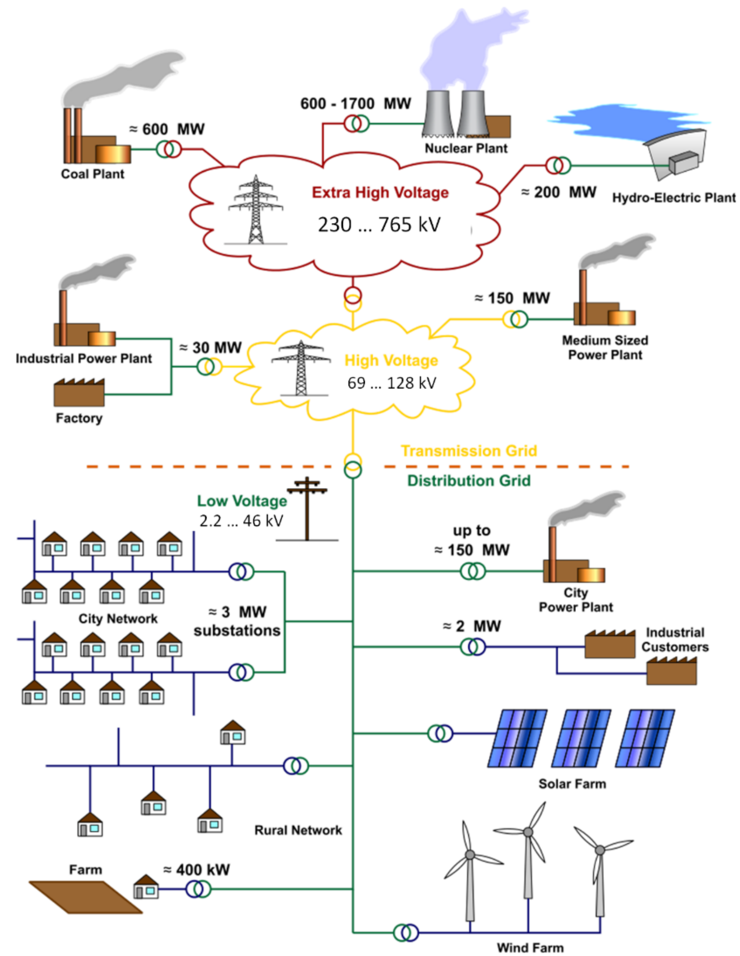
SECTION 9: ELECTRICAL POWER DISTRIBUTION

ESE 470 – Energy Distribution Systems

Introduction

The Electrical Grid

- Three main components to the electrical grid
  - Generation
    - ESE 450
  - Transmission
    - Transmission
    - Subtransmission
  - Distribution
    - Primary distribution
    - Secondary distribution
- Different voltage levels at each
  - Connected by transformers



Transmission Network

- Provides ***bulk power*** from generators to the grid
- Interconnection point between separate utilities or separate generators
  - Power bought and sold at this level
- ***High voltage*** for low loss, long-distance transmission
  - 230…765 kV
  - Generator step up transformers at power plant
- ***High power***
  - 400…4000 MVA per three-phase circuit
- Transmission network terminates at ***bulk-power*** or ***transmission substations***

Subtransmission Network

- Voltage stepped down at bulk-power substations
  - Typically 69 kV, but also 115 kV and 138 kV
- Large industrial customers may connect directly to the subtransmission network
  - Voltage stepped down at customer’s substation
- Subtransmission network terminates at ***distribution substations***

Primary Distribution

- Voltage stepped down at ***distribution substations***
  - 2.2 kV … 46 kV
  - 4 MVA … 30 MVA
- ***Feeders*** leave substations and run along streets
- ***Laterals*** tap off of feeders and run along streets
- Primary distribution network terminates at ***distribution transformers***

Secondary Distribution

- ***Distribution transformers*** step voltage down to customer utilization level
  - Single-phase 120 V … three-phase 480 V
- Secondary distribution is the connection to the customer
- May connect to a ***secondary main***
  - Serves several customers
- Or, one distribution transformer may serve a single customer

