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Power Grid Operation/Control and Resilient Architectures

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Overview

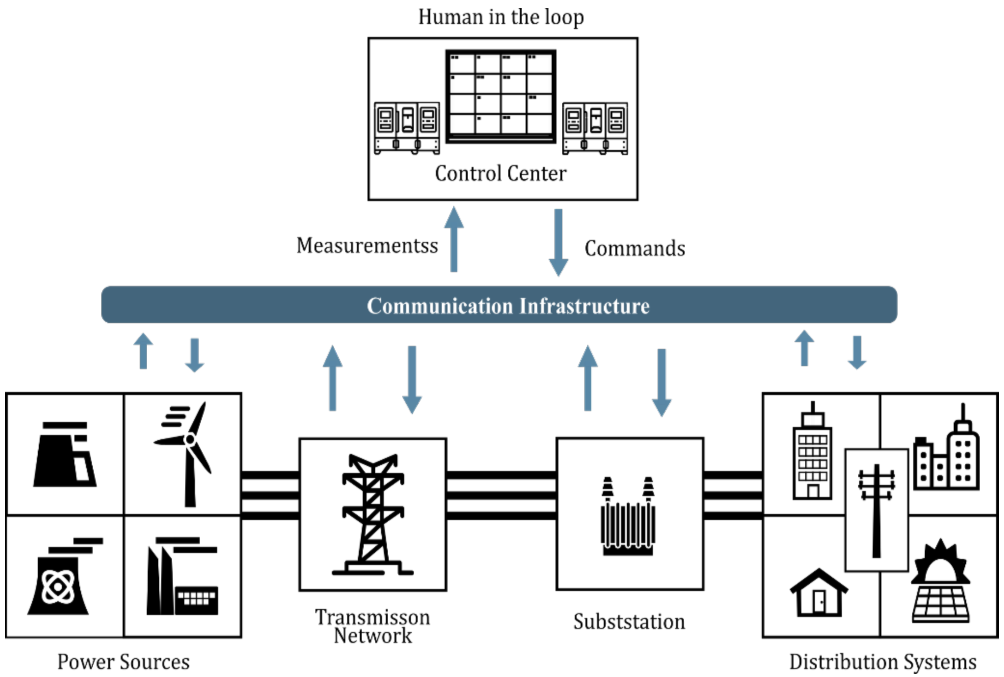
- Basic overview of electric power systems
- Power systems equipment
- Operating and coordinating a complex grid
- More information, distributed resources, and customer expectations.
- Balancing supply and demand in a dynamic system
- Grid operations evolving to enable more flexibility, adaptability, and responsiveness

Power System as a Use Case

- Resilient control can be applied in any cyber-physical system with
  - Distributed communication and controls
  - Automation support for human operators
- Power infrastructure is pervasive
  - Large, complex systems
  - Mix of decentralized and centralized control
  - Human operators with increasing automation support

Power System Control

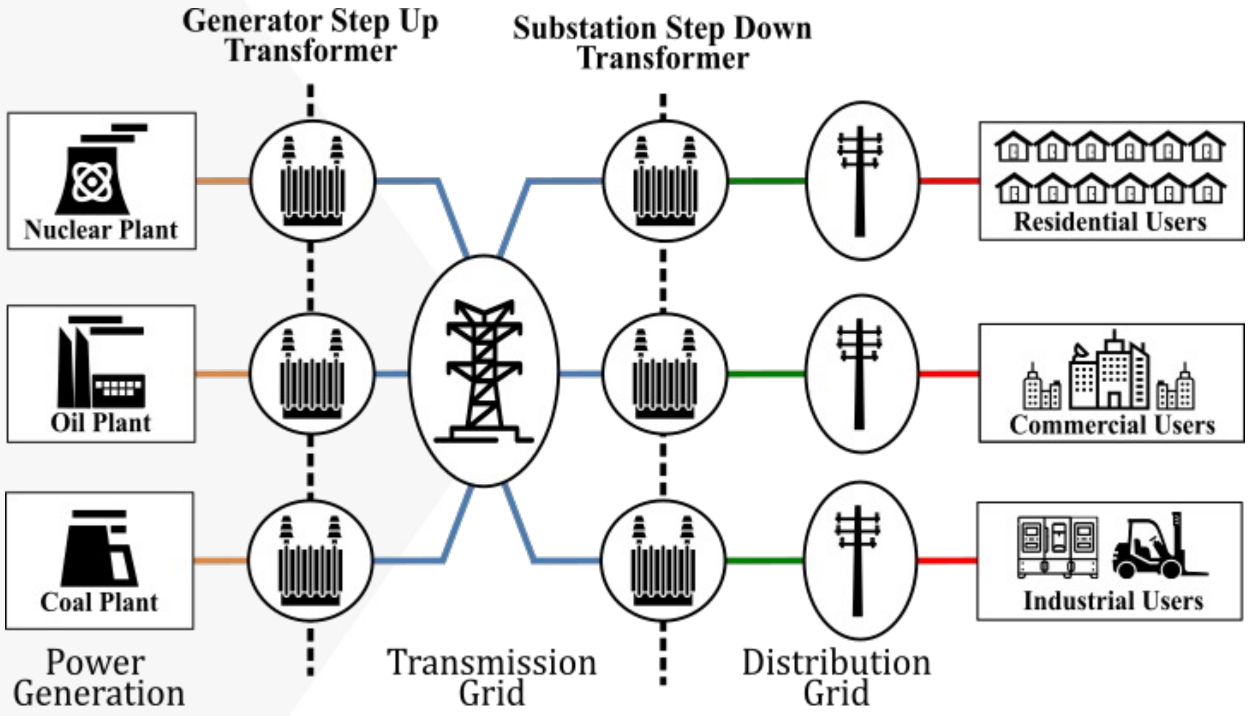
- Range of time scales
  - Cycles to seconds with autonomous controls
  - Tens of minutes to hours with operator response
- Local measurements versus communicated measurements



What is the Objective of the Power System?

- Transfer power from generation to end users
- Balance generation and load
  - Load varies
  - As does generation in some cases
    - Renewables
    - Non-dispatchable 3rd party owned

Historical Layout of Power Infrastructure



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Generation

- Significant generation from synchronous machines
  - Coal, Natural gas, Nuclear, Hydroelectric
  - Size from 10 MW to over 1000 MW machines
  - Mostly controlled by system operator (dispatchable)
- Generate at relatively low voltage
  - 12-24 kV
  - Transformers step up to transmission voltage

