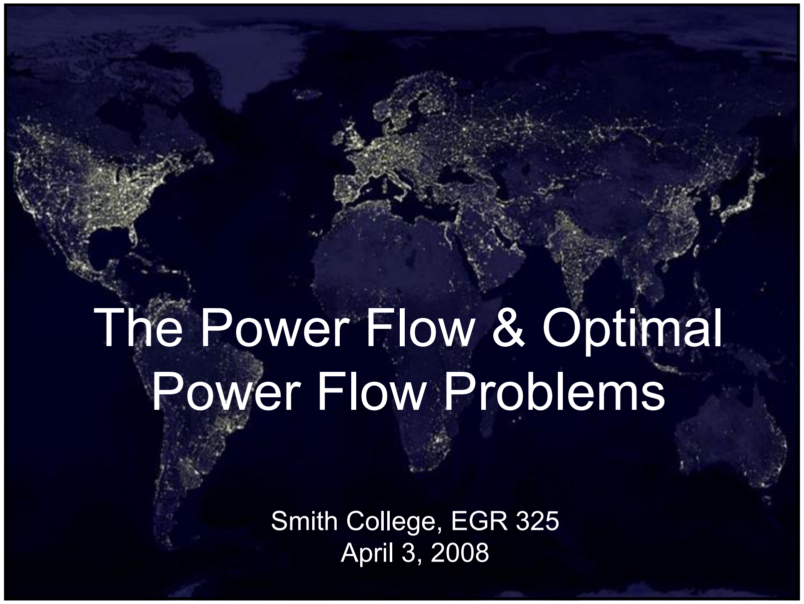

Objectives

- Recap the power flow problem
  - Numerical solution – issues?
- Revisit economic dispatch, combined with power flow
- Investigate two power flow programs
  - PowerWorld
  - MATPower

The Power Flow Problem

- We know
  - The system topology (the circuit diagram)
  - The impedance of each line, R, X, B
  - The load at each load bus (**S** = P + *j*Q)
  - The capability of each generator (P, V)
- We want to know
  - The output of each generator (**S**)
  - The voltage at each bus (**V** = $V\angle\theta$)
  - The power flow on each line (P_{flow})

Power Flow Equations

- Using KCL, we can write the current flow into the power system from any node *i*

  $$I_i = I_{Gi} - I_{Di} = \Sigma I_{ik}$$

- Since I = YV (where $Y = Z^{-1}$), we know

  $$I_i = I_{Gi} - I_{Di} = \Sigma Y_{ik} V_k$$

- What do “i” and “k” represent?

Power Flow Equations

- Turning to the power injection at node *i*, we can write

$$S_i = V_i I_i^* = V_i(\Sigma Y_{ik} V_k)^* = V_i \Sigma Y_{ik}^* V_k^*$$

- We want to be able to find P_i and Q_i separately, so we need to expand the expression for S_i into real and reactive components

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Power Flow Equations

- Use the following expressions to expand the equation for complex power
  - $Y_{ik} = G_{ik} + jB_{ik}$
  - $V_i = |Vi|<\theta_i = |Vi|e^{j\theta}$
    - $e^{j\theta} = \cos\theta + j\sin\theta$
  - $\theta_{ik} = \theta_i - \theta_i$
  - $S_i = P_i + jQ_i$

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Power Flow Equations

- Finally, we can write

$$S_i = P_i + jQ_i = V_i \Sigma Y_{ik}^* V_k^*$$
$$= \Sigma |V_i||V_k| e^{j\theta\_ik}(G_{ik} - jB_{ik})$$
$$= \Sigma |V_i||V_k|(\cos\theta_{ik} + j\sin\theta_{ik})(G_{ik} - jB_{ik})$$

- Separate this into real & reactive parts

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

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Real Power Flow Equations

- How many equations and how many unknowns?
- Numerical methods
  - Lack of convergence
  - Slack bus
    - Definition
    - Mathematical and physical role

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Power Flow: Iterative Solution

- We assume we know the following at each bus
  - Generator buses: P and |V|
  - Load buses: P and Q
  - Slack bus: |V| and $<\theta_v$

Power Flow: Iterative Solution

- To know P, Q, V and $<\theta_v$ at each bus, we must solve the power flow eq'ns

$$P_i = \Sigma\, |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di}$$
$$Q_i = \Sigma\, |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = Q_{Gi} - Q_{Di}$$

- Which we cannot solve in closed form
  → We must iterate
  → Practice with iteration activities h.o.

