EE 5240 - Lecture 10 Monday Feb 4, 2019

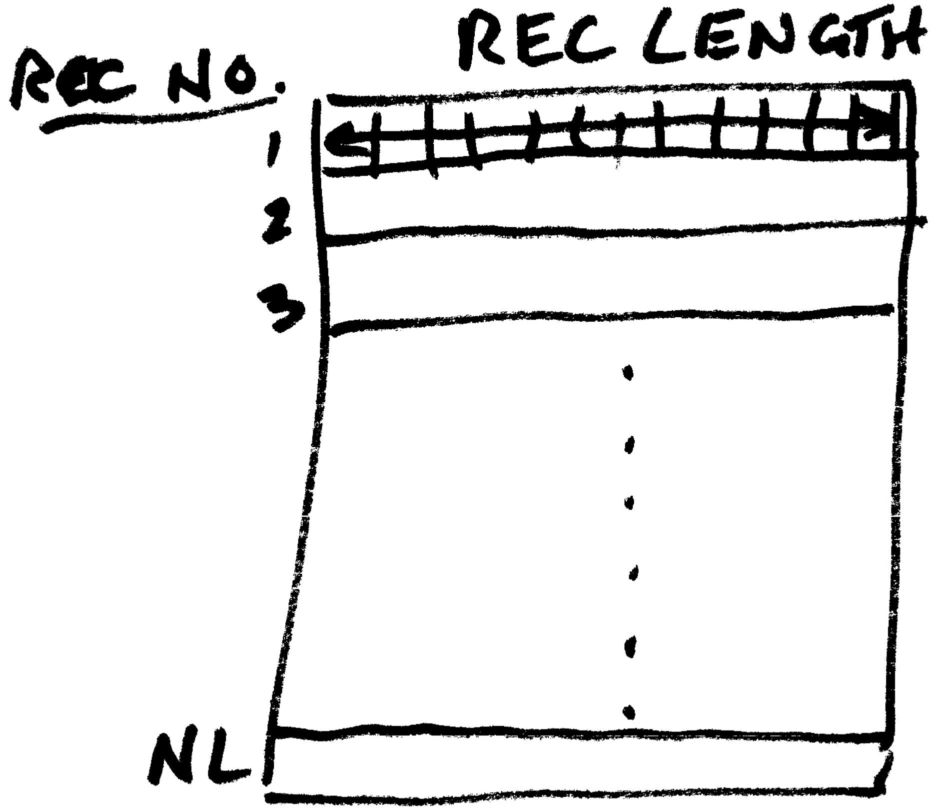
Topics for Today:

- Questions?
- Questions/Comments on Homework #4 ?
- Building [Y] for 14-bus IEEE system.
- Useful Matlab functions: fgetl, sscanf, format ‘%*23c%f’, spalloc, sparse, spy
- Newton Iteration, example for one-variable case
- Newton Iteration, example for two-variable case
- Loadflow Formulation: “NR Details” handout (Week 4)
- NR Algorithm implementation.

Coming up:

- More MatLab - build Jacobian, solve for $\Delta\delta$ and ΔV, iterate.
- Data structures, LU factorization, reordering to avoid zero divides and/or speed up solution.

② Direct Access



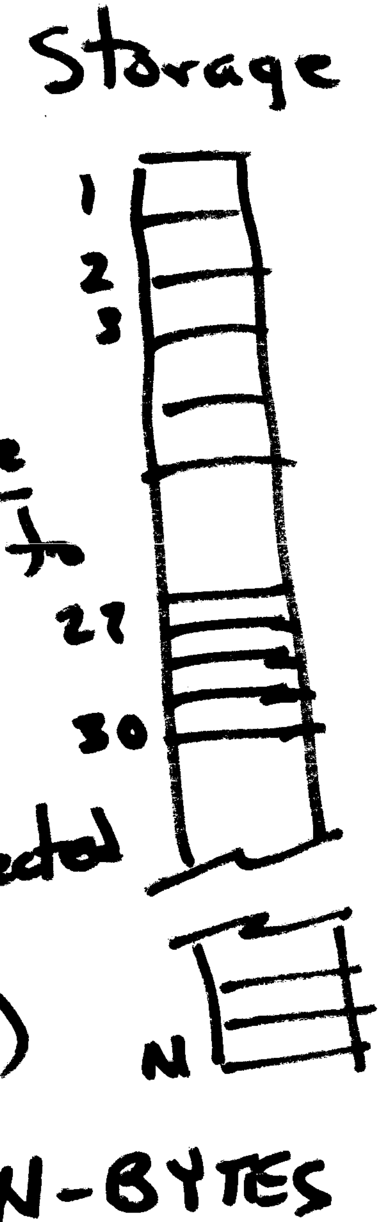
[FIXED LENGTH
DIRECT ACCESS]

offsets

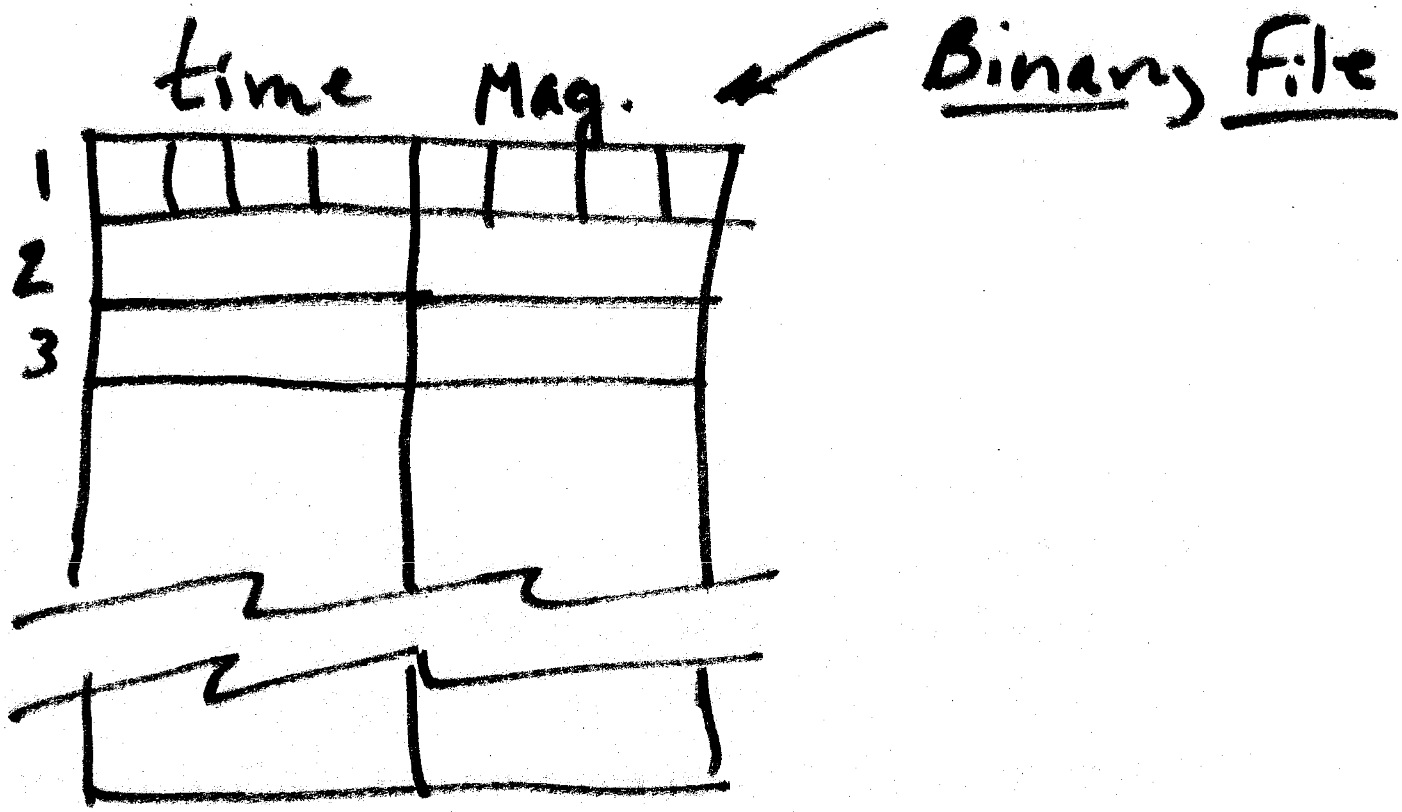
Bytes to skip *before* beginning to read.

