The Power Flow & Optimal Power Flow Problems
Smith College, EGR 325
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Overview

• Quick recap of power flow equations
• Begin using the PowerWorld simulator
  – Practice problems in class
  – Homework 2 & 3
• Begin creating Puerto Rico system model
Power Flow Self Quiz

• What is the purpose of power flow analysis?
• What is the process?
  • What data do we have and seek?
• How is our understanding improved by performing a power flow?

Power Factor Review for HW

• Complex power
  • \( \mathbf{S} = \mathbf{P} + j\mathbf{Q} = V\cos \theta + jV\sin \theta \)
• What is the power factor?
  • In words and mathematically
• Power factor = \( \cos (\theta_v - \theta_i) \) \( (= \cos \theta \) above\)
  • The phase angle \( (\theta_v - \theta_i) \) is defined as the power factor angle
  • Note that this is also the impedance angle – do you see why?
Power Factor Review for HW

• For inductive loads
  • The current lags the voltage, showing that $\theta_i$ is less than (or more negative than) $\theta_v$
  • Therefore, $(\theta_v - \theta_i) > 0$
  • The power factor is said to be lagging
  • The load is said to be lagging
  • Reactive power, $Q > 0 \rightarrow$ An inductor consumes $Q$

Power Factor Review for HW

• For capacitive loads
  • The current leads the voltage, showing that $\theta_i$ is greater than $\theta_v$
  • Therefore, $(\theta_v - \theta_i) < 0$
  • The power factor is said to be leading
  • The load is said to be leading
  • Reactive power, $Q < 0 \rightarrow$ A capacitor generates $Q$
Today: Power Flow Modeling

• For power systems, we know
  – The system topology (the circuit diagram)
  – The impedance of each line, $Z^{-1} = Y = G + jB$
  – PQ bus: The load at each load bus, $S = P + jQ$
  – PV bus: The capability of each generator, $P$ & $|V|$
  – The reference bus ($|V|$ and $\angle \theta = 0$)

• We want to know
  – The actual output of each generator ($S = P + jQ$)
  – The voltage at each bus ($V = V \angle \theta$), for maintaining system performance
  – The power flow on each line ($P_{\text{flow}}$), and ensure it does not exceed the line’s rating

Power Flow Model & Equations

• How many equations and how many unknowns?
  • Slack bus
  • Definition
  • Mathematical and physical role
  • Must identify one generator bus as the slack bus in a power flow simulation.
Power Flow Model & Equations

• How many equations and how many unknowns?

\[ P_i = \sum |V_i||V_k|(G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) = P_{Gi} - P_{Di} \]
\[ Q_i = \sum |V_i||V_k|(G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) = Q_{Gi} - Q_{Di} \]

• Numerical methods (iteration)
  – Reference (Slack) bus
  – Solution might not converge

Power Flow Analysis

• Analysis of electrical power flows
  – Simplify the actual 3-phase transmission system by modeling a single phase
    • “One-line” diagram

• The computer model includes data for
  – Transmission lines
  – Generators
  – Loads
\[ Y = Z^{-1} = \frac{1}{R + jX} = \frac{R - jX}{(R + jX)(R - jX)} \]

\[ = \frac{R - jX}{R^2 + X^2} = \frac{R}{R^2 + X^2} - \frac{jX}{R^2 + X^2} \]

\[ = G + jB = \text{conductance} + \text{susceptance} \]

**Power System Diagrams**

- One-line diagram

Generators are shown as circles

Transmission lines are shown as a single line

Arrows are used to show loads
New England 39-Bus Test System

To Obtain Simulator Yourself
http://www.powerworld.com/gloversarmaoverbye
Finding Power World Simulator (now version 20) in ...
Open PowerWorld Simulator and Click the file menu to get the drop down menu and dialog to open a case.

Or... double-click PowerWorld Case in Windows Explorer.
To zoom so you can see things

Small PowerWorld Simulator Case

Load with green arrows indicating amount of MW flow

Used to control output of generator

Note the power balance at each bus

Direction of arrow is used to indicate direction of real power (MW) flow
Three Bus Case on AGC

Generation is automatically changed to match change in load.
To run the Power World Simulator –
Using a One-line Diagram

Switch to ‘Run’ mode

Simulate the system operation by selecting the ‘Tools’ tab and clicking the green ‘Go’ arrow

To view the power system data:
Select Network
To Edit: Make sure you are in edit mode, and select the correct table in “Network” to edit data.
Power Flow: Iterative Solution

- We assume we know the following at each bus (input data to program)
  - Generator buses: P and |V|
  - Load buses: P and Q
  - Slack bus: |V| and <θv
  - …Along with the system topology
    - How buses are connected
    - Impedance (as admittance) of each line

Power World Simulator

- Open PowerWorld
- Do practice problems (next slides)
- Then, open the homework and begin it
Power World Simulator

• Open Example2_3.pwb
• Change the ‘kvar’ generation at the Load to minimize the kvar generation at the Generator
• Change both Load kW and kVAr
• What is the physical phenomenon being simulated?

Power World Simulator

• Open Example1_3.pwb
• Change the Load MW at each load
• Watch the changes in line flows and bus voltages
  – What happens that you expect?
  – What happens that you don’t expect?
  – Why?
HW 2 & 3: Puerto Rico Model

• Gather data
  – Transmission lines, generators, load centers
  – Be fanatical about providing citations, both those you used and those that might be useful

• Enter data into PowerWorld and create group model

• Use Slack (slack.com) to aid in coordination? Moodle???

• Generators
  – Fuel type (oil, natural gas, wind…)
  – MW rating, MVar rating
  – Where located, geographically
  – Entered into PowerWorld

• Transmission lines
  – Ratings (impedance values needed for PowerWorld, line flow limits)
  – Which buses (cities, generators…) they are connected to
  – Entered into PowerWorld

• Load centers
  – Name of city, town, village and geographical location
  – Maximum load
  – Monthly, weekly and hourly load data if possible (we will need this at some point, so start looking now)
  – Entered into PowerWorld
• Coordinators, still for HW 2
  – Perhaps 2 people to combine all the data into a single PowerWorld file

• For HW 3
  – Create a PowerWorld one-line diagram with all the system elements
  – Demonstrate that this Puerto Rico basecase model runs by performing a simple simulation of your own choosing.
  – Hand in a short memo (1 page), with appendices as needed, to explain to any reader what you did, why, and what you found so far.

Self-Quiz Questions

1) Define the physical significance of
   - S, P, Q. What are the units of each?
2) Define, compare and contrast
   - Energy and power; include units
3) If you were a system operator, what questions/problems would you use a power flow program to answer/solve?
4) What input data do you need to run a power flow model?
5) What results/output do you get from a power flow model?
   … and how do you use these results?
6) What is the slack bus and what role does it serve in the model? in the actual system?
7) How do we know if the model converges or not? What does it mean if it does not converge?