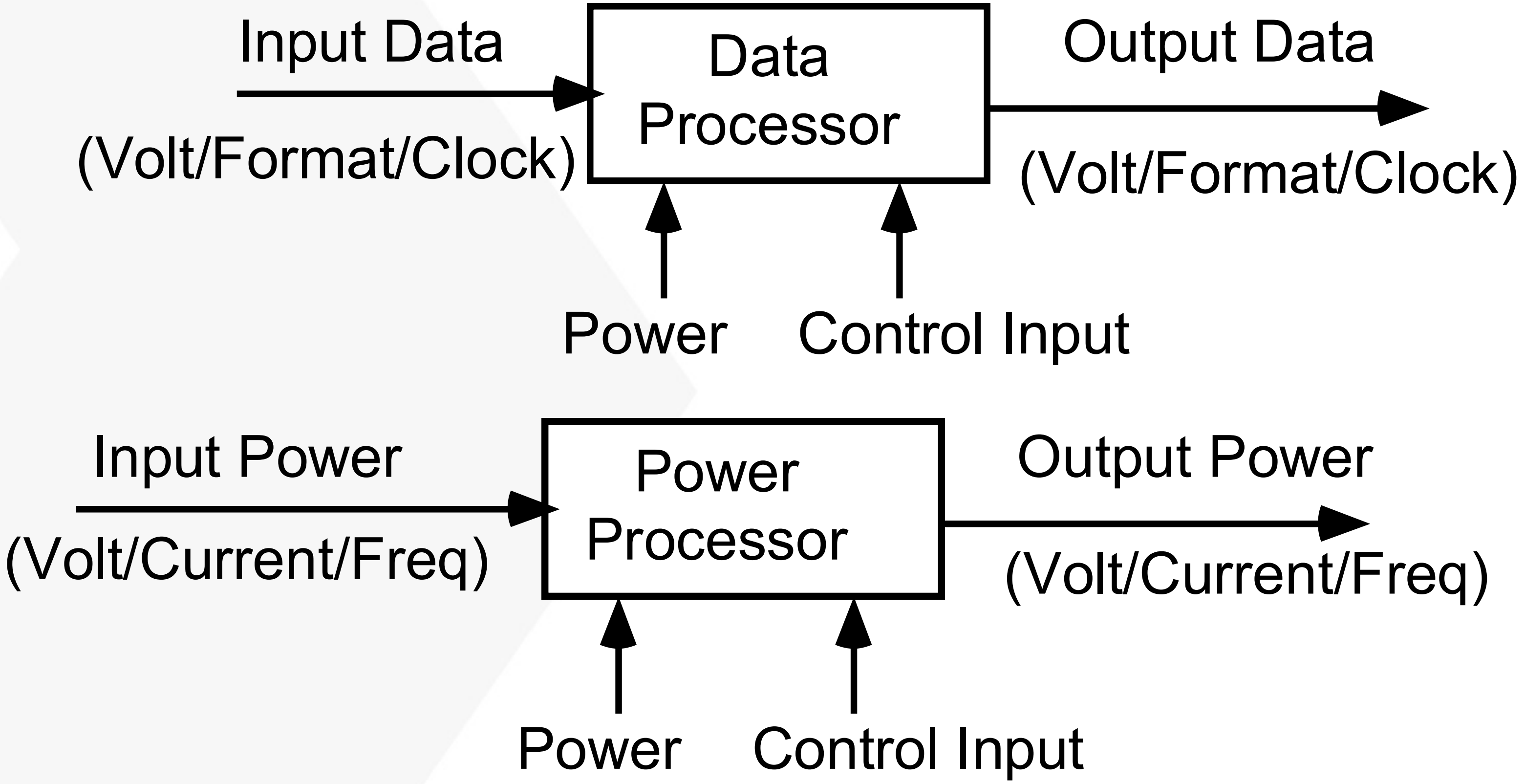
Synchronous Generators

- Speed of rotation aligned with power system frequency
  - Maintain synchronism
  - Closed loop control for power/frequency
- Large mass –stores kinetic energy
  - Steam-based turbines store more energy
- Inertial response
  - Exchange kinetic energy with grid to respond to disturbances
- Control response to rebalance and achieve more economic and reliable setpoint

Renewable Generation Sources

- Hydroelectric
  - Largely uses synchronous machines
- Wind generation
  - Mostly based on induction machines
  - Supplement with power electronic controls
- Photovoltaic (PV) generation
  - Rely on power electronic controls

Power Processing vs. Information Processing



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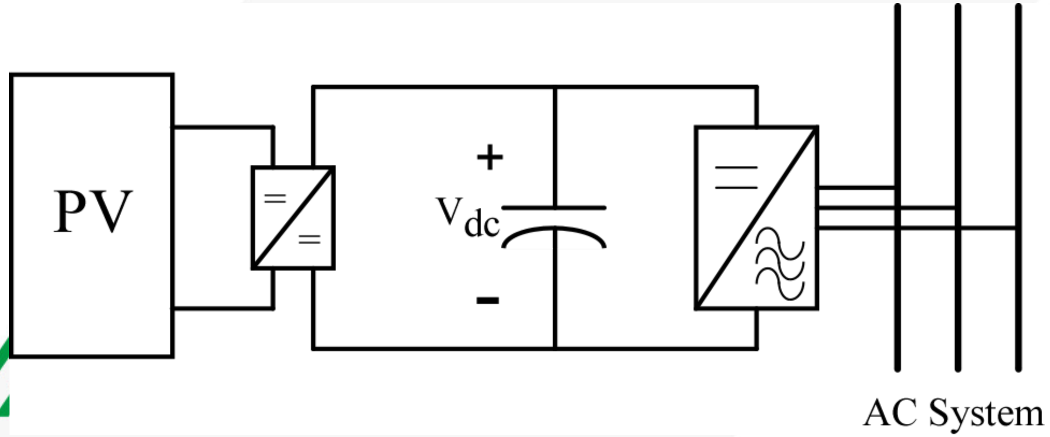
Power Conversion

- Solar cells output dc voltage and current
- Applied voltage across cells/panel/array determine current
  - Control for max power
- Need to convert dc to ac to connect to power system



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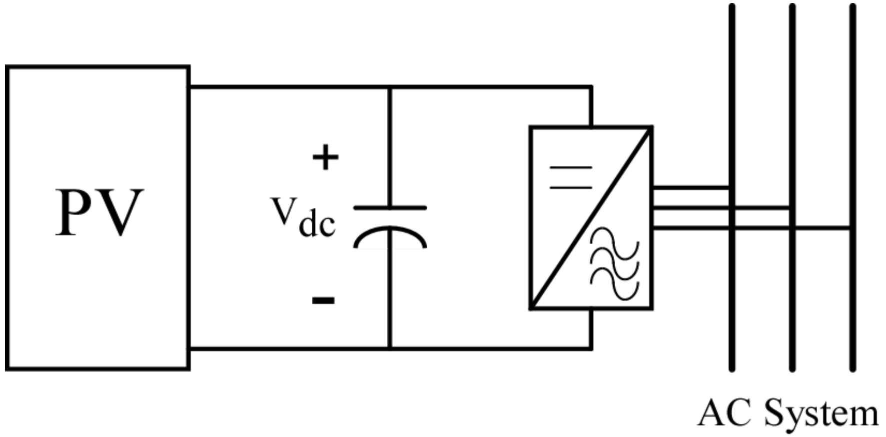
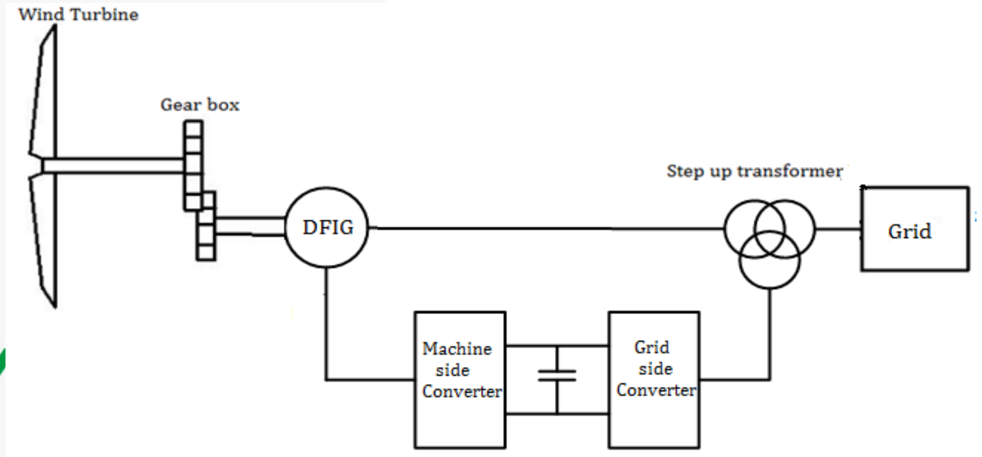


Type 3 WTG (Doubly-Fed Induction Generator)

- Wound rotor induction machine
- Variable frequency voltage/current to rotor (+/- 30% of power)
- Much wider wind speed range for power generator
- Most common for land-based applications last 10 year or so



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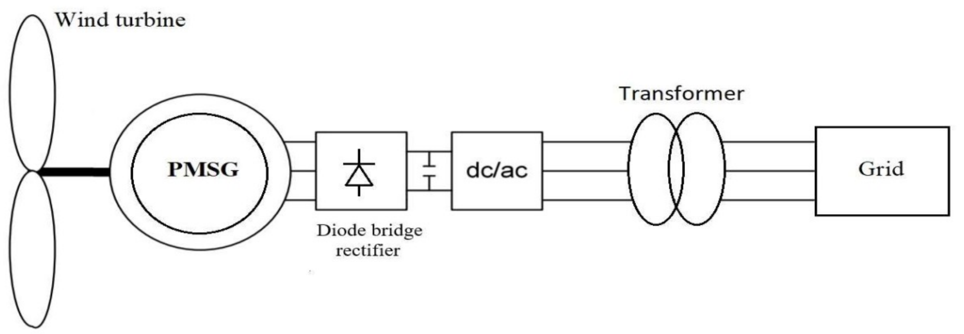
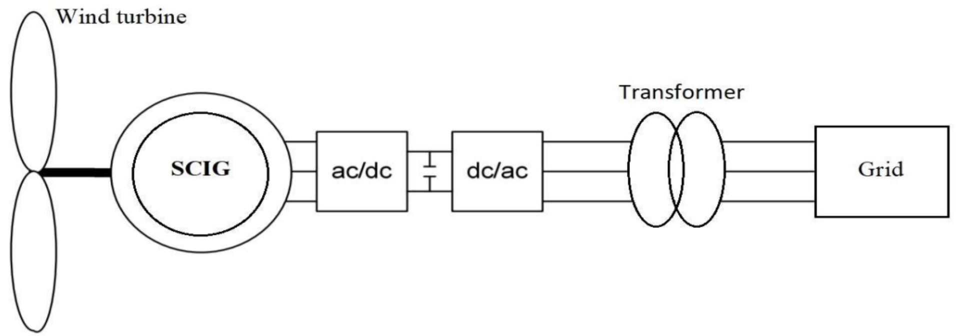
Type 4 WTG