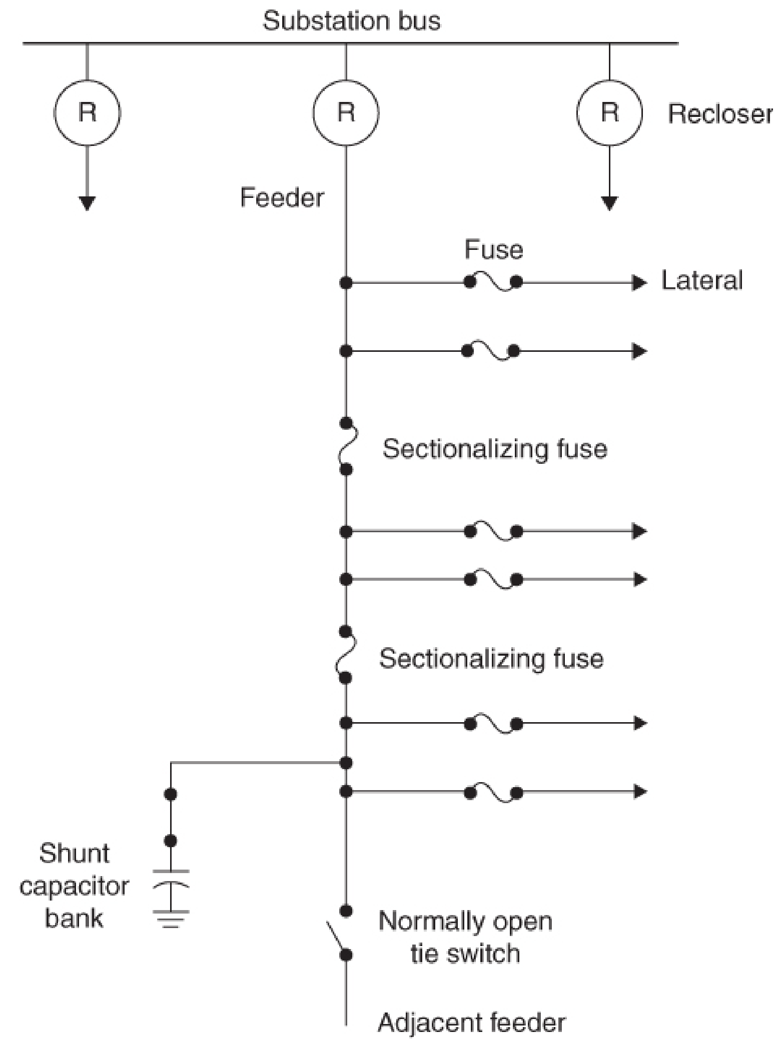
Primary Distribution

Distribution Substations

- Primary distribution network is fed from ***distribution substations:***
  - Step-down transformer
    - 2.2 kV … 46 kV
    - Typically 15 kV class: 12.47 kV, 13.2 kV, or 13.8 kV
  - Circuit protection
    - Surge arresters
    - Circuit breakers
  - ***Substation bus*** feeds the primary distribution network
- ***Feeders*** leave the substation to distribute power into the service area in one of three topologies
  - Primary ***radial*** system
  - Primary ***loop*** system
  - Primary ***network*** system

Primary Radial System

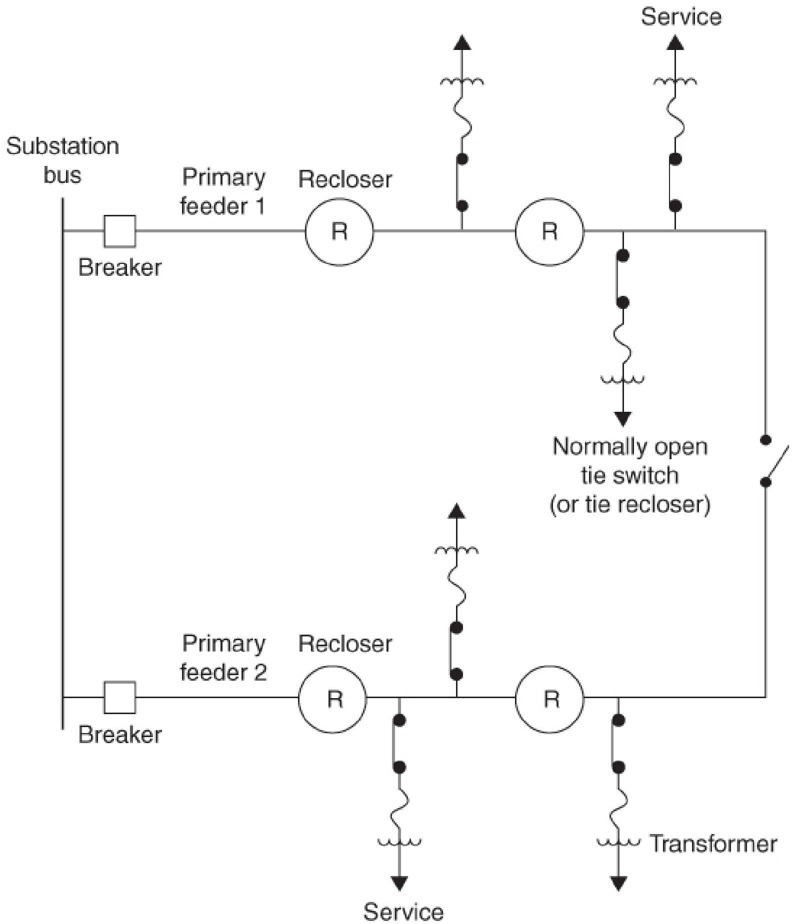
- Multiple radial feeders may leave a single substation
- Each load in the service area served by a single feeder
- Feeders run along streets
  - Overhead or underground
- Laterals tap off of feeders
  - Overhead or underground