Byte No

List-Directed Input
(27:30)



Ex:

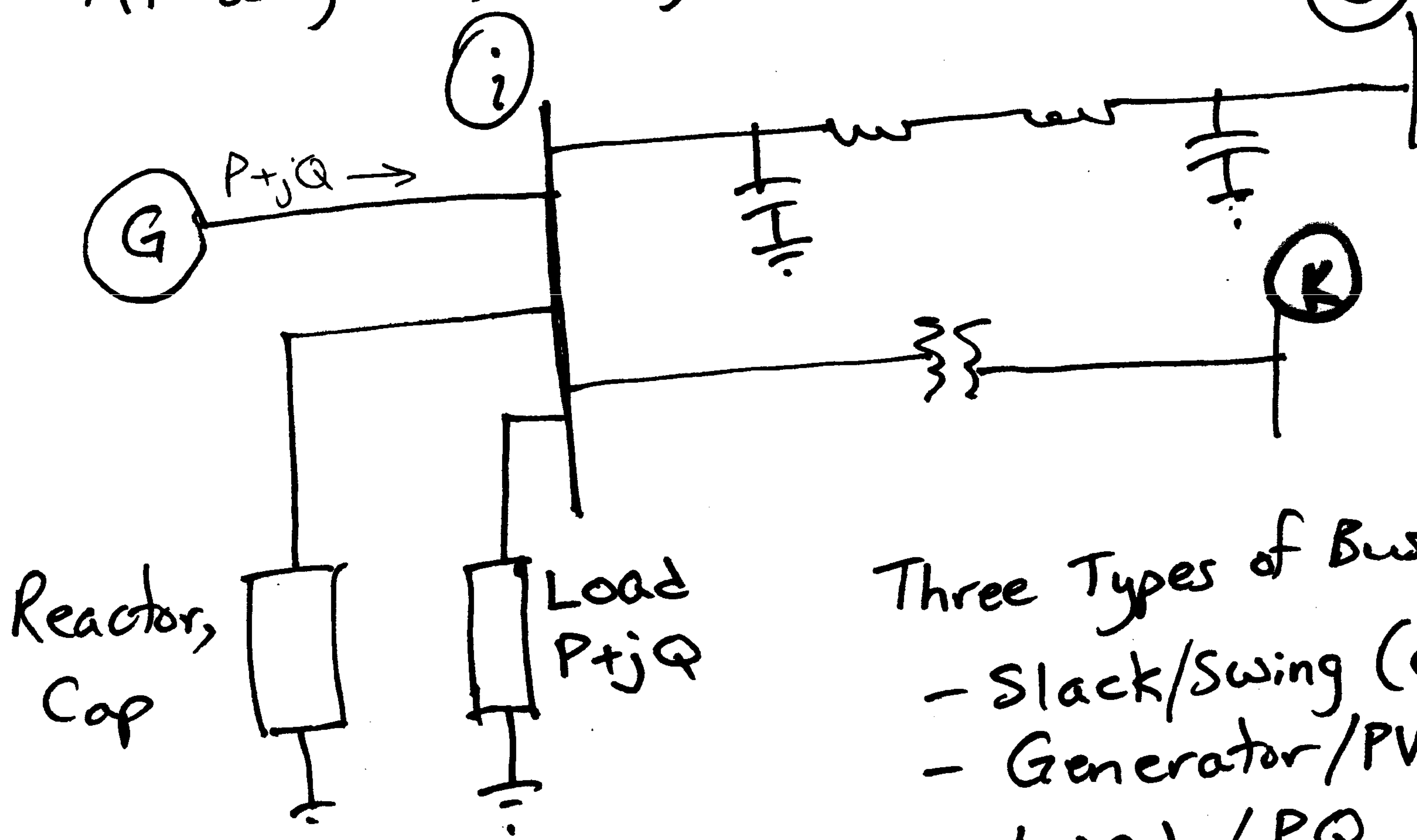


REC LENGTH = 8 Bytes

- Time: Single Prec Real
- Mag: " " "

