Power System review

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Basics of Power systems

- Network topology
  - Transmission and Distribution
- Load and Resource Balance
  - Economic Dispatch
- Steady State System Analysis
  - Power flow analysis
- Dynamic System Analysis
  - Transient stability
Network Topology

- Transmission Lines
  - High Voltage 69 kV – 500 kV
  - Power Capacity 50 – 1,000 MW
  - Carry power long distances
    - \[ P = 3V \times I \times \sin \Theta \]
  - Low energy losses, \[ P_{\text{loss}} = I^2 R \]
  - Large structures
Power Transmission In the United States

United States transmission grid
Source: FEMA
Network Topology

- **Distribution Circuits**
  - Primary: 12 – 34 kV AC
  - Secondary: 480 V – 120 V AC
  - Power capacity: 10 – 40 MW
  - Shorter distances, higher losses
  - Smaller overhead structures
  - Underground
  - Terminal equipment
    - Transformers
    - Capacitors
    - Lightning arresters
    - Switches
Customer Load

- Customer Power
  - Residential
    - Single phase, 220 – 120 V, resistive
  - Commercial
    - Three phase, 277 – 4,160 V, inductive

- Metering of Power Consumption
  - Conventional meters
  - Automatic Metering Infrastructure (AMI, aka: Smart Meter)

- Demand Response
  - Automatic
  - Manual
Generating Resources

- Different Types
  - Fossil Fuel
  - Hydroelectric
  - Nuclear
  - Geothermal
  - Renewable
    - Photovoltaics
    - Solar Thermal
    - Wind
    - Bio-gas
Power System Summary

Color Key:
Black: Generation
Blue: Transmission
Green: Distribution

Generating Station
Generating Step Up Transformer

Transmission lines
765, 500, 345, 230, and 138 kV

Transmission Customer
138kV or 230kV

Substation Step Down Transformer

Subtransmission Customer
26kV and 69kV

Primary Customer
13kV and 4kV

Secondary Customer
120V and 240V
What is economic dispatch?

“The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities.” (EPAct Section 1234)

There are two fundamental components to economic dispatch:

- Planning for tomorrow’s dispatch
- Dispatching the power system today
Planning for Tomorrow Dispatch

- Scheduling generating units for each hour of the next day's dispatch
  - Based on forecast load for the next day
  - Select generating units to be running and available for dispatch the next day (operating day)
  - Recognize each generating unit’s operating limit, including its:
    - Ramp rate (how quickly the generator’s output can be changed)
    - Maximum and minimum generation levels
    - Minimum amount of time the generator must run
    - Minimum amount of time the generator must stay off once turned off
Planning for Tomorrow’s Dispatch Cont’d

- Recognize generating unit characteristics, including:
  - Cost of generating, which depends on:
    - its efficiency (heat rate)
    - its variable operating costs (fuel and non-fuel)
    - Variable cost of environmental compliance
    - Start-up costs

- Next day scheduling is typically performed by a generation group or an independent market operator
Reliability Assessment For Dispatch

- Analyze forecasted load and transmission conditions in the area to ensure that scheduled generation dispatch can meet load reliably.
- If the scheduled dispatch is not feasible within the limits of the transmission system, revise it.
- This reliability assessment is typically performed by a transmission operations group.
Dispatching the Power System For Today

- Monitor load, generation and interchange (imports.exports) to ensure balance of supply and load
  - Monitor and maintain system frequency at 60 Hz during dispatch according to NERC standards, using Automatic Generation Control (AGC) to change generation dispatch as needed
  - Monitor hourly dispatch schedules to ensure that dispatch for the next hour will be in balance

- Monitor flows on transmission system
  - Keep transmission flows within reliability limits
  - Keep voltage levels within reliability ranges
  - Take corrective action, when needed, by:
    - Limiting new power flow schedules
    - Curtailing existing power flow schedules
    - Changing the dispatch
    - Shedding load

- This monitoring is typically performed by the transmission operator
Power Flow Analysis

- Assumes balanced three phase system
- Modeled as a single phase system
- A set of non-linear differential equations model both the Real (watts) and Reactive (Vars) power flow
- Matrices are developed for all impedances of transmission lines interconnecting substations (busses)
- Non-linear equations are solved through an iterative process, with an assumed initial conditions
Three Phase AC Power System

- Three phases oscillating at 60 Hz, 120 degrees out of phase
Rotating Phasor Diagram of Waveforms
Power System Electrical Components