source: Glover, Sarma, Overbye

Primary Loop System

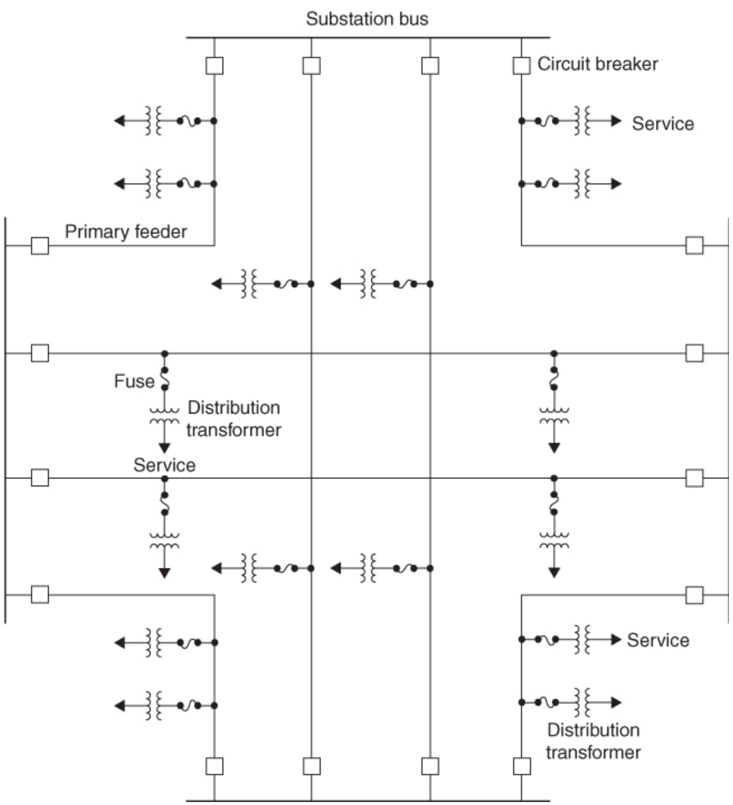
- ***Primary loop systems*** provide a reliability improvement over radial systems
- Two feeders loop from the distribution substation through service area
  - Normally-open tie switch completes the loop
- Reclosers around the loop isolate faults
- Tie switch closes to provide service downstream of isolated section



source: Glover, Sarma, Overbye

Primary Network System

- ***Primary network system*** provides further reliability improvement
- Service area supplied by a grid of interconnected feeders
  - Feeders originate from multiple substations
- Used in densely-populated urban centers



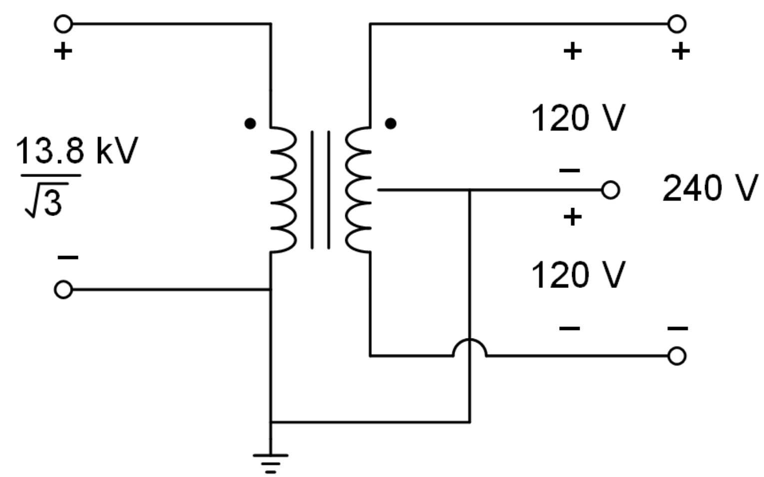
source: Glover, Sarma, Overbye

Secondary Distribution

Secondary Distribution

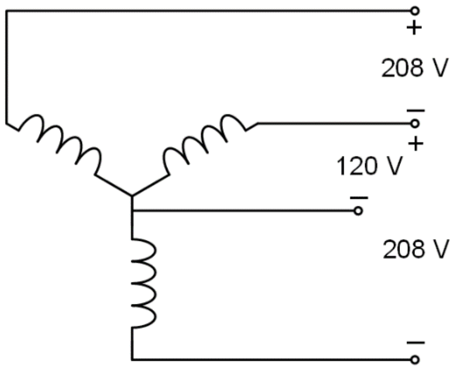
- The ***secondary distribution network*** connects customers to the primary distribution network
- Distribution transformers step voltages down to customer utilization levels