Load Flow Setup

At any bus, in general,



Three Types of Buses

- Slack/Swing (only one)
- Generator/PV
- Load / PQ

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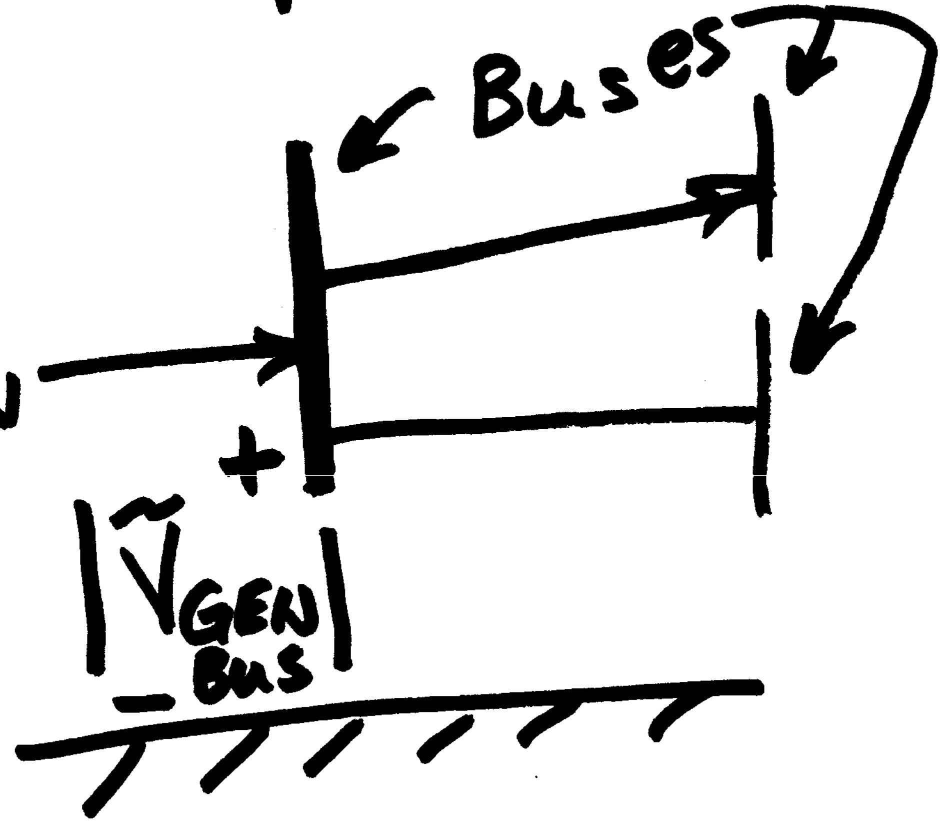
Load Flow

Gen is represented as



Governor
- Control P_{GEN}

Exciter:
- Control $|V_{BUS}|$

Variables

Bus Type	$\lvert\tilde{V}\rvert$	δ	P	Q
Slack	✓	✓	?	?
Gen	✓	?	✓	?
Load	?	?	✓	✓

$\underbrace{\lvert\tilde{V}\rvert \quad \delta}_{V_{Bus} = \lvert\tilde{V}\rvert \angle \delta}$ $\underbrace{P \quad Q}_{\text{Net P \& Q into bus due to gen and load}}$

Does not include Line, XFMR, reactor.

KEY

✓ = known

? = unknown

Next – Combine

- [Y_{Bus}]
- Knowns & unknowns, produce [J], [f^m]
- Apply NR iteration to solve.

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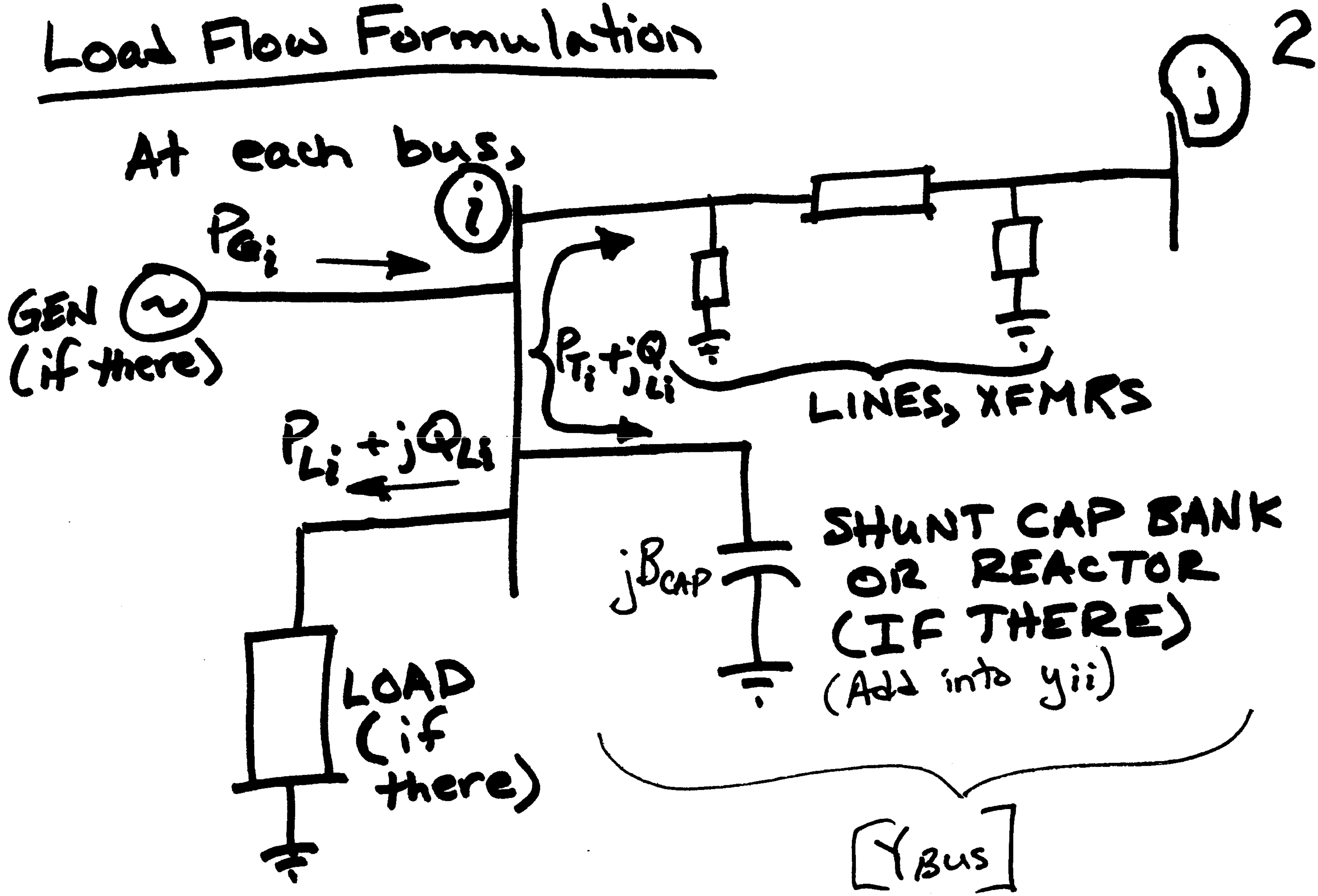
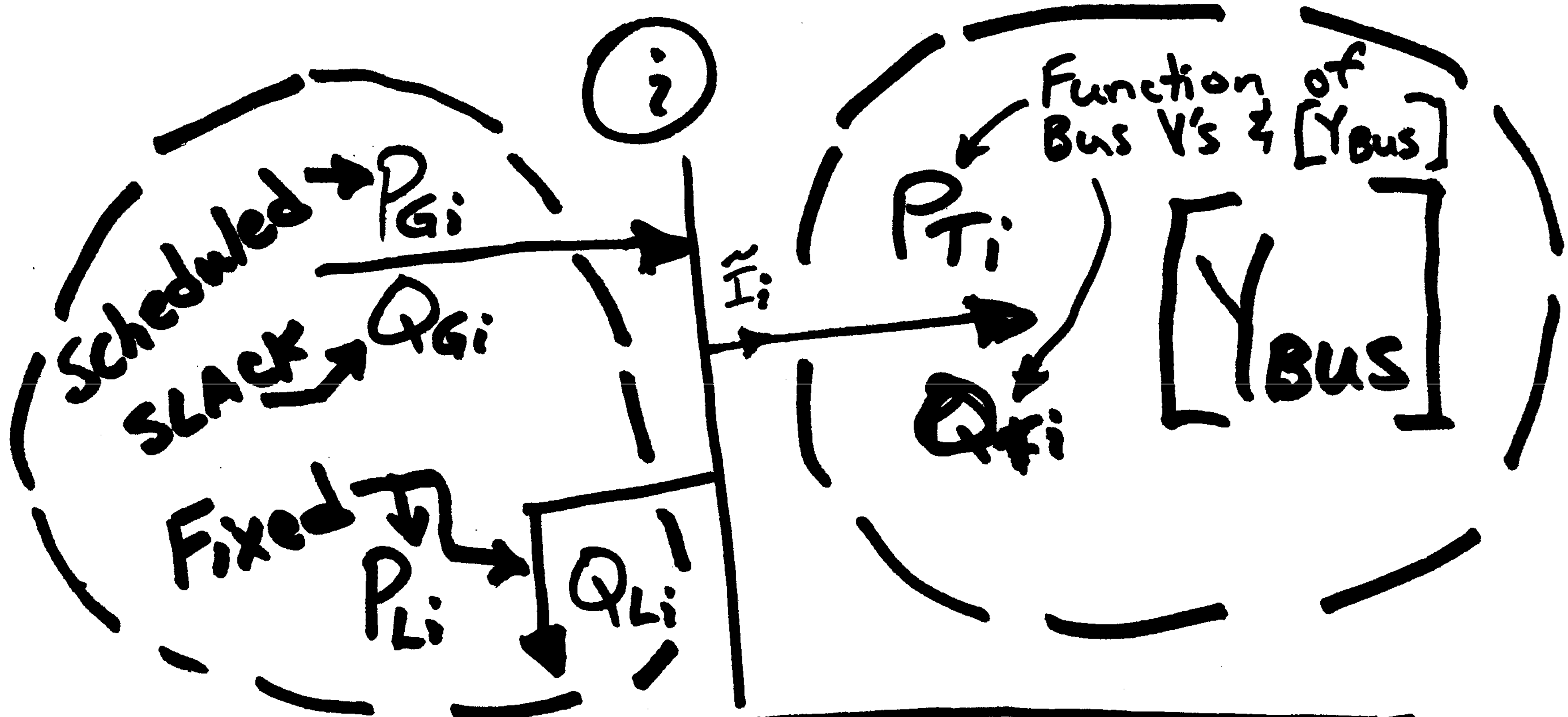
Load Flow Formulation