- Two options for machines
- Variable frequency voltage/current to rotor
- Most common for off-shore applications last 10 years or so





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Energy Storage

- Fairly limited use in North America
- Older facilities: hydroelectric plants
  - Many have some ability to act as storage
  - However, often “Run of the river” facilities → little storage
- Dedicated pumped storage projects
  - Several in US
  - Some merchant projects

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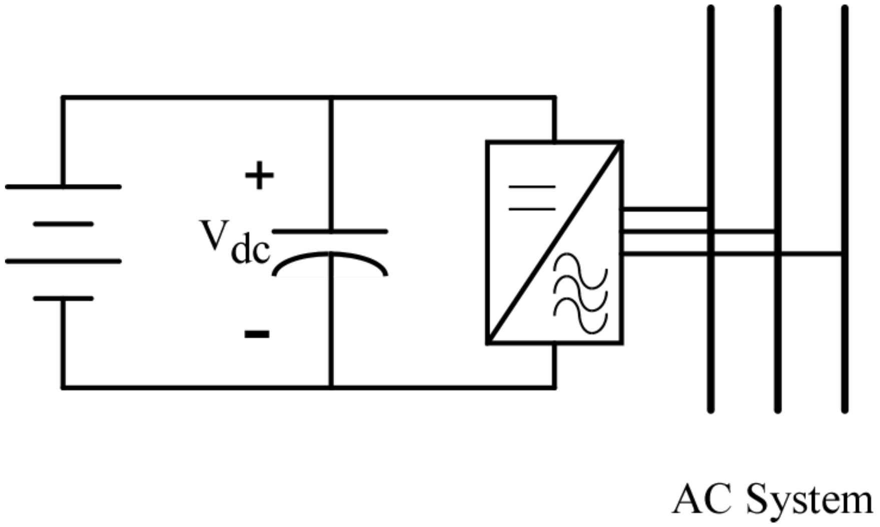
Energy Storage Technologies

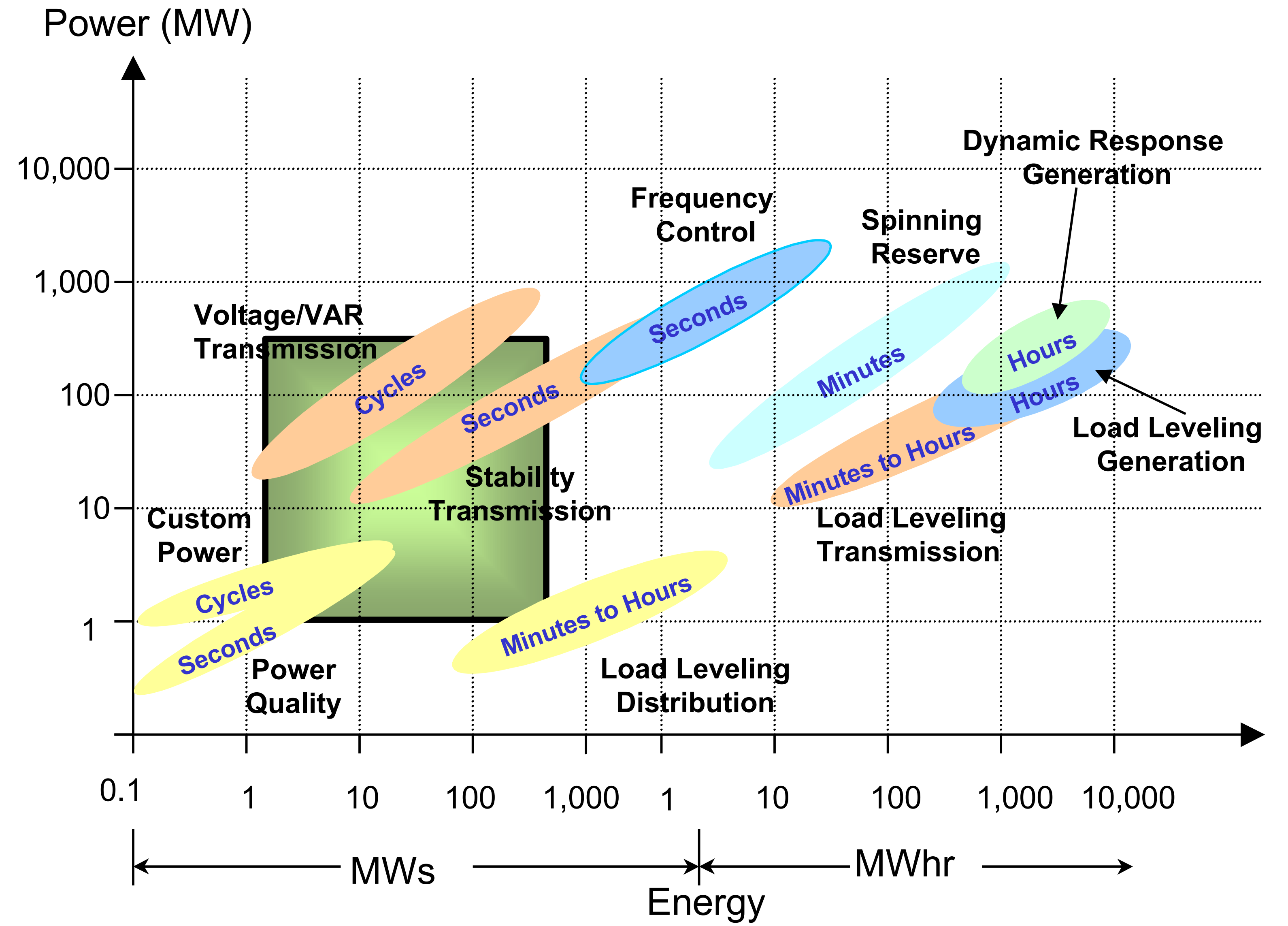
- Batteries—increasing application
  - Lithium ion and variants
  - Flow batteries
- Other technologies
  - Fuel cells
  - Flywheels
  - Ice



Rating Energy Storage

- Instantaneous power (kW, MW)
- Energy (kWhr, MWhr, Joules)
- Application specific

