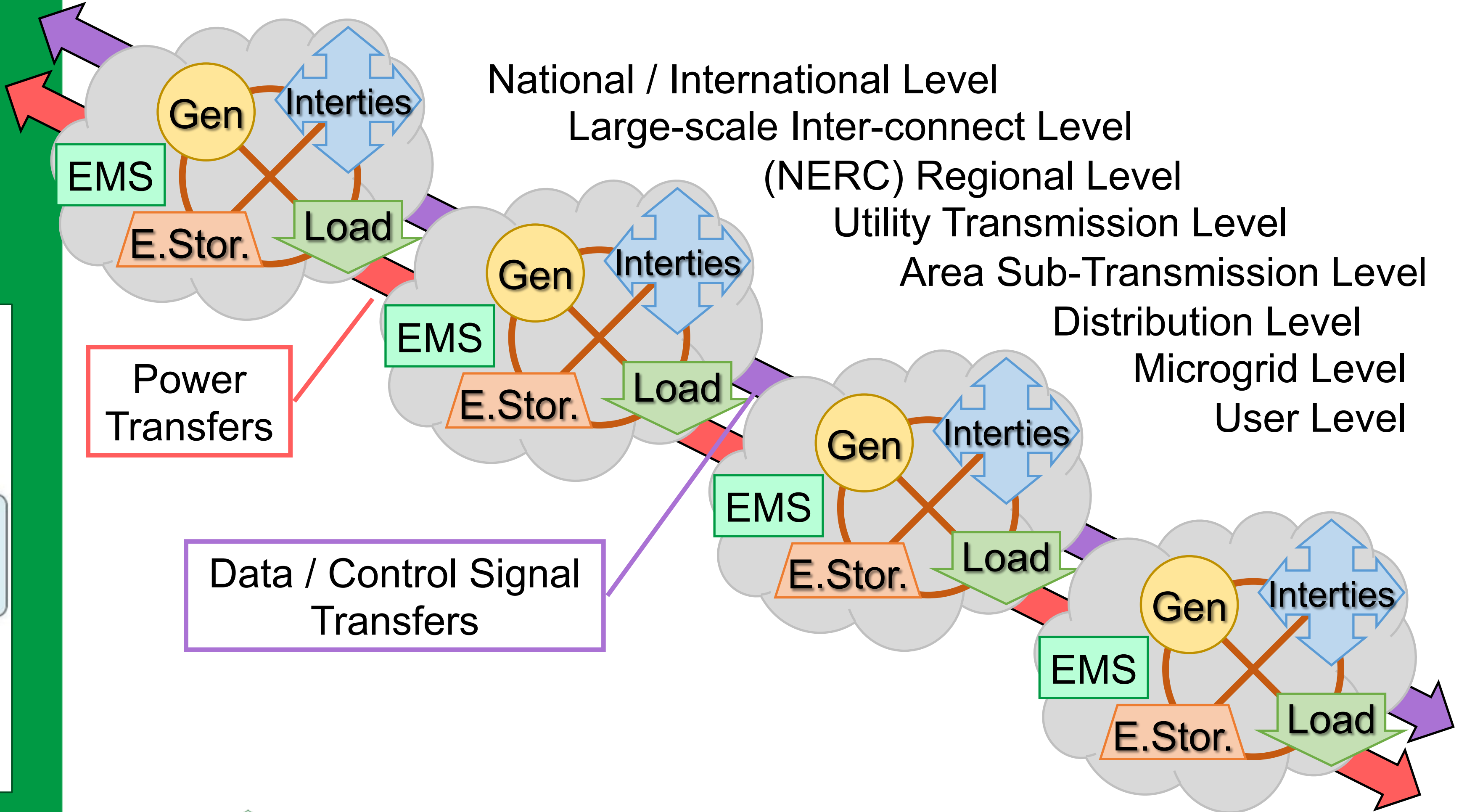
Power System Resiliency

- Grid control improvements towards resiliency
  - Long history of continuous improvement
  - Characteristics today
    - Complex network
      - SCADA structure
      - Energy Management System
    - Distributed controls
      - Power plant operations
      - Substation operations
      - Equipment
      - Utility service area control center
  - Technologies advancements
    - Synchro-phasor measurements
      - Direct measurement of voltage and current phase angles
    - Dynamic state estimation
      - Estimate the dynamic state variables of the system in addition to the classical static state variables
      - Integrated circuit breaker status with system model
    - Real time digital simulation (for Digital twin)
      - Faster than real time calculation of system dynamic behavior