At each bus,



At each bus,



$\Sigma P_{OUT} = 0 \Rightarrow$ $\boxed{P_i = -P_{Gi} + P_{Li} + P_{Ti}}$ } Gen Buses, Load Buses

$\Sigma Q_{OUT} = 0 \Rightarrow$ $\boxed{Q_i = -Q_{Gi} + Q_{Li} + Q_{Ti}}$ – Only at Load Buses

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$$\begin{bmatrix} P_i \\ \hdashline Q_i \end{bmatrix} = \left[\begin{array}{c:c} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \hdashline \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{array}\right] \begin{bmatrix} \Delta\delta \\ \hdashline \Delta|V| \end{bmatrix}$$

No. Eqns

$2 \times N_{LOAD} + N_{GEN}$

From $[Y_{BUS}]$

$$[I_{inj}] = [Y_{BUS}][V]$$

$$\begin{bmatrix} \tilde{I}_1 \\ \\ \\ \\ \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & y_{13} & \cdots & y_{1N} \\ & & & & \\ & & & & \\ & & & & \end{bmatrix} \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \\ \vdots \\ V_N \end{bmatrix}$$

$$\therefore \boxed{\tilde{I}_i = \sum_{n=1}^{N} y_{in} \tilde{V}_n}$$

$$\boxed{\bar{S}_{Ti} = \tilde{V}_i \tilde{I}_i^*}$$

$$= \tilde{V}_i \left(\sum_{n=1}^{N} y_{in} \tilde{V}_n \right)^*$$

$$P_{Ti} = \sum_{n=1}^{N} |\tilde{V}_i||\tilde{V}_n||y_{in}| \cos(-\delta_n + \delta_i - \gamma_{in})$$

$$Q_{Ti} = \sum_{n=1}^{N} |\tilde{V}_i||\tilde{V}_n||y_{in}| \sin(\delta_i - \delta_n - \gamma_{in})$$

Newton Iteration

Nonlinear Systems of Equations

- If closed form then we can use symbolic solvers (Mathmatica)
- If not in closed form or if there are <u>many</u> variables, then an iterative method is better. (Numerical).

Newton Iteration:

Based on Taylor Expansion

If $f(x)=0$, then if a slightly different value of the dependent variable, x^0, is evaluated, then $f(x)$ can be approximated as

$$f(x) = f(x^0) + \frac{df(x^0)}{dx}(x-x^0) + \frac{1}{2}\frac{d^2f(x^0)}{dx^2}(x-x^0)^2 + \cdots$$

Depending on severity of the nonlinearity, the series can be truncated at some point and thus yield an approximation of $f(x)$.

Newton Method - Truncate after first term.

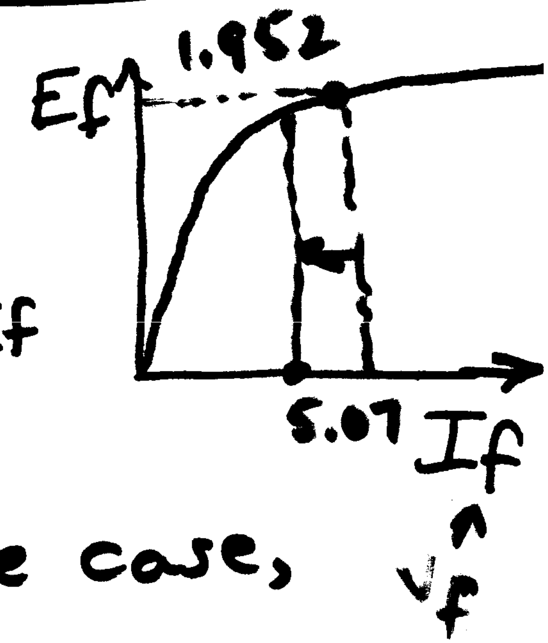
$$\boxed{f(x) \cong f(x^0) + \frac{df(x^0)}{dx}(x-x^0)}$$

Truncation Error = ?

$$\boxed{f(x) - f(x^0) - \frac{df(x^0)}{dx}(x - x^0)}$$

<u>Ex:</u>

$$I_f(E_f) = E_f + A e^{B E_f}$$



Find E_f given I_f.

$$I_f(E_f) = E_f + .0008\, e^{4.3 E_f}$$

If I_f has dropped 20% from base case, find E_f. Base case is defined as

$$E_f = 1.952 \text{ p.u.} \Longrightarrow I_f = 5.07 \text{ p.u.}$$

$\therefore$ find E_f for $I_f = 5.07(.8) = 4.06$ p.u.

