SECTION 9: ELECTRICAL POWER DISTRIBUTION
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
The secondary distribution network connects customers to the primary distribution network. Distribution transformers step voltages down to customer utilization levels. Common secondary distribution voltages include:

- Single-phase 120/240 V
  - Three wire
  - Residential
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

![Diagram of distribution transformer system]
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

- 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

source: www.tdworld.com
Voltage Regulation – Load Tap Changers

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

Source: Glover, Sarma, Overbye
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
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.

**System Average Interruption Frequency Index (SAIFI)**
- Average number of interruptions per customer per year:
  
  \[
  SAIFI = \frac{\# \text{ customer interruptions}}{\# \text{ customers served}}
  \]

  - N. American median \( \approx 1.1 \) interruptions.
Distribution Reliability

- **System Average Interruption Duration Index (SAIDI)**
  - Average outage time per customer per year
  
  \[
  SAIDI = \frac{\sum \text{customer interruption durations}}{\# \text{customers served}}
  \]
  
  - N. American median \(\approx 1.5\) hours

- **Customer Average Interruption Duration Index (CAIDI)**
  - Average interruption duration
  
  \[
  CAIDI = \frac{\sum \text{customer interruption durations}}{\# \text{customer interruptions}} = \frac{SAIDI}{SAIFI}
  \]
  
  - N. American median \(\approx 1.36\) 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
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

source: Glover, Sarma, Overbye
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

- **Storage**
  - 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

- **Microgrids**
  - 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 to the grid
  - Improved reliability of the overall grid
  - The smart grid may be an *interconnection of microgrids*
Microgrids

Source: www.clean-coalition.org