Iteration Exercises

- Find x if $4 = x^2$
- Find x if $\frac{1}{2} = \cos(x)$
- Find x if $6 = x^2$!
- Find x if $4 = x^2 + \cos(x$
  - Note we can easily solve $4 = x^2 + 3x$
  - Now find x if $4 = x^2 + \cos(x)$

Running a Power Flow Program

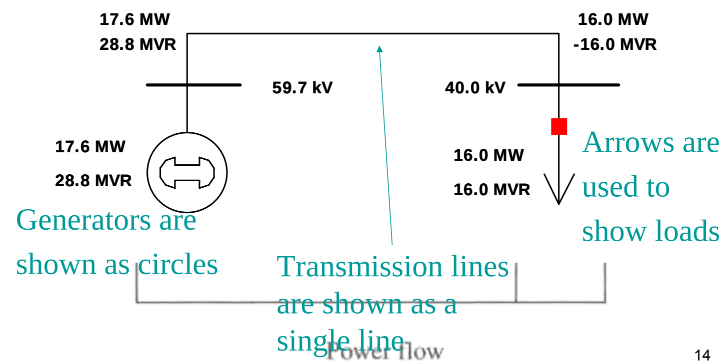
- Programs created in the days of FORTRAN programming
- Input data one of two standard formats
  - IEEE
  - PTI
- Output data format designed by the programmer
- ** *Cases may or may not converge!* **

Running a Power Flow Program

- We will use two popular programs
  - MATPower
    - tabular data input and output
    - relatively easy to use
  - PowerWorld
    - visual
    - more difficult to use
- Terminology
  - One-line diagrams
  - per unit system (normalize all values)