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If we isolate first deriv. on right side,

$$f(x)=0 \Rightarrow \cancel{f(x)} - f(x^0) \cong \underbrace{\frac{df(x^0)}{dx}}_{f'(x^0)} \underbrace{(x-x^0)}_{\Delta x}$$

$$-f(x^0) \cong f'(x^0)\,\Delta x$$

$$\cong f'(x^0)(x-x^0)$$

ITERATE

$$\Delta x' \cong \frac{-f(x^0)}{f'(x^0)}$$

stop when $\Delta x \le \epsilon$

$$x' \cong \frac{-f(x^0)}{f'(x^0)} + x^0$$

$$E_f^1 = -\frac{E_f^0 + .0008\, e^{4.3 E_f^0} - I_f}{1 + 4.3 \times .0008\, e^{4.3 E_f^0}} + E_f^0$$

1st Iteration:

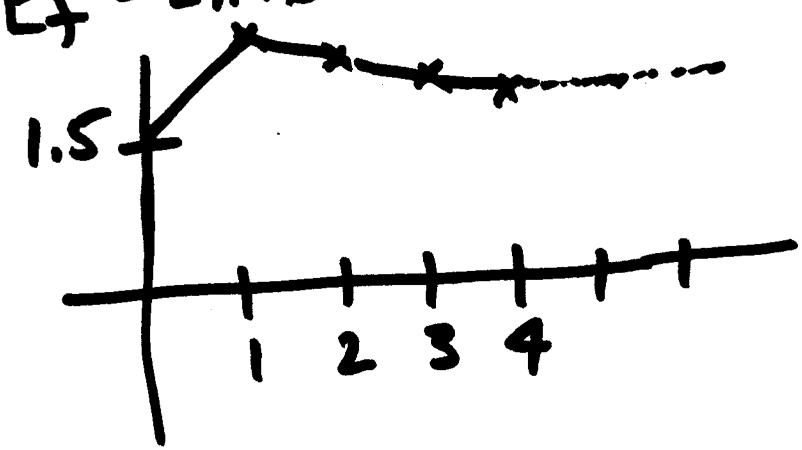
Guess $E_f = 1.5$

$$E_f^1 = -\frac{1.5 + .0008\, e^{4.3 \cdot 1.5} - 4.06}{1 + 4.3 \times .0008\, e^{4.3 \cdot 1.5}} + 1.5$$

$$= 2.146$$

2nd Iter.

