POWER SYSTEM ANALYSIS

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Power Flow Analysis

- When analyzing power systems we know neither the complex bus voltages nor the complex current injections
- Rather, we know the complex power being consumed by the load, and the power being injected by the generators plus their voltage magnitudes
- Therefore we can not directly use the Y_{bus} equations, but rather must use the power balance equations

Power Balance Equations

From KCL we know at each bus i in an n bus system the current injection, I_i, must be equal to the current that flows into the network

$$I_i = I_{Gi} - I_{Di} = \sum_{k=1}^{n} I_{ik}$$

Since $\mathbf{I} = \mathbf{Y}_{\text{bus}}\mathbf{V}$ we also know

$$I_i = I_{Gi} - I_{Di} = \sum_{k=1}^{n} Y_{ik} V_k$$

The network power injection is then $S_i = V_i I_i^*$

Real Power Balance Equations

$$\mathrm{S_i} = P_i + jQ_i = V_i \sum_{k=1}^{n} Y_{ik}^{*} V_k^{*} = \sum_{k=1}^{n} |V_i||V_k| \, e^{j\theta_{ik}} (G_{ik} - jB_{ik})$$

$$= \sum_{k=1}^{n} |V_i||V_k| \, (\cos\theta_{ik} + j\sin\theta_{ik})(G_{ik} - jB_{ik})$$

Resolving into the real and imaginary parts

$$\mathrm{P_i} = \sum_{k=1}^{n} |V_i||V_k| (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di}$$

$$\mathrm{Q_i} = \sum_{k=1}^{n} |V_i||V_k| (G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = Q_{Gi} - Q_{Di}$$

Power Flow Requires Iterative Solution

In the power flow we assume we know S_i and the $\mathbf{Y}_{bus}$. We would like to solve for the V's. The problem is the below equation has no closed form solution:

$$S_i = V_i I_i^* = V_i \left(\sum_{k=1}^{n} Y_{ik} V_k \right)^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^*$$

Rather, we must pursue an iterative approach.

Gauss Iteration

There are a number of different iterative methods we can use. We'll consider two: Gauss and Newton.

With the Gauss method we need to rewrite our equation in an implicit form: $x = h(x)$

To iterate we first make an initial guess of x, $x^{(0)}$, and then iteratively solve $x^{(v+1)} = h(x^{(v)})$ until we find a "fixed point", $\hat{x}$, such that $\hat{x} = h(\hat{x})$.

Gauss Power Flow

We first need to put the equation in the correct form

$$S_i = V_i I_i^* = V_i \left(\sum_{k=1}^{n} Y_{ik} V_k \right)^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^*$$

$$S_i^* = V_i^* I_i = V_i^* \sum_{k=1}^{n} Y_{ik} V_k = V_i^* \sum_{k=1}^{n} Y_{ik} V_k$$

$$\frac{S_i^*}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k = Y_{ii} V_i + \sum_{k=1, k \neq i}^{n} Y_{ik} V_k$$

$$V_i = \frac{1}{Y_{ii}} \left(\frac{S_i^*}{V_i^*} - \sum_{k=1, k \neq i}^{n} Y_{ik} V_k \right)$$

Three Types of Power Flow Buses

There are three main types of power flow buses

- Load (PQ) at which P/Q are fixed; iteration solves for voltage magnitude and angle.
- Slack at which the voltage magnitude and angle are fixed; iteration solves for P/Q injections
- Generator (PV) at which P and $|V|$ are fixed; iteration solves for voltage angle and Q injection
- special coding is needed to include PV buses in the Gauss-Seidel iteration (covered in book, but not in slides since Gauss-Seidel is no longer commonly used

Newton-Raphson Algorithm

- The second major power flow solution method is the Newton-Raphson algorithm
- Key idea behind Newton-Raphson is to use sequential linearization

General form of problem: Find an x such that

$$f(\hat{x}) = 0$$

PV Buses

- Since the voltage magnitude at PV buses is fixed there is no need to explicitly include these voltages in **x** or write the reactive power balance equations
  - the reactive power output of the generator varies to maintain the fixed terminal voltage (within limits)
  - optionally these variations/equations can be included by just writing the explicit voltage constraint for the generator bus

$$|V_i| - V_{i\ \mathrm{setpoint}} = 0$$

Generator Reactive Power Limits

- The reactive power output of generators varies to maintain the terminal voltage; on a real generator this is done by the exciter
- To maintain higher voltages requires more reactive power
- Generators have reactive power limits, which are dependent upon the generator's MW output
- These limits must be considered during the power flow solution
- These limits will be discussed further with the Newton-Raphson algorithm

Generator Reactive Limits, cont'd

- During power flow once a solution is obtained check to make generator reactive power output is within its limits
- If the reactive power is outside of the limits, fix Q at the max or min value, and resolve treating the generator as a PQ bus
  - this is know as "type-switching"
  - also need to check if a PQ generator can again regulate
- Rule of thumb: to raise system voltage we need to supply more vars

Thank Q