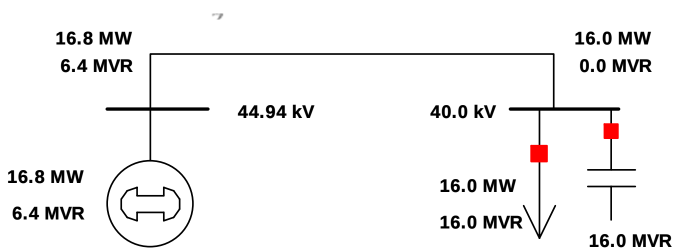
Power System Diagrams

- Circuit vs. one-line diagram

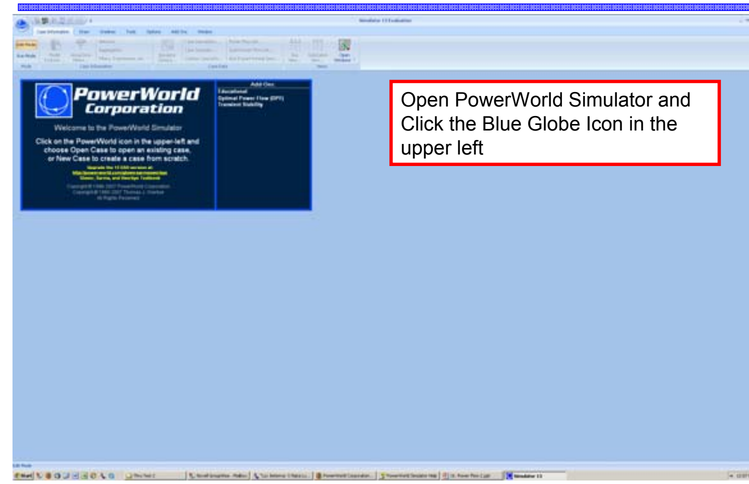


Power System Diagrams

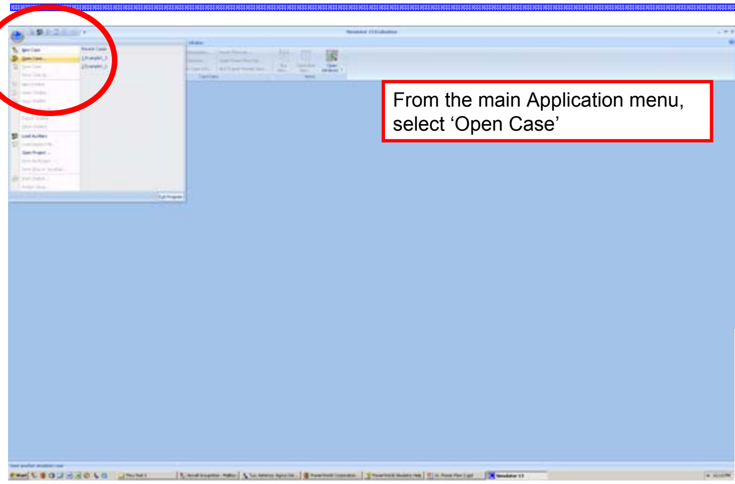
- Circuit vs. one-line diagram



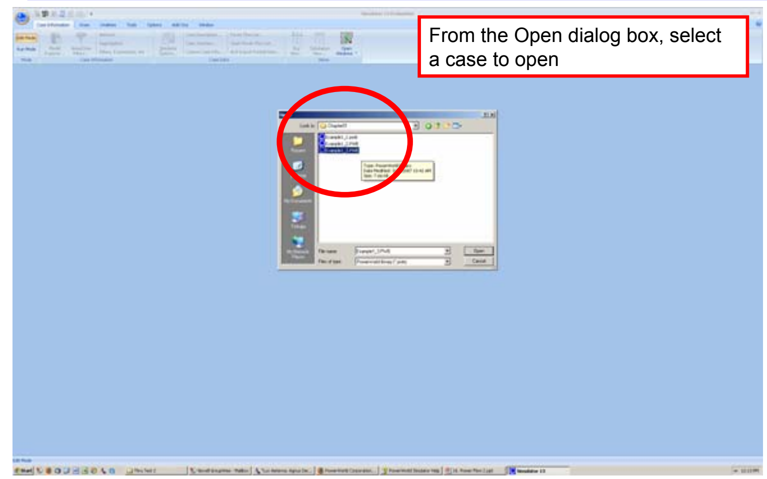
Power World Simulator – Start-up



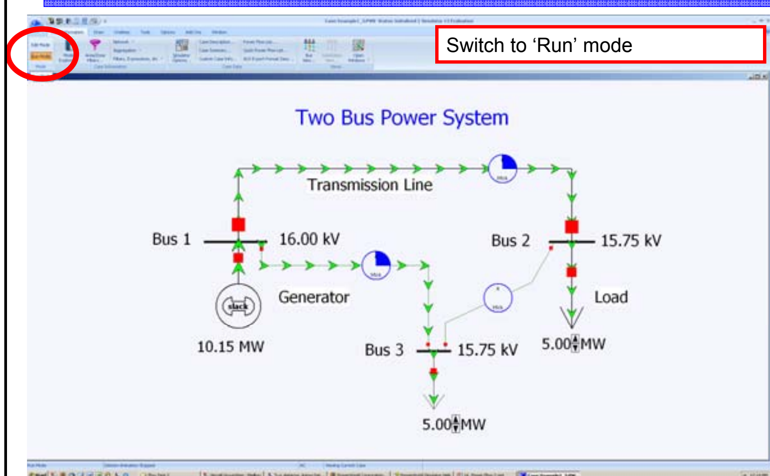
Power World Simulator – Open Case



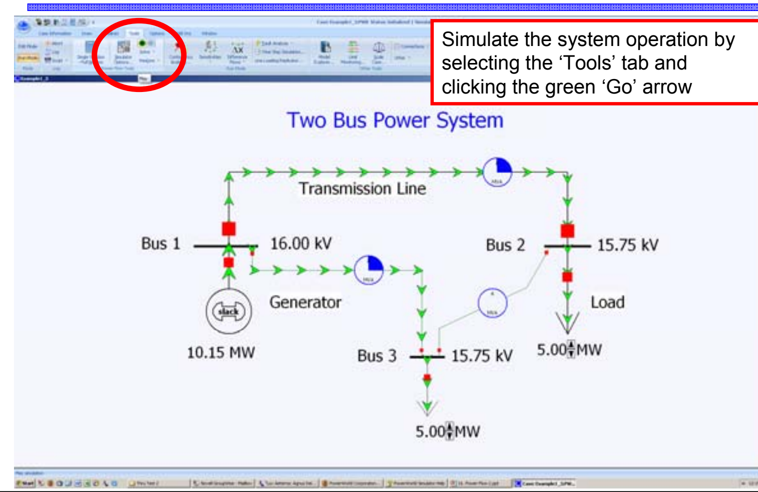
Power World Simulator – Open Case



Power World Simulator – One-line Diagram



Power World Simulator - Run



Power World Simulator

- You can open help files by opening the file
  - Pwrworld.chm
  - In directory
    - C:\Program Files\PowerWorld_GS\Simulator
    - Or thereabouts

Power World Simulator

- Open PowerWorld
- Open Example1_1.pwb in the Chapter 1 folder
- Begin the simulation
- Increase the load until the transmission line overloads
  - At what MW amount does this occur?
- Click the red boxes
  - What do these do? What do the represent?

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?

MATPower Power Flow Program

- Uses MATLAB