$E_f^1 = 2.146$



Repeat, $\Rightarrow$ $E_f^2 = 1.973$

$E_f^3 = 1.872$

$E_f^4 = 1.845$

$E_f^5 = 1.843$

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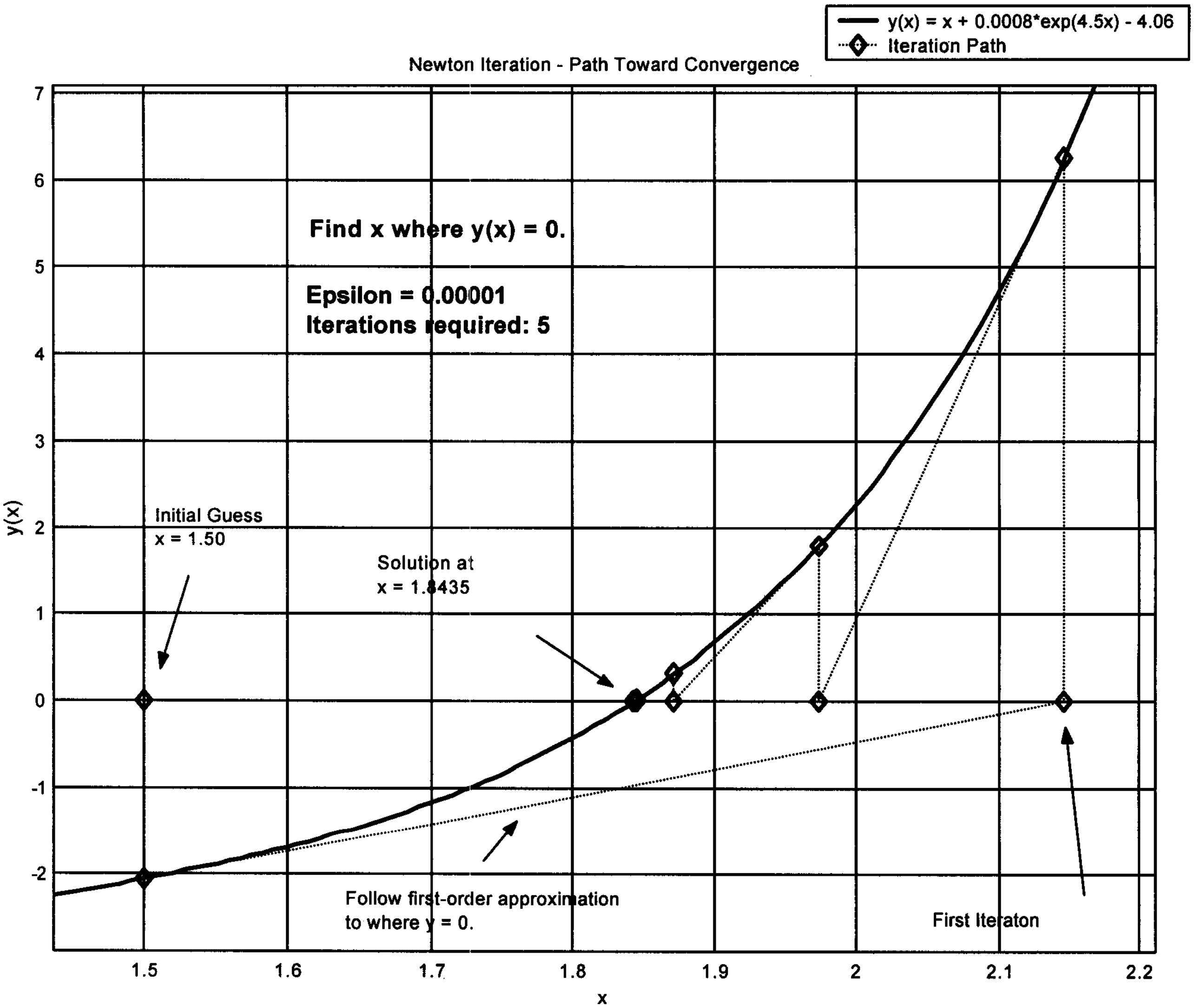
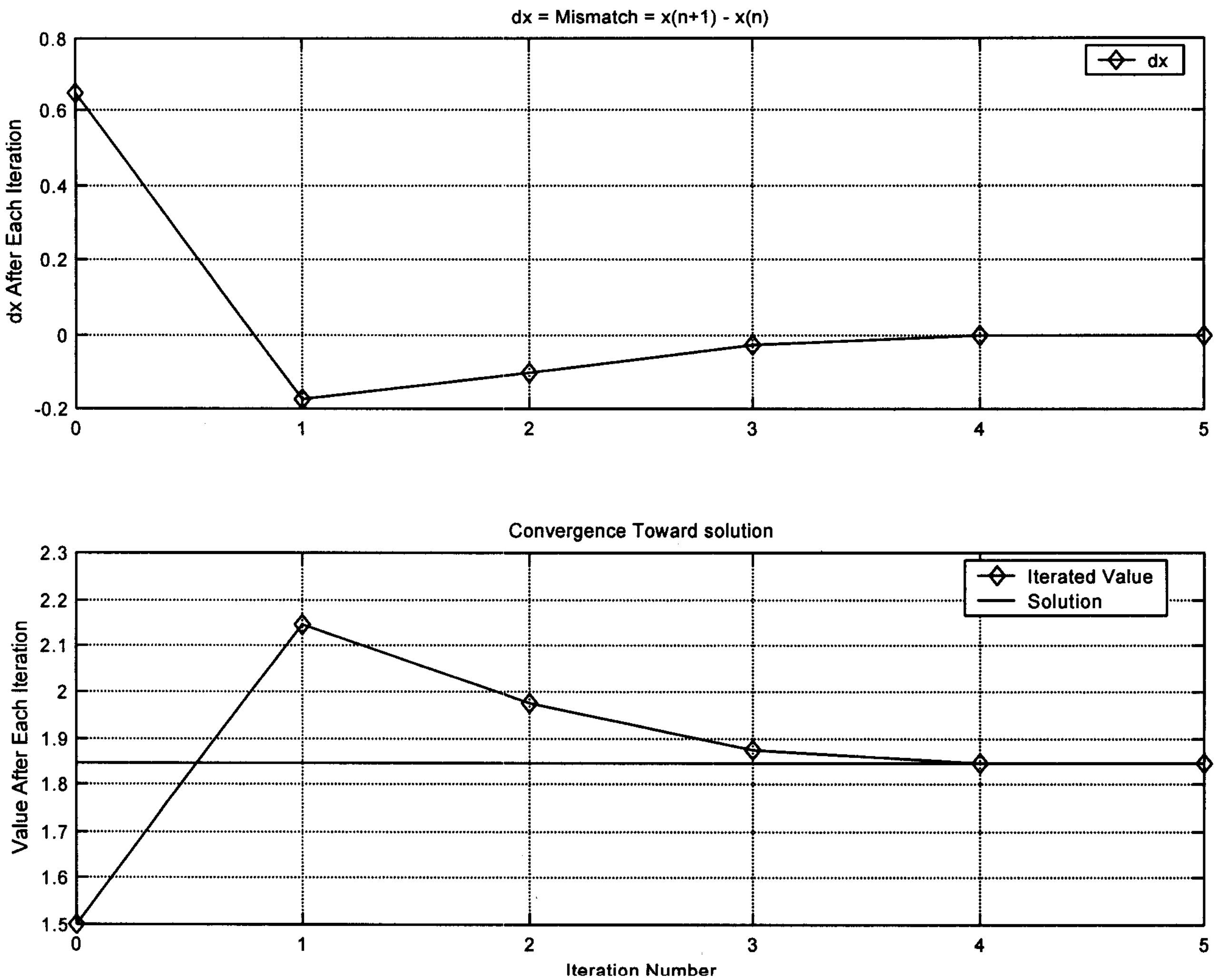

y(x) = x + 0.0008*exp(4.5x) - 4.06
Iteration Path
Newton Iteration - Path Toward Convergence
Find x where y(x) = 0.
Epsilon = 0.00001
Iterations required: 5
Initial Guess
x = 1.50
Solution at
x = 1.8435
Follow first-order approximation
to where y = 0.
First Iteraton
y(x)
x
7
6
5
4
3
2
1
0
-1
-2
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2



dx = Mismatch = x(n+1) - x(n)
dx
dx After Each Iteration
0.8
0.6
0.4
0.2
0
-0.2
0
1
2
3
4
5
Convergence Toward solution
Iterated Value
Solution
Value After Each Iteration
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
Iteration Number

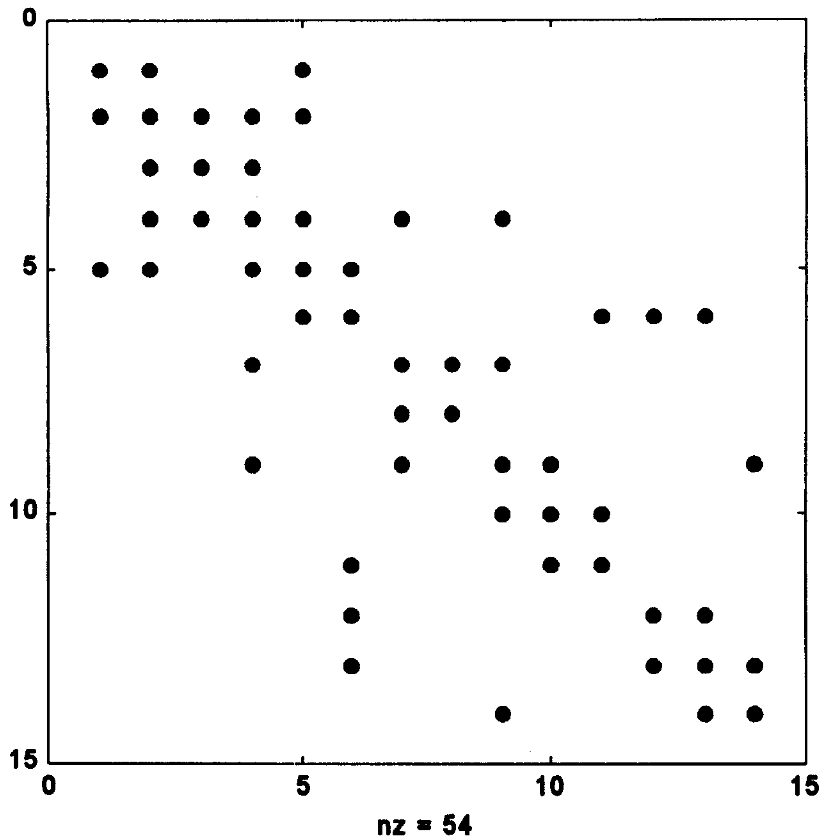
[Ybus] for 14-bus IEEE system: **IEEE14.cdf**