- Common secondary distribution voltages:
  - Single-phase 120/240 V
    - Three wire
    - Residential

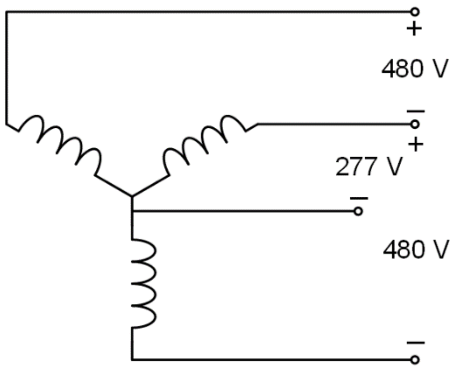


Secondary Distribution

- Common secondary distribution voltages (cont'd):
  - Three-phase/single-phase 208Y/120 V
    - Four wire
    - Dense residential/commercial



  - Three-phase/single-phase 480Y/277 V
    - Four wire
    - Commercial/industrial/high rise
    - Single-phase 277 V for fluorescent lighting
    - Three-phase 480 V for motors
    - Transformers provide single-phase 120 V for outlets



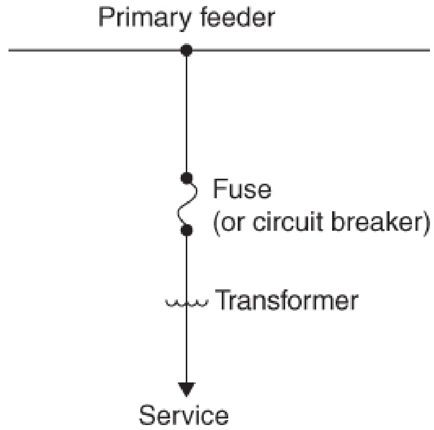
Distribution Transformers

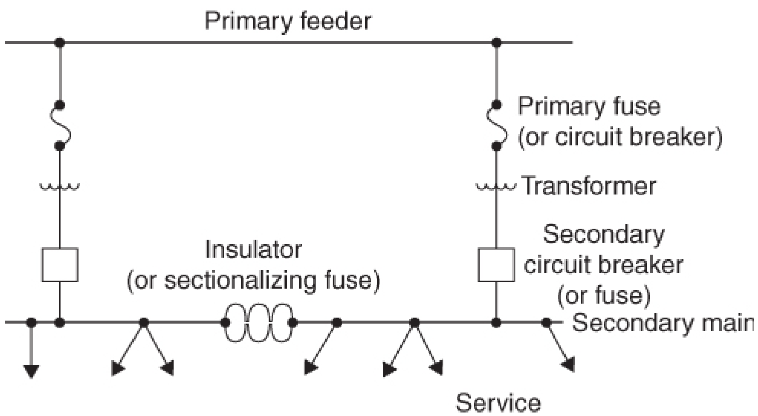
- ***Distribution transformers*** step voltages down to customer levels
  - Pole-mount
  - Pad-mount
  - Vault

- Two possible configurations:
  - One transformer per customer
  - Common secondary main

Distribution Transformers

- One distribution transformer per customer
  - Rural areas
  - Large loads
- Common secondary main
  - One transformer serves several customers
  - Densely-populated areas
  - Multiple transformers may connect in parallel to the secondary main – ***banked secondary***





Ancillary Services

Ancillary Services

- Primary function of the electrical power system is to supply the exact amount of power required to satisfy demand
  - Constantly fluctuating load
  - Adequate power quality and reliability must be maintained

- ***Ancillary services:*** all of the secondary functions of the electric utilities necessary to ensure power quality and reliability
  - Some provided at the generation level
  - Some at the transmission and distribution networks

Ancillary Services

- FERC regulations specify ancillary service requirements for utilities
  - Capability to inject power – real and reactive – onto the grid as needed
  - Services differ in the time frame corresponding to the required power

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- Ancillary Services:
  - Load following
  - Frequency regulation
  - Voltage regulation
  - Spinning reserve
  - Supplemental reserve
  - Replacement reserve

Ancillary Services

- **Load following**
  - Variation of generated power to track the daily load profile
  - Response time: minutes to hours
  - Location: generation