- **Resistance (Ohms)**
  - $E = IR$

- **Inductance (Henry)**
  - $X_l = 2\pi f \times L$, $E = L(di/dt)$

- **Capacitance (Farads)**
  - $X_c = 1/2\pi \times C$, $I = C (dv/dt)$
Transmission Line Model

- Transmission Lines consist of series resistance, inductance, and capacitance

- These components can be modeled as a complex impedance $Z$, the inverse of $Z$ is admittance $Y$
Power System Representation

Links: Transmission Lines

Nodes: Buses (Substations)

Generator

Customer Loads
We define:

\[ Y_{\text{bus}} = [Y_{ij}] \]

Diagonal Elements:

\[ Y_{ii} = y_i + \sum_{k=1,k\neq i}^{N} y_{ik} \]

Off-diagonal Elements:

\[ Y_{ij} = -y_{ij} \]

- Note that \( Y_{\text{bus}} \) matrix depends on the power grid topology and the admittance of all transmission lines.
- \( N \) is the number of busses in the grid.
Example of Admittance Matrix for four bus example:

\[
Y_{bus} = \begin{bmatrix}
  y_{11} + y_{12} + y_{13} + y_{14} & -y_{12} & -y_{13} & -y_{14} \\
  -y_{21} & y_{22} + y_{21} + y_{23} + y_{24} & -y_{23} & -y_{24} \\
  -y_{31} & -y_{32} & y_{33} + y_{31} + y_{32} + y_{34} & -y_{34} \\
  -y_{41} & -y_{42} & -y_{43} & y_{44} + y_{41} + y_{42} + y_{43}
\end{bmatrix}
\]

After separating the real and reactive parts:

\[
Y_{bus} = G + jB
\]
Bus Voltage

- Let $V_i$ denote the voltage at bus $i$
- $V_i$ is a phasor with *magnitude* and *angle* 

$$V_i = |V_i| \angle \theta_i$$
Power Flow Equations

- Substituting the admittance and voltage. The power flow equations become:

\[
P_k = \sum_{j=1}^{N} |V_k||V_j|\left(G_{kj} \cos(\theta_k - \theta_j) + B_{kj} \sin(\theta_k - \theta_j)\right)
\]

\[
Q_k = \sum_{j=1}^{N} |V_k||V_j|\left(G_{kj} \sin(\theta_k - \theta_j) - B_{kj} \cos(\theta_k - \theta_j)\right)
\]

- We can solve these set of non-linear equations through iterative solution techniques
  - **Gauss-Seidel Method** – substitute voltages and solve equations, begin a new iteration using previously calculated voltages, until minimum tolerance is achieved
  - **Newton-Raphson Method** – faster iterative solution using Taylor series expansion

- Solution can be linearized, by making assumptions about susceptance, bus voltages, and power angle. Faster solution, less accurate for reactive power values.
**Power Flow Simulation Scenarios**

- **Maintenance or Force Outage Response:** Loss of power line, calculate load flow and determine if overloads will occur, re-dispatch generation or drop load

- **Sudden Change in generation:** Generation forced outage, Renewable Generation change, determine transmission line overloads, re-dispatch generation

- **Others?**
Transient Stability Analysis of Power Systems

- Same set of non-linear power equations as steady state power flow analysis
- Generator inertia and control system response is included
- Iterative time step solution is used to determine system response of each generator and active control loop
Transient Stability Analysis

- Power transfer equation:

\[ V_s = V_1 \angle \delta, \quad V_r = V_2 \angle 0^\circ \]

\[ P_e = P_s = P_r = \frac{V_1 V_2}{X} \sin \delta = P_{\text{max}} \sin \delta \]
Equal Area Criteria for Transient Stability

- $A_1$ must be less than $A_2$ for the system to have a stable response

Critical Clearing Angle
Modern power systems are interconnected and operate close to their transient and steady state stability limits.

In large interconnected systems, it is common to find a natural response of a group of closely coupled machines oscillating against other groups of machines.
Transient Stability Simulations

Unstable Condition

Poorly Damped Response

Marginally Damped Response

\( \delta \text{ [°]} \)

\( S^+ > S^- \)

\( S^+ < S^- \)

\( S^+ = S^- \)

\( \delta_{\text{krit}} \)

CCT = Critical Clearing Time
Multi – Machine Response

February 26, 2013 Load Rejection Denver, Co
Transmission and Distribution systems are extensive and complex.
Fundamental defining power system equations are non-linear and highly coupled.
Economic dispatch is becoming more difficult with additional renewable resources, due to uncertainty.
Transient Stability analysis is an important tool to ensure reliable power system operation.
Questions