Storage Applications



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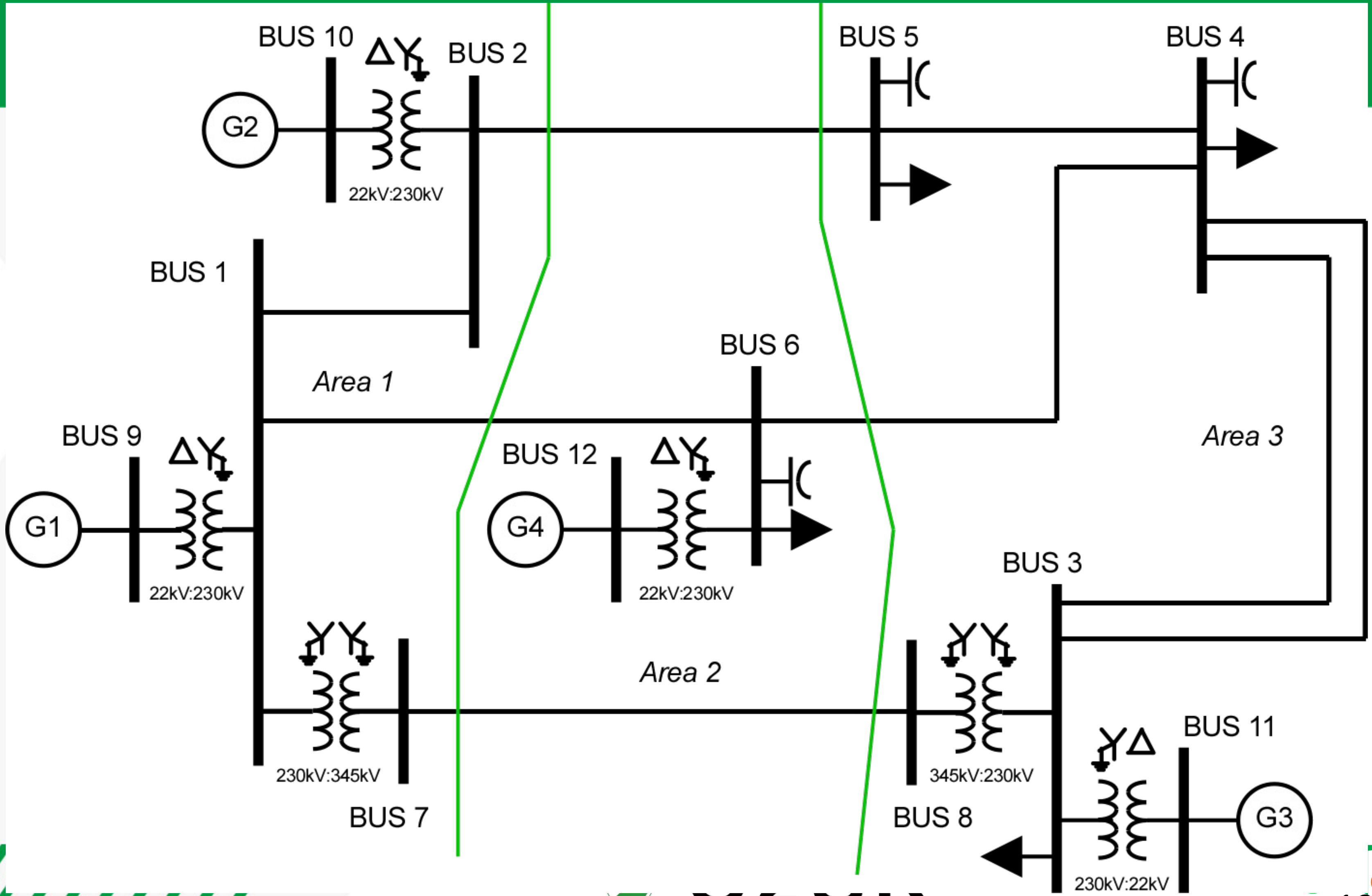
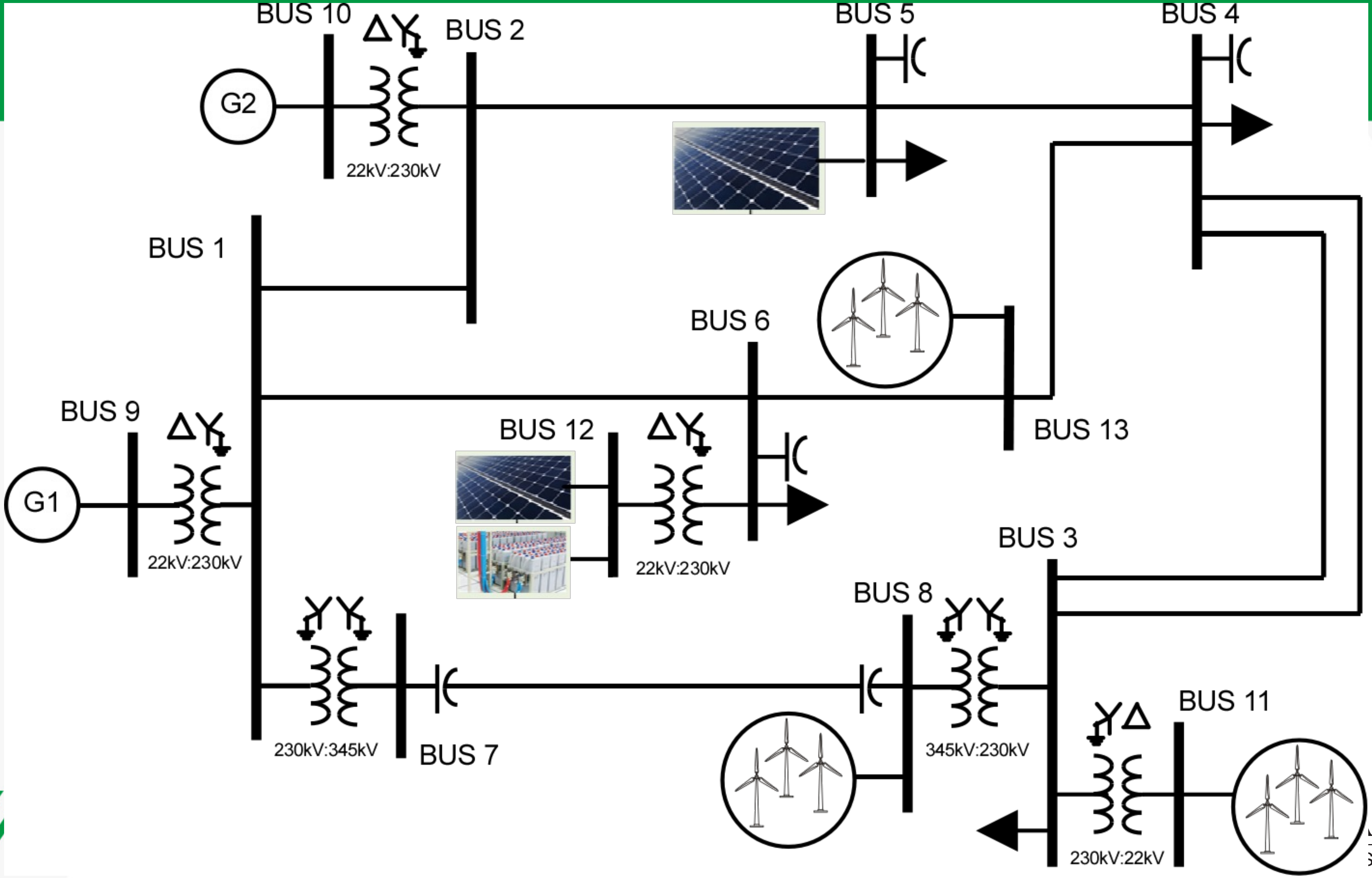
Operational Considerations

- State of charge
- When to charge/discharge
- Who controls it
  - What signals?
  - Objectives for the control?

Transmission

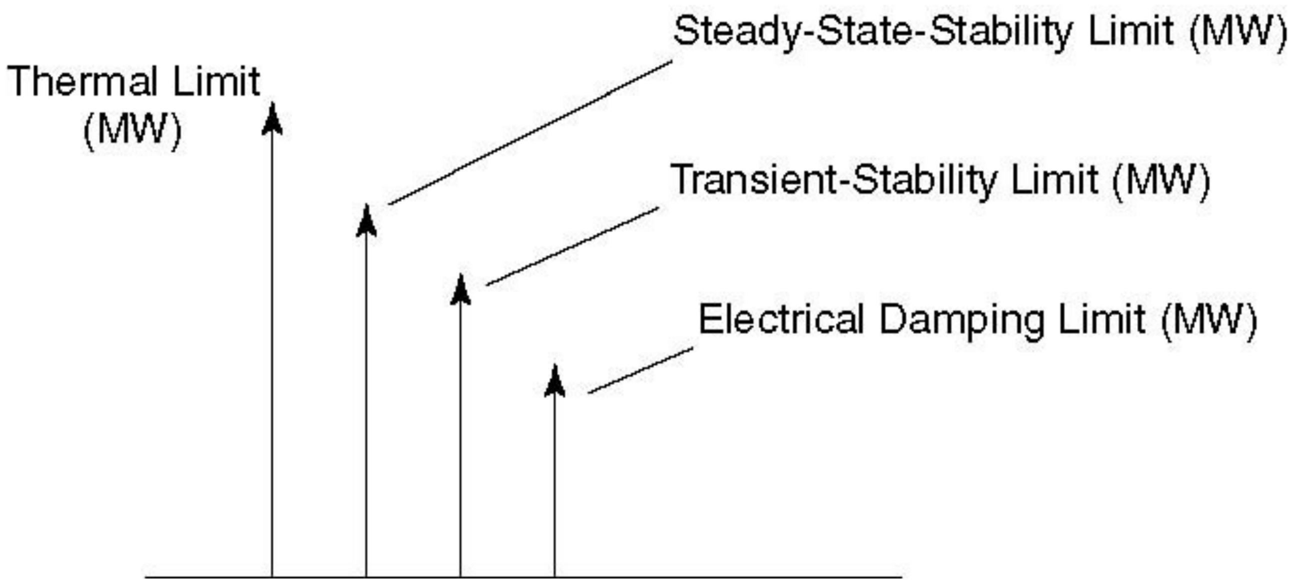


Transmission – Changing Needs



Control of Transmission

- Limited options to directly control line flows
- Current distributed based on physics
  - Can't force current into one line based on a contract
- Limits for transmission system components
- Impact of decreased system inertia