- **Frequency regulation**
  - Tracking of short-term load variations to ensure that grid frequency remains at 60 Hz
  - Response time: seconds to minutes
  - Location: typically at the generator

Ancillary Services

- **Voltage regulation**
  - Maintaining line voltage levels near nominal values
    - Injection or absorption of reactive power
    - Adjusting transformer tap settings
  - Response time: seconds
  - Location: generation, transmission, distribution

- **Spinning reserve**
  - Online generation with spare capacity
    - Able to respond quickly to compensate for generation outages
  - Response time: seconds to minutes
  - Location: generation

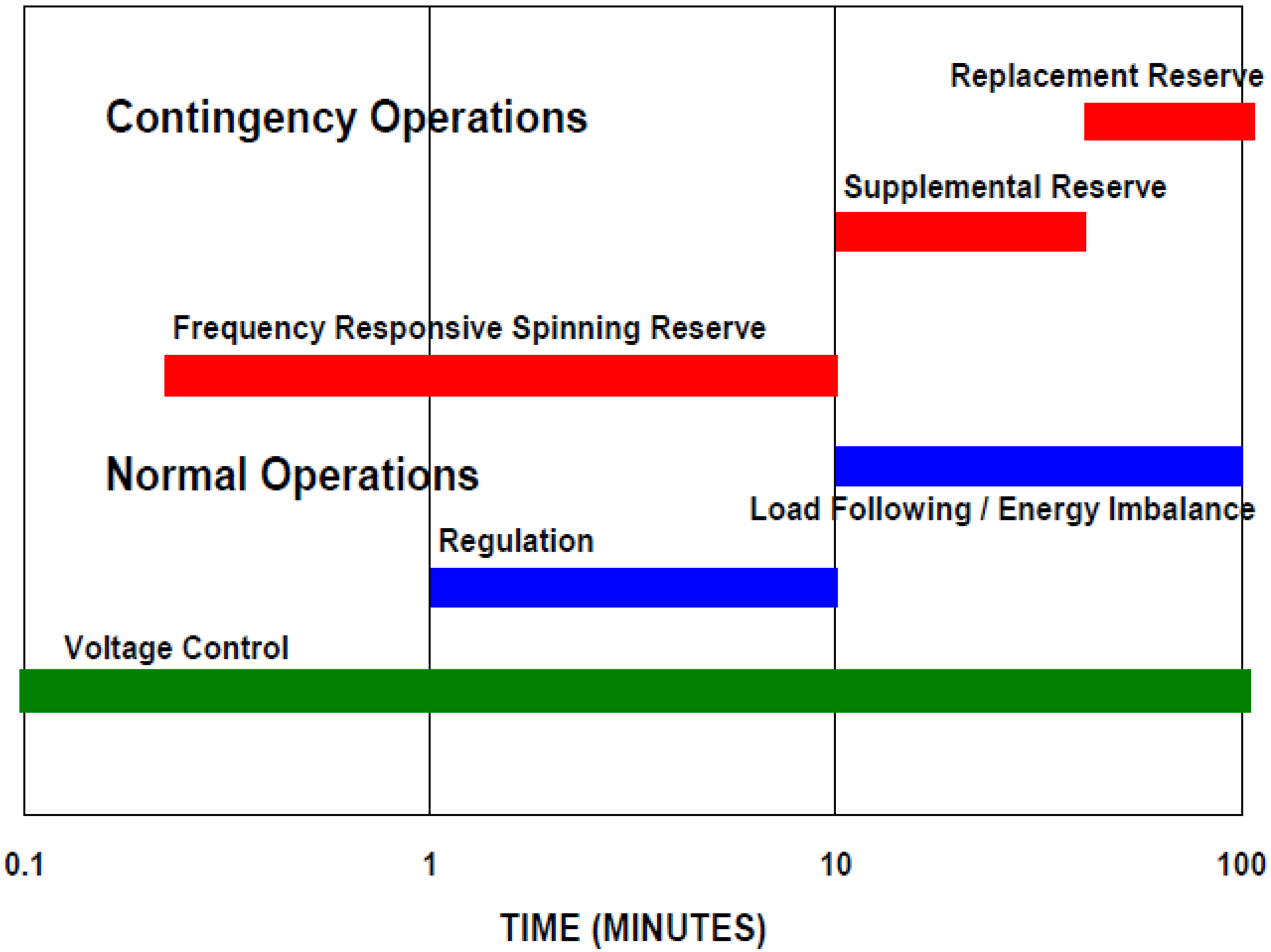
Ancillary Services

- **Supplemental reserve**
  - Online or offline spare generation capacity
  - Response time: minutes
  - Location: generation

- **Replacement reserve**
  - Typically offline generation capacity
    - Takes over for spinning and supplemental reserves
  - Response time: tens of minutes
  - Location: generation