- Free from http://www.pserc.cornell.edu/matpower
- Uses text input and output
  - –Matlab editor for input files
  - –Matlab output window for output

MATPower Input Data

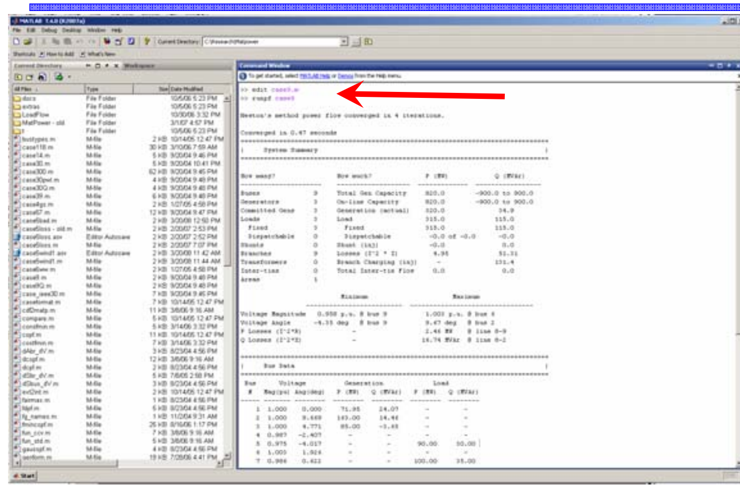
```
%% bus data
%     bus_i   type    Pd  Qd  Gs   Bs   area    Vm  Va  baseKV  zone     Vmax     Vmin
bus = [
    1   3   0   0   0   0   1   1   0    345 1    1.1 0.9;
    2   2   0   0   0   0   1   1   0    345 1    1.1 0.9;
    3   2   0   0   0   0   1   1   0    345 1    1.1 0.9;
    4   1   0   0   0   0   1   1   0    345 1    1.1 0.9;
    5   1   90  30  0   0   1   1   0    345 1    1.1 0.9;
    6   1   0   0   0   0   1   1   0    345 1    1.1 0.9;
    7   1   100 35  0   0   1   1   0    345 1    1.1 0.9;
    8   1   0   0   0   0   1   1   0    345 1    1.1 0.9;
    9   1   125 50  0   0   1   1   0    345 1    1.1 0.9;
];

%% generator data
%   bus Pg  Qg  Qmax  Qmin    Vg  mBase   status  Pmax    Pmin
gen = [
    1   0   0    300 -300    1   100     1   250     10;
    2   163 0    300 -300    1   100     1   300     10;
    3   85  0    300 -300    1   100     1   270     10;
];
```