Resilient Grid Control



- Scalable control areas
  - Each area is responsible for balancing
  - Each area has similar control functions

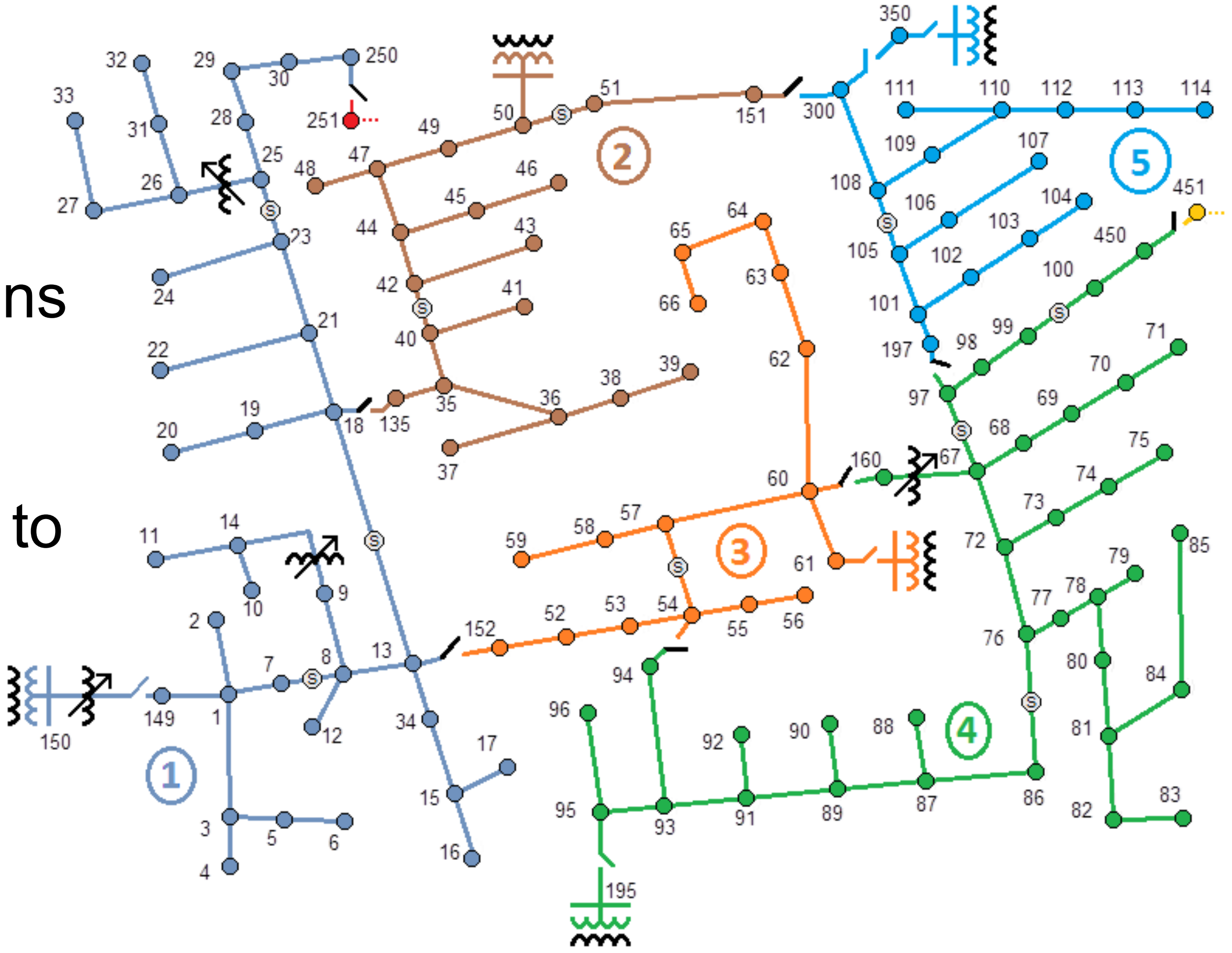


Resilient Distribution Systems

- Past design objectives:
  - Generally a radial distribution network with single power source from a substation
  - When and where economical, provide interconnections between distribution networks
    - Located at the edges of the networks, providing back feeding power after isolating damaged sections
    - Normally open-switch network loops for manual operation by line personnel
    - Coordination of reclosers (circuit breakers), line sectionalizers (switches), and fuses
- Today designs:
  - Radial distribution network with many more open loops and open mesh circuits
  - Digital logic system for activating remote-controlled sectionalizers
- Future designs:
  - Automated network sectionalizing based on fault location system