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AC Transmission Challenges

- Bulk power flow over long distances
- Dynamic response to disturbances
- Transmission bottlenecks due to
  - Steady-state Stability Limits
  - Transient Stability Limits
  - Power System Oscillation Limit
  - Inadvertent Flows
  - Short Circuit Current Limits
  - Thermal Limits

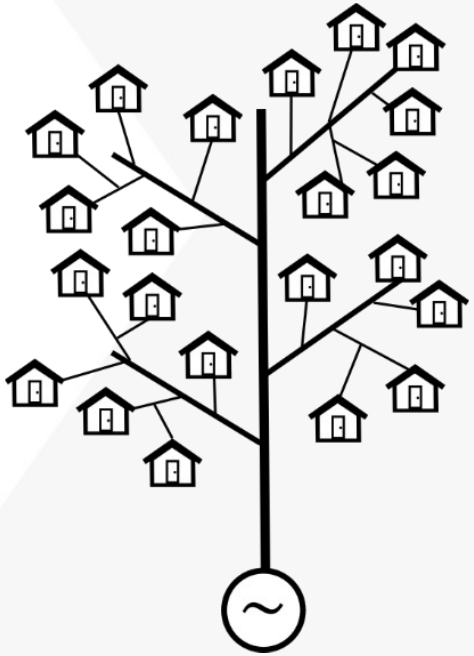
Sub Transmission

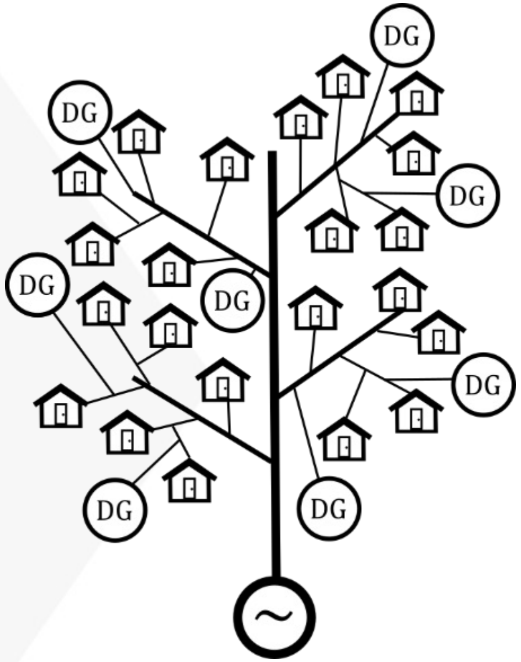
- Definition voltage level varies by utility
- Typically, 34.5-132kV
  - Shorter lines
  - Connect transmission to distribution substation
- Often connected such that have an equivalent source at each end
  - Redundant supply

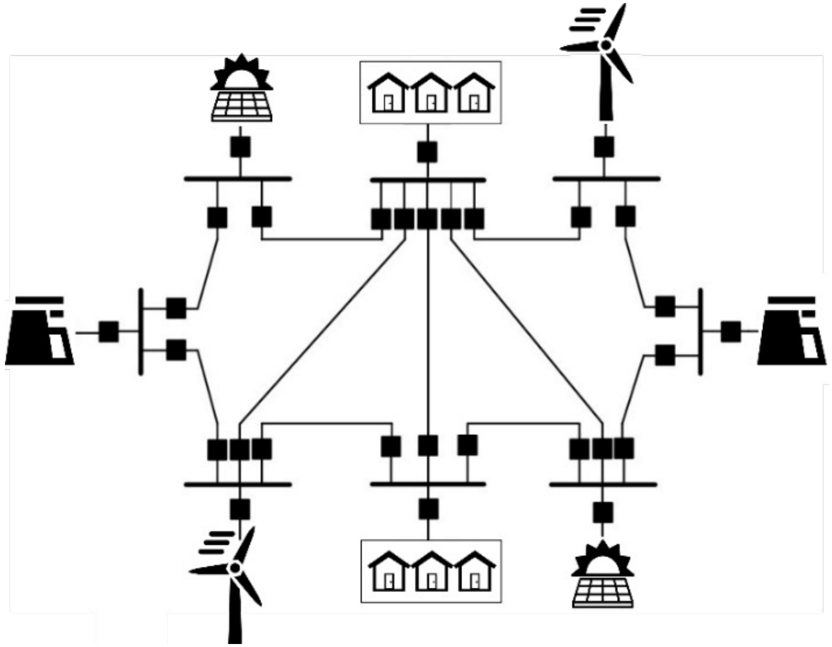
Distribution

- Typically, below 24kV
- Mostly radial systems with normally open switches that can be closed
- Often somewhat unbalanced
- Historically designed assuming no power sources connected to system
- Extensive facilities for most utilities

Distribution: Radial and Meshed







Performance Expectations

- Maintain frequency to tight tolerance
- Maintain voltage magnitude
- Reliability
  - So successful that taken for granted
- Low cost/losses
  - Others…

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Power System Protection

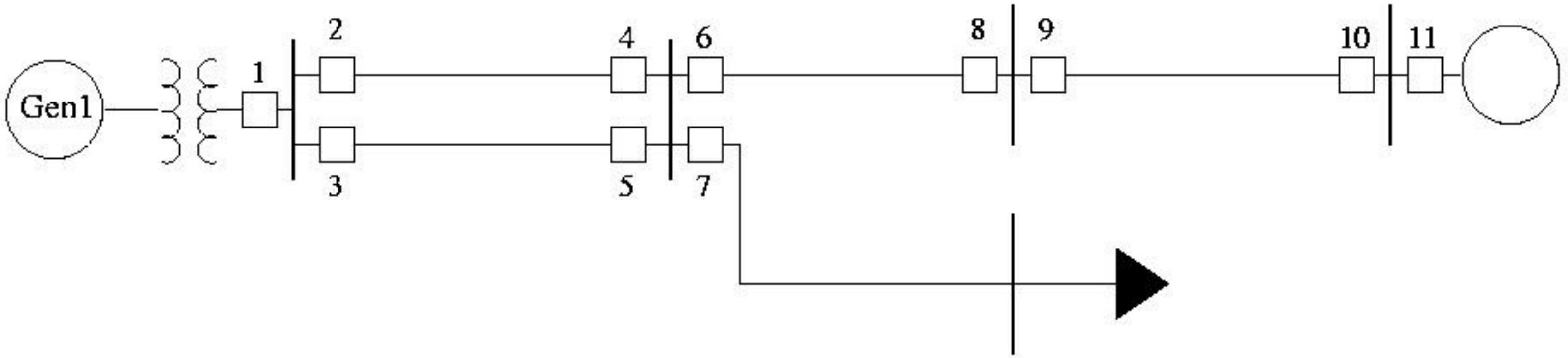
- Local protection
    - Protection of immediate equipment
    - Minimize disruption of loads
        - Duration or interruption or abnormal condition
- Larger system issues?
    - Impacts on stability of larger system
    - Potential for distant impact

What Events Require Protective Actions

- Faults
- Abnormal operation
- Response
  - Detect fault in less than cycle
  - Open circuit breaker – faster for transmission
  - Start timer and act when timer expires