MATPower Input Data

```
%% branch data
% fbus tbus  r    x    b   rateA   rateB   rateC   ratio   angle   status
branch = [
    1   4   0       0.0576  0       250  250  250  0     0     1;
    4   5   0.017   0.092   0.158   250  250  250  0     0     1;
    5   6   0.039   0.17    0.358   150  150  150  0     0     1;
    3   6   0       0.0586  0       300  300  300  0     0     1;
    6   7   0.0119  0.1008  0.209   150  150  150  0     0     1;
    7   8   0.0085  0.072   0.149   250  250  250  0     0     1;
    8   2   0       0.0625  0       250  250  250  0     0     1;
    8   9   0.032   0.161   0.306   250  250  250  0     0     1;
    9   4   0.01    0.085   0.176   250  250  250  0     0     1;
];
```


Running MATPower



MATPower Output

Converged in 0.47 seconds

System Summary

How many?		How much?	P (MW)	Q (MVAr)
Buses	9	Total Gen Capacity	820.0	-900.0 to 900.0
Generators	3	On-line Capacity	820.0	-900.0 to 900.0
Committed Gens	3	Generation (actual)	320.0	34.9
Loads	3	Load	315.0	115.0
Fixed	3	Fixed	315.0	115.0
Dispatchable	0	Dispatchable	-0.0 of -0.0	-0.0
Shunts	0	Shunt (inj)	-0.0	0.0
Branches	9	Losses (I^2 * Z)	4.95	51.31
Transformers	0	Branch Charging (inj)	-	131.4
Inter-ties	0	Total Inter-tie Flow	0.0	0.0
Areas	1			

	Minimum		Maximum	
Voltage Magnitude	0.958 p.u.	@ bus 9	1.003 p.u.	@ bus 6
Voltage Angle	-4.35 deg	@ bus 9	9.67 deg	@ bus 2
P Losses (I^2*R)	-		2.46 MW	@ line 8-9
Q Losses (I^2*X)	-		16.74 MVAr	@ line 8-2

MATPower Output

Bus Data

Bus #	Voltage Mag(pu)	Voltage Ang(deg)	Generation P (MW)	Generation Q (MVAr)	Load P (MW)	Load Q (MVAr)
1	1.000	0.000	71.95	24.07	-	-
2	1.000	9.669	163.00	14.46	-	-
3	1.000	4.771	85.00	-3.65	-	-
4	0.987	-2.407	-	-	-	-
5	0.975	-4.017	-	-	90.00	30.00
6	1.003	1.926	-	-	-	-
7	0.986	0.622	-	-	100.00	35.00
8	0.996	3.799	-	-	-	-
9	0.958	-4.350	-	-	125.00	50.00
		Total:	319.95	34.88	315.00	115.00

MATPower Output

Branch Data

Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	1	4	71.95	24.07	-71.95	-20.75	-0.000	3.32
2	4	5	30.73	-0.59	-30.55	-13.69	0.174	0.94
3	5	6	-59.45	-16.31	60.89	-12.43	1.449	6.31
4	3	6	85.00	-3.65	-85.00	7.89	-0.000	4.24
5	6	7	24.11	4.54	-24.01	-24.40	0.095	0.81
6	7	8	-75.99	-10.60	76.50	0.26	0.506	4.29
7	8	2	-163.00	2.28	163.00	14.46	-0.000	16.74
8	8	9	86.50	-2.53	-84.04	-14.28	2.465	12.40
9	9	4	-40.96	-35.72	41.23	21.34	0.266	2.26
						Total:	4.955	51.31

Summary

- Second look at the power flow problem
- Introduction to the power flow programs
- Numerical methods
  - Significance of lack of convergence
  - Slack bus