Produced by: lf.m
Programmed by: Bruce Mork
Date: 01 Feb 2006

(1,1)	6.0250 -19.4471i
(2,1)	-4.9991 +15.2631i
(5,1)	-1.0259 + 4.2350i
(1,2)	-4.9991 +15.2631i
(2,2)	9.5213 -30.2721i
(3,2)	-1.1350 + 4.7819i
(4,2)	-1.6860 + 5.1158i
(5,2)	-1.7011 + 5.1939i
(2,3)	-1.1350 + 4.7819i
(3,3)	3.1210 - 9.8224i
(4,3)	-1.9860 + 5.0688i
(2,4)	-1.6860 + 5.1158i
(3,4)	-1.9860 + 5.0688i
(4,4)	10.5130 -38.6542i
(5,4)	-6.8410 +21.5786i
(7,4)	0 + 4.8895i
(9,4)	0 + 1.8555i
(1,5)	-1.0259 + 4.2350i
(2,5)	-1.7011 + 5.1939i
(4,5)	-6.8410 +21.5786i
(5,5)	9.5680 -35.5336i
(6,5)	0 + 4.2574i
(5,6)	0 + 4.2574i
(6,6)	6.5799 -17.3407i
(11,6)	-1.9550 + 4.0941i
(12,6)	-1.5260 + 3.1760i
(13,6)	-3.0989 + 6.1028i
(4,7)	0 + 4.8895i
(7,7)	0 -19.5490i
(8,7)	0 + 5.6770i
(9,7)	0 + 9.0901i
(7,8)	0 + 5.6770i
(8,8)	0 - 5.6770i
(4,9)	0 + 1.8555i
(7,9)	0 + 9.0901i
(9,9)	5.3261 -24.0925i
(10,9)	-3.9020 +10.3654i
(14,9)	-1.4240 + 3.0291i
(9,10)	-3.9020 +10.3654i
(10,10)	5.7829 -14.7683i
(11,10)	-1.8809 + 4.4029i
(6,11)	-1.9550 + 4.0941i
(10,11)	-1.8809 + 4.4029i
(11,11)	3.8359 - 8.4970i
(6,12)	-1.5260 + 3.1760i
(12,12)	4.0150 - 5.4279i
(13,12)	-2.4890 + 2.2520i
(6,13)	-3.0989 + 6.1028i
(12,13)	-2.4890 + 2.2520i
(13,13)	6.7249 -10.6697i
(14,13)	-1.1370 + 2.3150i
(9,14)	-1.4240 + 3.0291i
(13,14)	-1.1370 + 2.3150i
(14,14)	2.5610 - 5.3440i

Network topology, spy(Ybus):

2



Sparsity = 54/14x14 = 27.55%

2-Variable NR

$$[A][x] = [B]$$

① $2x + y = 4$

② $2x + y^2 = 6$

②-① $y^2 - y = 2 \Rightarrow \begin{matrix} x = 1 \\ y = 2 \end{matrix}$

define
$$f(x,y) = 2x + y - 4 = 0$$
$$g(x,y) = 2x + y^2 - 6 = 0$$

Taylor Expansion

iteration index

$$0 = f(x,y) = f(x^m, y^m) + \frac{\partial f(x^m, y^m)}{\partial x}(x - x^m) + \frac{\partial f(x^m, y^m)}{\partial y}(y-$$

$$0 = g(x,y) = g(x^m, y^m) + \frac{\partial g(x^m, y^m)}{\partial x}(x - x^m) + \frac{\partial g(x^m, y^m)}{\partial y}(y - y^m)$$

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Rearranging terms:

$$\frac{\partial f^m}{\partial x}\Delta x + \frac{\partial f^m}{\partial y}\Delta y = -f^m \qquad \underbrace{f(x,y)}_{=0} - f(x^m, y^m)$$

$$\frac{\partial g^m}{\partial x}\Delta x + \frac{\partial g^m}{\partial y}\Delta y = -g^m$$

In matrix form

$$\underbrace{\begin{bmatrix} \frac{\partial f^m}{\partial x} & \frac{\partial f^m}{\partial y} \\ \frac{\partial g^m}{\partial x} & \frac{\partial g^m}{\partial y} \end{bmatrix}}_{\text{JACOBIAN}} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = - \begin{bmatrix} f^m \\ g^m \end{bmatrix}$$

$\Delta x = \underline{x - x^m}$

$\Delta y = y - y^m$

$f(x^m, y^m)$

$g(x^m, y^m)$

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = -\begin{bmatrix} J^m \end{bmatrix}^{-1} \begin{bmatrix} f^m \\ g^m \end{bmatrix} \cong \begin{bmatrix} x - x^m \\ y - y^m \end{bmatrix}$$

Estimate of (x, y) for next iteration:

$$\underline{\underline{\Delta x}} \cong x - \underline{\underline{x^m}} \Rightarrow x^{m+1} = x^m + \Delta x$$

$$\Delta y \cong y - y^m \Rightarrow y^{m+1} = y^m + \Delta y$$

use (x^{m+1}, y^{m+1}) for next iteration,

Continue until "converged".

Common tests: 1 → Δx & Δy both $< \epsilon$

2 $\| \Delta x, \Delta y \| < \epsilon$

Norm: $\sqrt{\Delta x_1^2 + \Delta x_2^2 + \cdots \Delta x_N^2}$ (for N-variable system)

for this case,

Norm is $\| \Delta x, \Delta y \| = \sqrt{\Delta x^2 + \Delta y^2}$

Back to example:

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = -\begin{bmatrix} J^m \end{bmatrix}^{-1} \begin{bmatrix} f^m \\ g^m \end{bmatrix}$$

Start: $m = 0$ (0th iteration is initial guess)

$$[J] = \begin{bmatrix} 2 & 1 \\ 2 & 2y \end{bmatrix}$$

guess: $\begin{bmatrix} 0 \\ 3 \end{bmatrix} = \begin{bmatrix} x^0 \\ y^0 \end{bmatrix}$

$$\left[J^{0}\right] = \begin{bmatrix} 2 & 1 \\ 2 & 6 \end{bmatrix} \Rightarrow \left[J^{0}\right]^{-1} = \begin{bmatrix} -.6 & .1 \\ .2 & -.2 \end{bmatrix}$$

$$\begin{bmatrix} f^{0} \\ g^{0} \end{bmatrix} = \begin{bmatrix} f(0) \\ g(3) \end{bmatrix} = \begin{bmatrix} -1 \\ 3 \end{bmatrix}$$

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} -.6 & .1 \\ .2 & -.2 \end{bmatrix} \begin{bmatrix} -1 \\ 3 \end{bmatrix} = \begin{bmatrix} .9 \\ -.8 \end{bmatrix} = \begin{bmatrix} x - x^{0} \\ y - y^{0} \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} x^{0} \\ y^{0} \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} +0.9 \\ +2.2 \end{bmatrix}$$

- Next, repeat iteration using $\begin{bmatrix} x' \\ y' \end{bmatrix}$
- Test $\|\Delta x, \Delta y\| \leq \epsilon$ at each iteration.