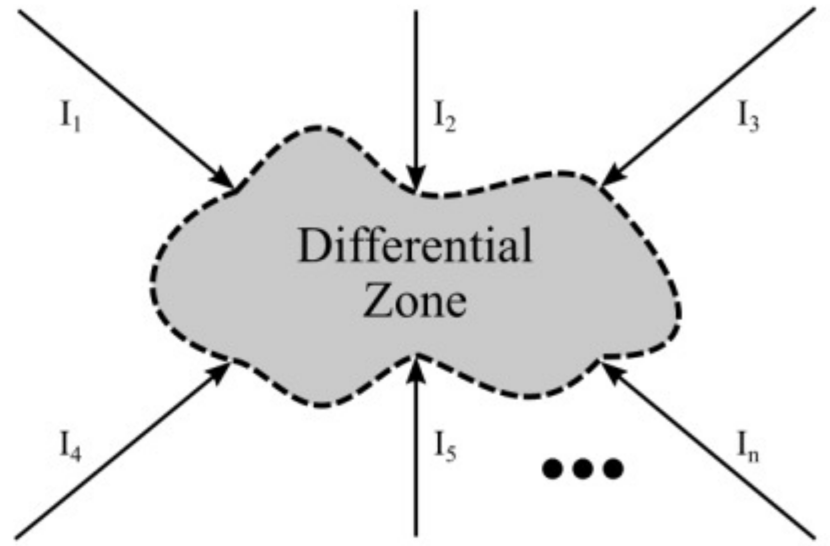
Redundancy

- Overlapping zones of protection are common
- Backup in case relay or breaker fails
- Time delay if out of primary zone
- Often more sensitive in secondary zone
- Coordination is a key issue



Evaluate Measured Data Based on Algorithm

- Overcurrent→ common in radial distribution systems
- Impedance (distance protection)→ transmission
- Differential



Historical Power System Architecture

- Move toward regulated monopoly to avoid duplication of apparatus
- Provided efficiencies in operation/growth that held for decades

Evolving Architecture

- Utility owns generation, transmission and distribution
  - US investor owned, municipal or cooperative
  - Some federally controlled transmission: BPA, WAPA, TVA
- Transmission only own generation and load
- Interconnect to neighbors grew in middle 1900s
- Blackouts in 1960s led to reliability councils
- Evolving exchange between utilities

Technology Changes

- Communication technology
  - Initial Supervisory Control and Data Acquisition (SCADA)
  - 50-year history
- Computational tools and techniques
- Electronic control and now digital control
- Big impact on system design and system operations

Extending Control to Larger System

- Decentralized, automated in short term
  - Dispatched generators share in load following for small excursions
- Centralized control schemes in midterm
- Operators in slower regime
- Role of communication
- Renewable generation poses challenges

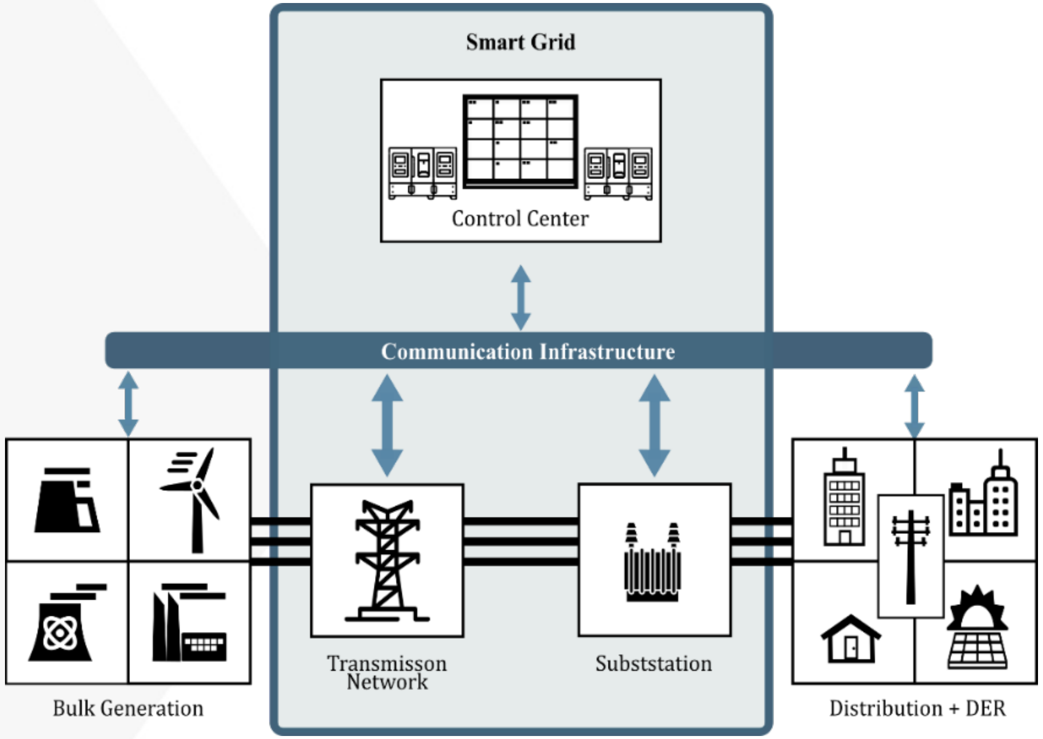
Real-Time Operations

- Monitor the system using SCADA –evolved over decades
  - Supervisory Control and Data Acquisition
  - Now hybrid with phasor measurements, etc.
- Periodic updates
- Scan rate decreasing with faster computers
- Determine "state" of the system
- Contingency analysis – "what if" simulations

Time Synchronized Measurements

- Satellite time source
- Provides common time reference for phase angle
- Faster message rate than SCADA systems
- Improve observability of system for operators and autonomous systems
- Enable wide area measurement and control schemes (WAMS, WACS)

Emerging Architecture



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Role of Improved Computation and Communication

- Much more data available
- At higher sampling rates
- Much greater visibility on the system
- Allows operation with far smaller margins than in the past
- More responsive more reliable
- Not without risks

Risks with Increased Communication

- Can operate the power system much closer to physical limits
  - Impact of loss of communication
- Cyberattacks
  - Extreme cases: try to bring down system
  - Reconnaissance
  - Market manipulation
- Resilience of communication infrastructure and power infrastructure

Operator Interface

- Operators receive processed data from measurements
- Current state of the system—violations
- Violations if certain events occur
- Managing increasing amounts of data
- Human machine interfaces
  - Transmission system
  - Distribution level
  - Substation and facility level
- Handling increasing data and faster changing system

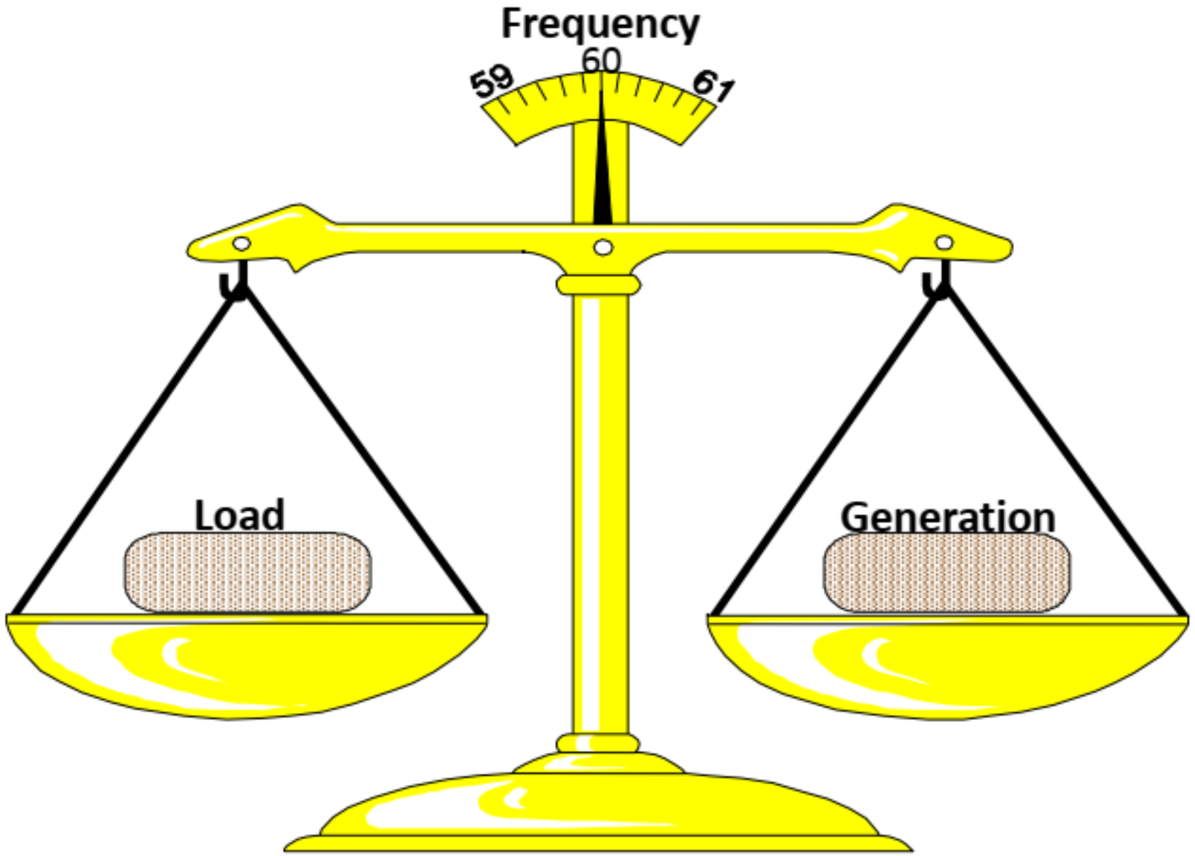
System Operations: Classical Approach

- Frequency
  - Real Power → Generator Governors
- Voltage
  - Reactive Power→ Generator Exciters