Resilient Distribution Systems

- Area: Radial distribution networks
- Challenge: Loss of electrical connections due to damaged feeder circuits
  - islanded sections of the network
- Objective: Restore electrical pathways to undamaged but isolated sections
- Approach: Take advantage of nearby live feeders to connect with islanded sections



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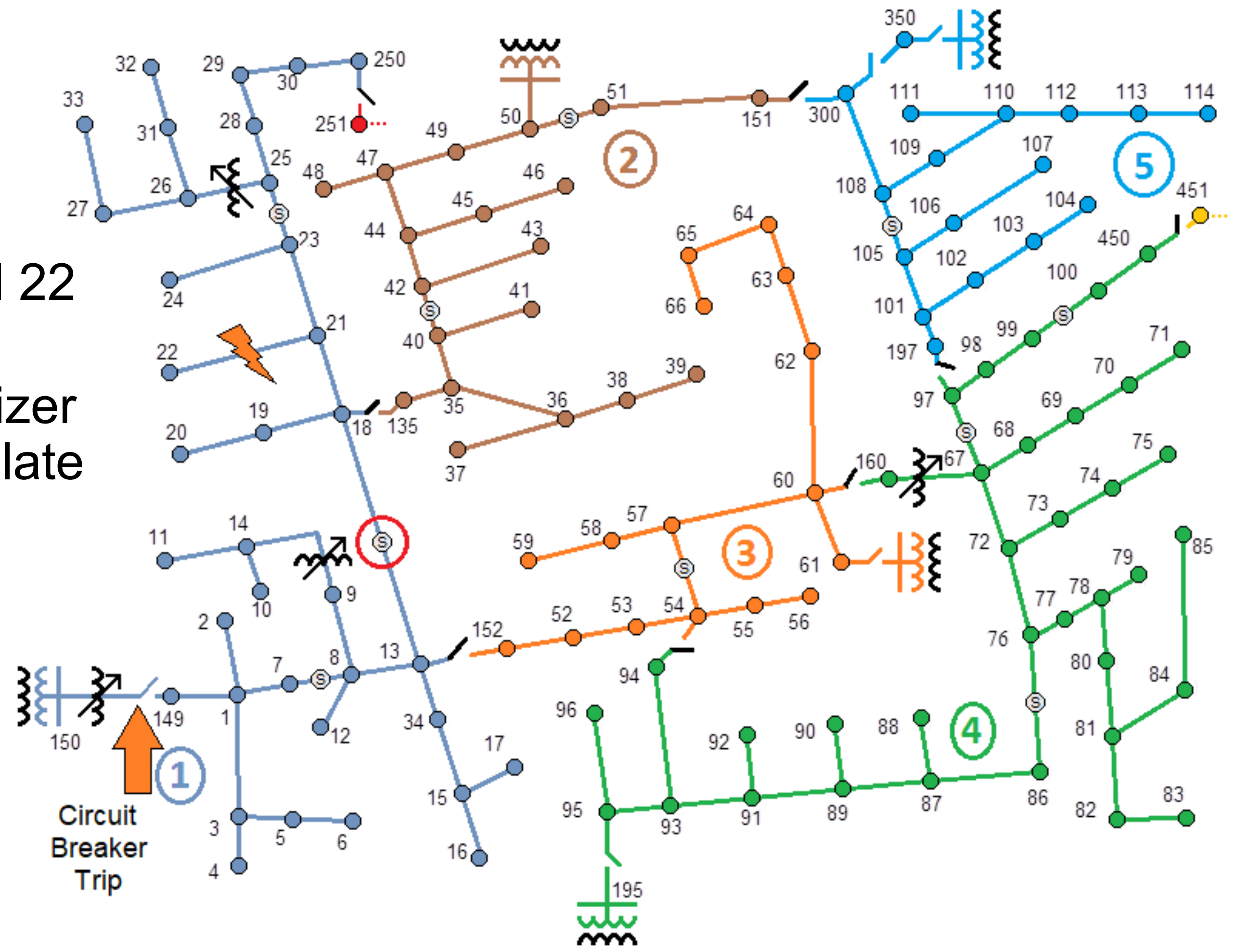
Resilient Distribution Systems