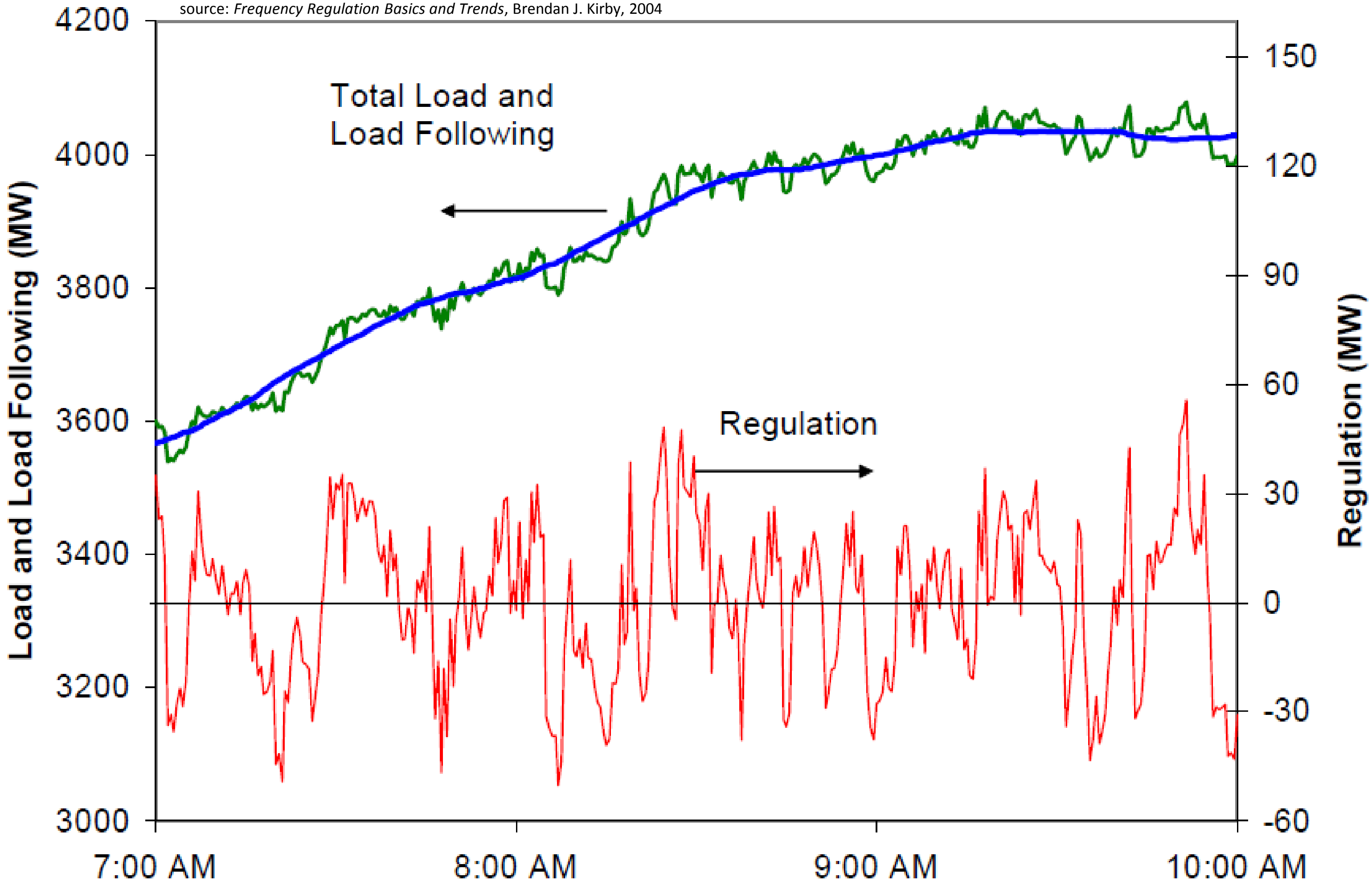
Ancillary Services – Response Time

source: *Frequency Regulation Basics and Trends*, Brendan J. Kirby, 2004



Regulation and Load Following

source: *Frequency Regulation Basics and Trends*, Brendan J. Kirby, 2004



Voltage Regulation

- Many of the required ancillary services are provided at the generation level
  - As storage technologies advance, some will be moved to the distribution network
- Voltage regulation occurs, in large part, in the transmission and distribution networks
- Two primary means of voltage regulation in the transmission/distribution networks:
  - Reactive power control
  - Varying transformer tap settings