Generation

- Most generation located away from load centers
  - Some generation nearby for local support
    - Reactive power and somewhat on real power
    - In many cities this was coal fired, some oil or gas
    - Decommissioned for pollution reasons
      - More recently for economic reasons
    - Challenges as a result

Frequency as indicate of Energy Balance



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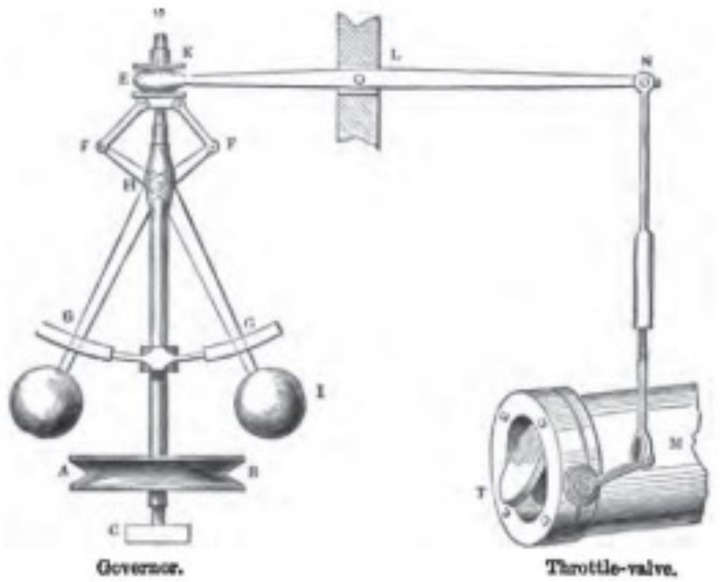
Generator Governor



- Take action without control center input
  - Increase power output when see low frequency
  - Decrease power output when see high frequency
- Frequency as a communicated system-wide control signal

Generator Dispatch: Classical approach

- Base load
  - Large, coal/nuclear → keep at optimum operating point
- Intermediate (mid) load
  - Smaller gas (or oil or coal) or hydro that cycle on/off
- Peaking units
  - Combustion turbines used in high demand
  - Demand response schemes as an alternative

Hydroelectric Plants

- Fuel is "free," but many constraints on operation
- Many hydro plants are run of the river plants
  - Limited range of pond height variation
    - Dams in series on a river → coordination needed
  - Coordinating with other water users
  - Fixed amounts of water
- Some regions use hydro to offset variable generation
  - Seasonal variations in availability for up or down regulation

Wind and Photovoltaic

- Wind and photovoltaic typically operate at max available power
- Can be quite variable at times
  - Weather forecasting
  - PV more predictable, but can have fast ramps
  - Wind less predictable but slower ramps
  - Advantages of regional diversity
- Growth of behind the meter photovoltaic

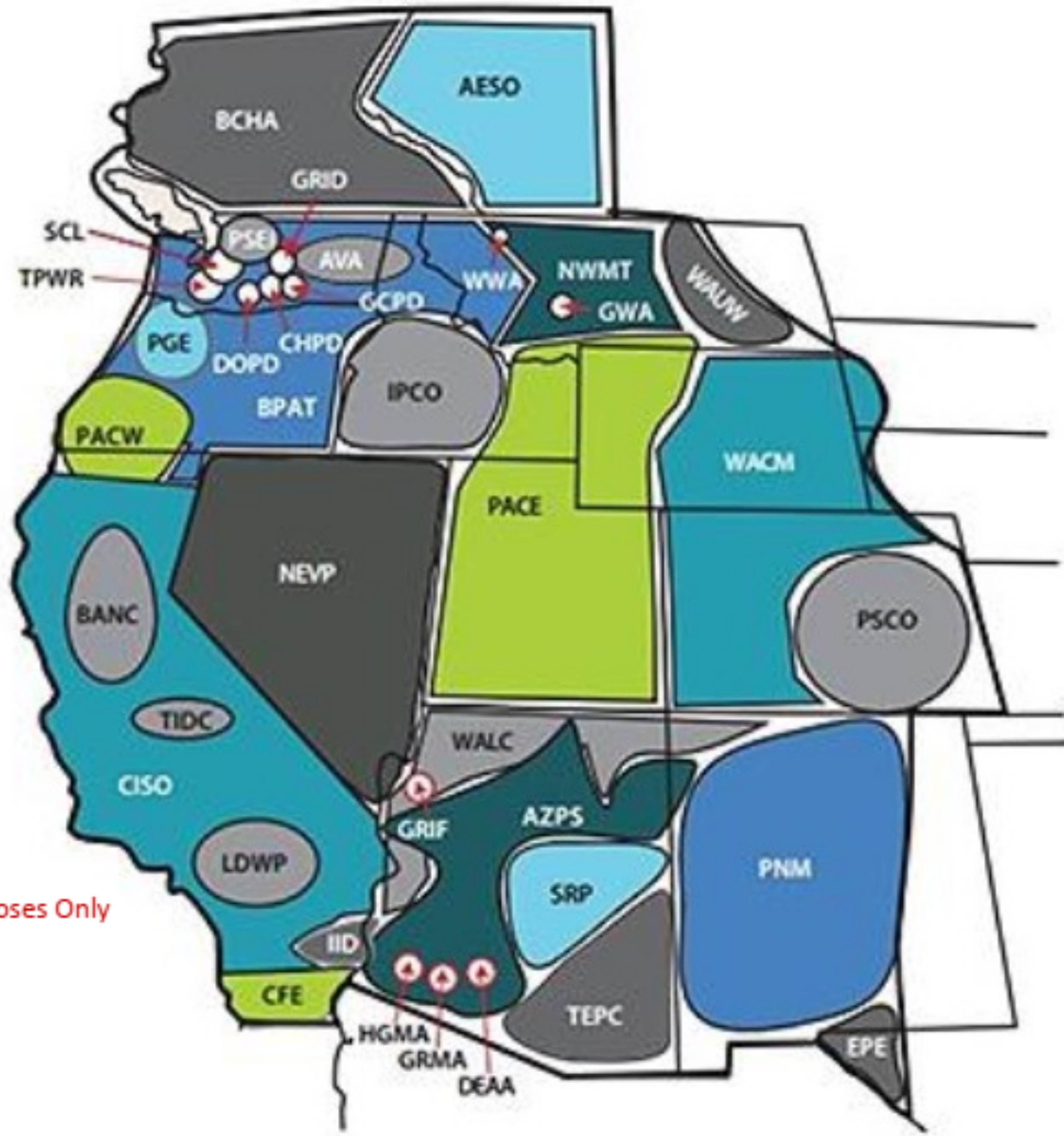
Transmission Versus Distribution Control

- Transmission
  - Energy Management System
  - Automatic Generation Control
  - Independent System Operator
- Distribution
  - Distribution Management System
  - Distribution System Operator
  - Increasing automation

Automatic Generation Control (AGC)

- Generator governors
- Scheduled versus actual interchange
  - Coordinated between balancing authorities
  - Actual is measured flow
  - Unintentional flows
- Area control error (ACE)
- Time error
- NERC control criteria

Balancing authorities



Boundaries are approximate and for Illustrative Purposes Only

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Balancing Authority responsibilities

- Balance load, generation and net interchange
- Control frequency and time error
- Implement interchange transactions