- Example
  - Faulted network #1 between loads 21 and 22
  - Reclosing operations trigger the sectionalizer between 13 and 18 to open circuit and isolate the northwest section of network #1



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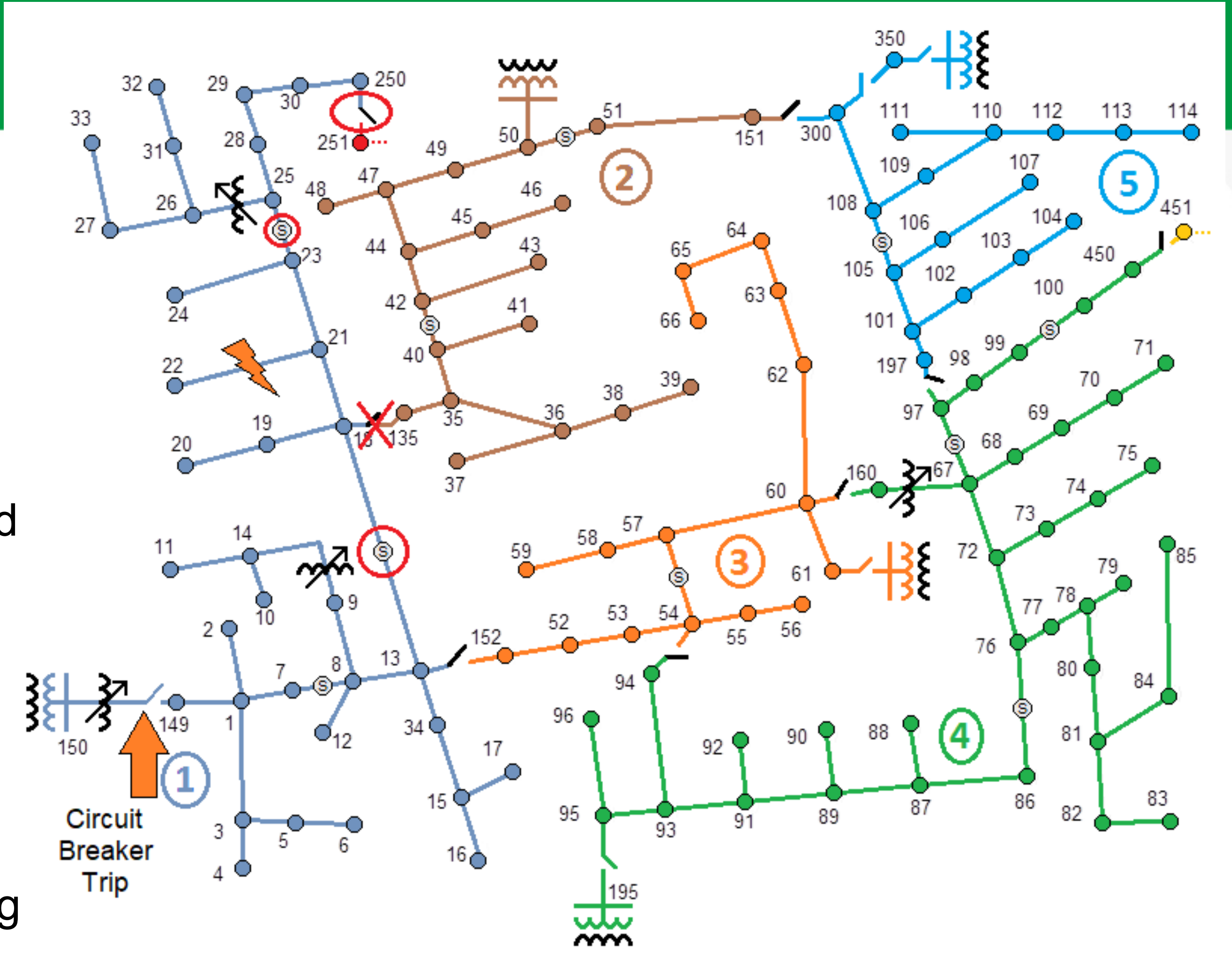
Resilient Distribution Systems

- Example
  - Post fault reconfiguration
    - Interconnection between Network 2 and Network 1 should not be closed
    - Interconnection between Network 1 and the network further north (250-251) should be closed to back feed power to loads 25 through 30
    - Sectionalizer between 23 and 25 should be opened before closing the northern interconnection
  - Requires significant data to automate
    - Fault locating and automatic sectionalizing



Questions