Voltage Regulation – Reactive Power Control

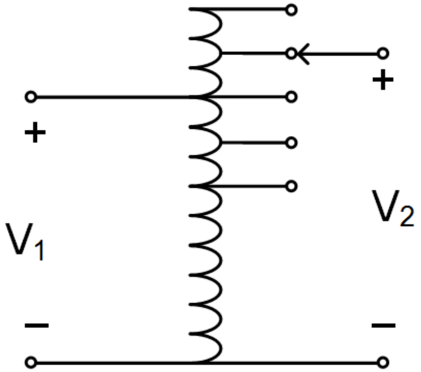
- As reactive power at the load varies, line voltage varies
- Shunt compensation elements switched in and out with varying load
  - ***Static var compensators*** (SVCs) at transmission substations
  - Shunt capacitors located along primary feeders
    - Switched based on local measurements
    - Switched remotely from a control center

Voltage Regulation – Load Tap Changers

- **<u>Load Tap Changers (LTCs)</u>**
  - Transformers with adjustable turns ratios
  - Located at distribution substations
  - Internal motors automatically adjust secondary-side tap settings

Voltage Regulation – Voltage Regulators

- **Voltage Regulators**
  - Autotransformers with automatically-variable tap settings
  - At distribution substations or along primary feeders
  - Internal motors automatically adjust secondary-side tap settings



Distribution Reliability

Distribution Reliability

- Primary function of the electrical power system is to supply the required load *and* to do so *reliably*
- Several commonly-used distribution reliability metrics
  - Measures of the amount of service interruption over a period of time

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- **System Average Interruption Frequency Index (SAIFI)**
  - Average number of interruptions per customer per year

$$SAIFI = \frac{\#\ customer\ interruptions}{\#\ customers\ served}$$

  - N. American median ≈ 1.1 interruptions

Distribution Reliability

- **<u>System Average Interruption Duration Index (SAIDI)</u>**
  - Average outage time per customer per year

$$SAIDI = \frac{\sum customer\ interruption\ durations}{\#\ customers\ served}$$

  - N. American median ≈ 1.5 hours

- **<u>Customer Average Interruption Duration Index (CAIDI)</u>**
  - Average interruption duration

$$CAIDI = \frac{\sum customer\ interruption\ durations}{\#\ customer\ interruptions} = \frac{SAIDI}{SAIFI}$$

  - N. American median ≈ 1.36 hours

- Only interruptions exceeding 5 minutes are accounted for in these metrics

Smart Grid

The Existing Grid

- The existing electrical grid has evolved slowly over the past century
- Issues facing the current electrical grid include:
  - Generation and transmission/distribution capacity sized to serve peak loads
    - Underutilized most of the time
  - Proliferation of distributed generation from renewable resources will stress the grid
    - Erratic nature of generation
    - Lack of centralized control and monitoring
  - Growth in demand outpacing growth in capacity
  - Susceptible to widespread blackouts
  - Lack of demand-side control
  - Customers lack the ability to make informed energy-usage decisions

The Smart Grid

- The ***smart grid*** will be an evolution of the existing electrical grid
- Integration of technology for:
  - Measurement/monitoring
  - Communication
  - Control
  - Incorporation of renewables
  - Storage
- Much of this will occur in the ***distribution network***
  - Vast majority of interruptions caused in the distribution network

Control and Monitoring of the Current Grid

- Utilities do currently have some level of real-time visibility of and control over their transmission/distribution networks
  - ***Supervisory control and data acquisition (SCADA)***
- A precursor to what will become the ***smart grid***

- For example:
  - Radio-controlled reclosers and sectionalizing switches

Features of the Smart Grid

- **Measurement**
  - Sensors throughout the transmission/distribution networks will monitor loads and voltages
  - Advanced metering infrastructure (AMI) will provide visibility into individual loads
    - Smart meters
- **Communication**
  - Two-way communication between customers and utilities
    - Customers provided with real-time pricing information allowing them to make informed usage decisions

Features of the Smart Grid

- **Control**
  - Utilities may have increased control over loads
    - E.g., water heaters, HVAC, etc.
    - Coordination of loads in an area without sacrificing customer requirements
  - Ability to more effectively re-route power flows
    - Increased reliability
    - Self-healing networks

- **Incorporation of renewables**
  - Proliferation of distributed, renewable generation will stress the grid
  - Smart grid will include technology for incorporating renewables into the grid
    - Without sacrificing stability or quality of power
    - Control over reactive power supplied by renewable sources – FACTS controllers
    - Use of ***storage*** to smooth variable generation