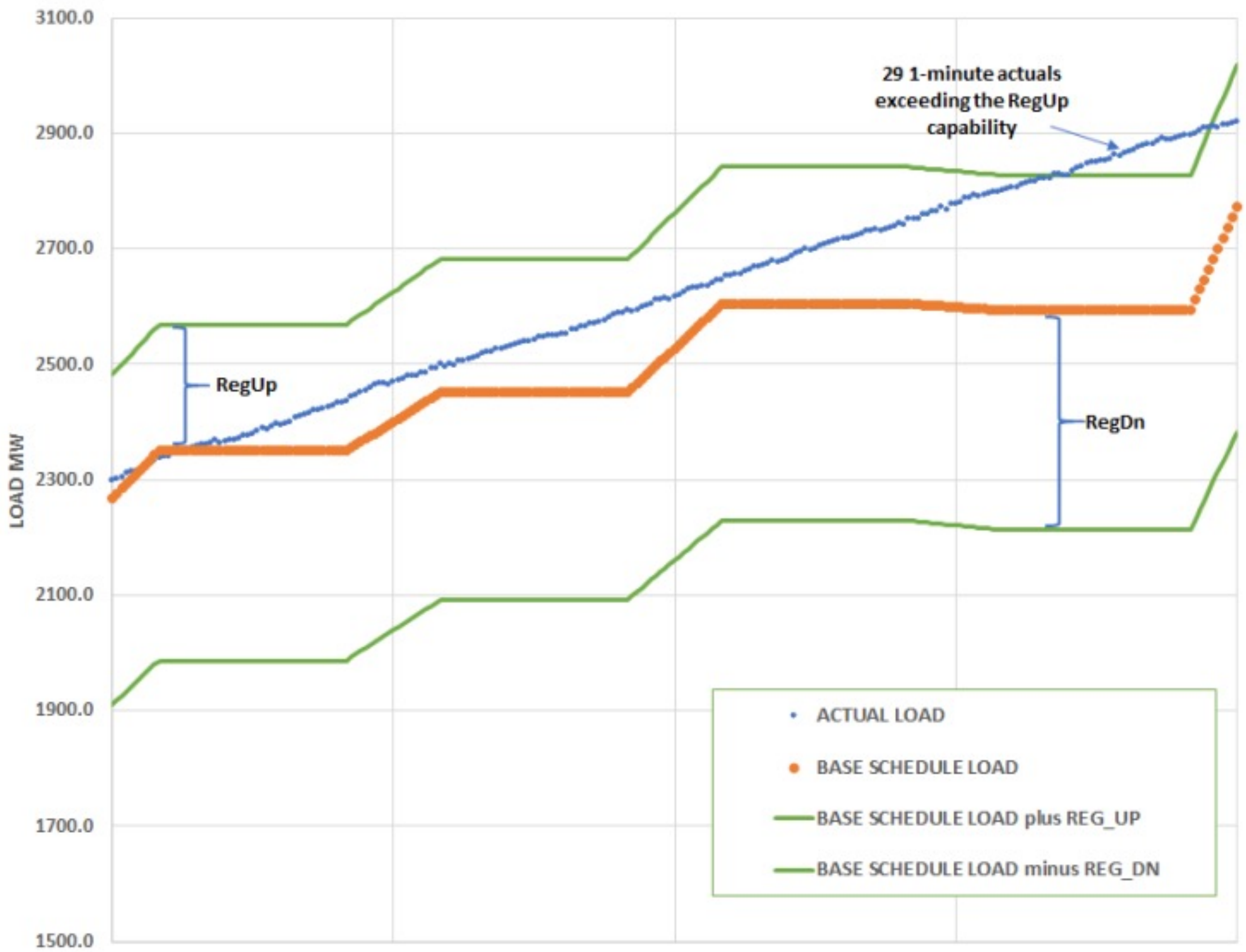
Frequency Disturbance Response

- Major generator trips
- Stored energy in system (in rotating inertia) supplies load
- Synchronous generators slow down
- Governors act to stabilize frequency
- AGC acts over time to restore frequency

Control Error

- Errors of moderate magnitude acceptable
- Control errors that help frequency are good
  - Generating too much power when frequency is low
- Control errors that hurt frequency are bad
- Also look at magnitude of error over time

Maintaining Regulating Reserves



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Maintaining Regulating Reserves

- Adding variable generation to load variation increases reserve requirements
- “Spinning reserve”
- Responsive to AGC
- Regulate up versus regulate down
- Need to maintain reserve around forecasted net load
- Who pays?

Contingency Reserves

- Replace lost generator
- Meet disturbance control standard
- Greater of:
  - MW of most severe contingency
  - Percentage of hourly integrated load + hourly integrated gen.

Options for Meeting Reserves

- Self supply
  - Generation
  - Energy Storage
- Market structure
- Reserve sharing group/power pool

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Operating Limits

- System designed/planned to handle single (or double contingencies)
- Combinations of conditions may require special remedial actions
- Equipment current limits→ thermal
  - Line and transformers
- Voltage limits
- Stability limits

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Remedial Action Schemes

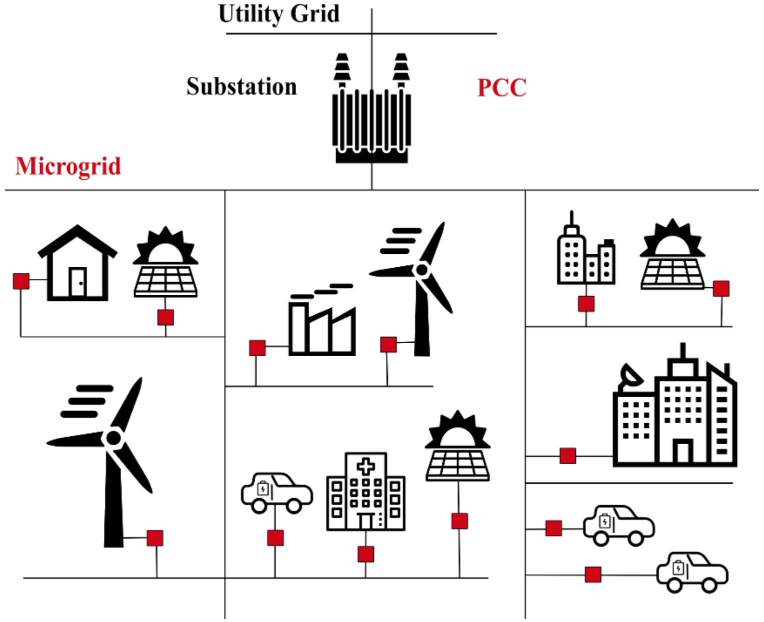
- Autonomous schemes act in specific circumstances
- Often armed by operator
- Act when preset conditions met
- Increased used as power system is run closer to limits

Abnormal Situations - Power Outages

- Natural disasters
  - Windstorms, fires, tornados, hurricanes, floods, temperature extremes, etc.
- Failure of generation or transmission equipment
- Misoperation of the protective equipment
- Cyberattacks can bring down the system

Microgrids

- Serve local load in abnormal conditions
- Power generation resources
- Electrical loads
- Energy storage system (optional)
- Microgrid controller



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Measures of Performance Planning Versus Operations

- Reliability
  - Interruptions
  - Time duration of interruptions
  - Frequency of interruptions
  - Distribution company point of view versus end user
- Power quality
  - Voltage magnitude
  - Voltage and current distortion
- Resilience?

Some Reliability Metrics

- System Average Interruption Duration Index (SAIDI)

$$SAIDI = \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customers} = \frac{\sum_i UiNi}{\sum_i Ni}$$

- System Average Interruption Frequency Index (SAIFI)

$$SAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\sum_i \lambda iNi}{\sum_i N\ i}$$

Reliability Metrics

- Customer Average Interruption Duration Index (CAIDI)

$$CAIDI = \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customer\ interrutions} = \frac{\sum_i UiNi}{\sum_i \lambda iNi}$$

$$CAIDI = \frac{SAIDI}{SAIFI}$$

Reliability Metrics

- Customer Average Interruption Frequency Index (CAIFI)
- Average System Availability Index (ASAI) –A single customer's hour of service demand is 8760 hours for an entire year.

$$ASAI = \frac{customer\ hours\ of\ available\ service}{customer\ hours\ demanded} = \frac{\sum_i Ni * 8760 - \sum_i UiNi}{\sum_i Ni * 8760}$$

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Reliability Metrics

- Average System Unavailability Index (ASUI) - The customers hours of service unavailability divided by the customer hours service demand. Again, the customer's hours service demand is 8760 hours for an entire year.

$$ASUI = 1 - ASAI$$

Reliability Metrics

- Average System Unavailability Index (ASUI) - The customers hours of service unavailability divided by the customer hours service demand. Again, the customer's hours service demand is 8760 hours for an entire year.

$$ASUI = 1 - ASAI$$

Summary

- Brief overview of power system structure
- Communication and automation
- Operations
- Some measures of performance