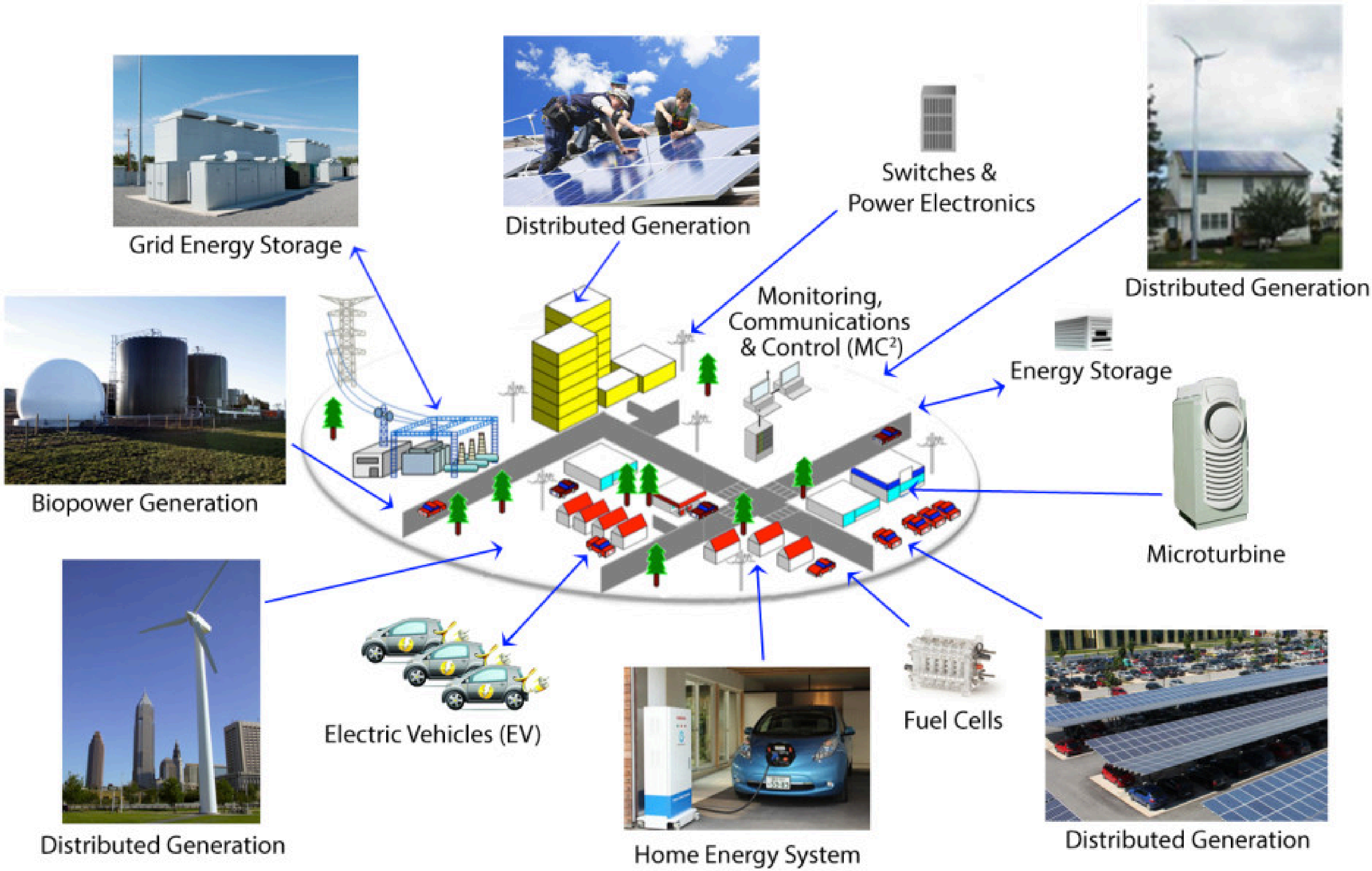
Features of the Smart Grid

- **<u>Storage</u>**
  - Energy storage will be an important component of the smart grid
    - Batteries – Li-ion, flow batteries
    - Compressed air (CAES)
    - Pumped hydro – likely little new development
    - Flywheel
    - Super capacitors
    - Superconducting magnetic energy storage (SMES)
  - Fixed energy storage
    - Near solar/wind farms
    - Distribution substations
  - Mobile energy storage
    - E.g., electric vehicles
    - Utilities may have some control over and access to the energy stored in electric vehicles attached to the grid.

Features of the Smart Grid

- **<u>Microgrids</u>**
  - Increased distributed generation and storage will enable the creation of ***microgrids***
    - Local portions of the electrical grid, which are capable of disconnecting from the grid and operating autonomously
    - Distributed generation
    - Storage
    - Control of the local network and its connection the grid
  - Improved reliability of the overall grid
  - The smart grid may be an ***interconnection of microgrids***

Microgrids



source: www.clean-coalition.org