After 3 iterations, $\underline{\epsilon < 0.001}$

$x = 1.000$
$y = 2.000$

typical for p.u. load flow.

Notes: – Convergence rate not dependent on no. of variables.

– Important to make intelligent guess of initial values.

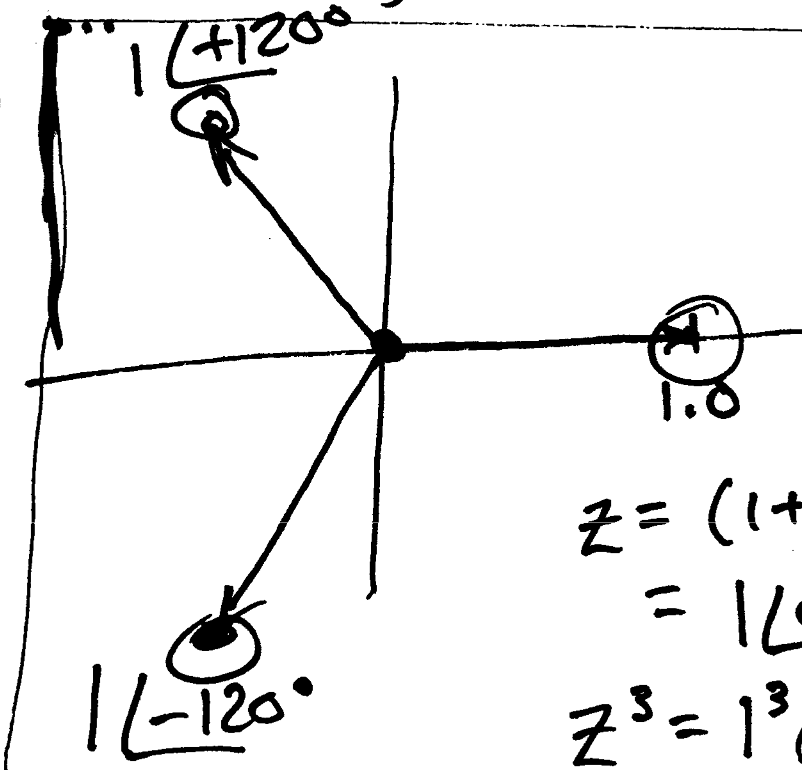
e.g. $\left\{ \begin{array}{l} |\tilde{V}_{Bus}| = 1.0 \text{ p.u.} \\ \delta = 0° \quad (\delta = \angle V_{Bus}) \end{array} \right.$

Flat start

– NR can fail to converge. Important to have correct system data.

– Possible to converge to wrong solution.

Ex: $z^3 = 1$



$$z = (1 + j0) = 1\angle 0°$$

$$z^3 = 1^3\angle 3 \times 0° = 1\angle 0°$$

Which of the 3 roots will solution converge to for an arbitrary initial value? Your guess is as good as mine. Must let NR iteration converge to find out.

Note: We can generate some beautiful fractal patterns in this way. Let each initial condition on the rectangular area be assigned a color depending on which root it converges to. (Each pixel = initial condition).

$$\bar{S}_{Ti} = P_{Ti} + j\,Q_{Ti}$$

$$P = |\tilde{V}_i| \sum_{n=1}^{N} |\tilde{V}_n||y_{in}| \cos(\delta_i - \delta_n - \theta_{in})$$

$$Q = |\tilde{V}_i| \sum_{n=1}^{N} |\tilde{V}_n||y_{in}| \sin(\delta_i - \delta_n - \theta_{in})$$

Assume:

$$\tilde{V}_i = |\tilde{V}_i| \angle \delta_i$$

$$\tilde{V}_n = |\tilde{V}_n| \angle \delta_n$$

$$y_{in} = |y_{in}| \angle \theta_{in}$$

For referenced current, P, Q, flow directions,

See Lectur 8 p.4.

EE 5200

Newton-Raphson Power Flow

- **Active and Reactive Power Flowing INTO bus k:** $\Rightarrow J_k = \sum_{n=1}^{N} Y_{kn} V_n$

$S = V I^*$

$$\begin{cases} P_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| \cos(\delta_k - \delta_n - \theta_{kn}) \\ Q_k = |V_k| \sum_{n=1}^{N} |Y_{kn}||V_n| \sin(\delta_k - \delta_n - \theta_{kn}) \end{cases} \qquad \text{k=1,2,...,N}$$

$V_k = |V_k| e^{j\delta_k}$

$Y_{kn} = |Y_{kn}| e^{j\theta_{kn}}$

$S_k = |V_k| e^{j\delta_k} \left[\sum_{n=1}^{N} |Y_{kn}| e^{j\theta_{kn}} |V_n e^{j\delta_n}| \right]^*$

- Let:

$$x = \begin{bmatrix} \delta \\ V \end{bmatrix} = \begin{bmatrix} \delta_2 \\ \cdot \\ \cdot \\ \delta_N \\ V_2 \\ \cdot \\ \cdot \\ V_N \end{bmatrix} \qquad y = \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P_2 \\ \cdot \\ \cdot \\ P_N \\ Q_2 \\ \cdot \\ \cdot \\ Q_N \end{bmatrix} \qquad f(x) = \begin{bmatrix} P(x) \\ Q(x) \end{bmatrix} = \begin{bmatrix} P_2(x) \\ \cdot \\ \cdot \\ P_N(x) \\ Q_2(x) \\ \cdot \\ \cdot \\ Q_N(x) \end{bmatrix}$$

where V, P, and Q terms are in per unit and δ terms are in radians.

$$J = \begin{array}{c} \begin{array}{cc} \quad 1 \quad & \quad 2 \quad \end{array} \\ \left[\begin{array}{cccc|cccc} \frac{\partial P_2}{\partial \delta_2} & \cdot & \cdot & \frac{\partial P_2}{\partial \delta_N} & \frac{\partial P_2}{\partial V_2} & \cdot & \cdot & \frac{\partial P_2}{\partial V_N} \\ \cdot & & & \cdot & \cdot & & & \cdot \\ \cdot & & & \cdot & \cdot & & & \cdot \\ \frac{\partial P_N}{\partial \delta_2} & \cdot & \cdot & \frac{\partial P_N}{\partial \delta_N} & \frac{\partial P_N}{\partial V_2} & \cdot & \cdot & \frac{\partial P_N}{\partial V_N} \\ \hline \frac{\partial Q_2}{\partial \delta_2} & \cdot & \cdot & \frac{\partial Q_2}{\partial \delta_N} & \frac{\partial Q_2}{\partial V_2} & \cdot & \cdot & \frac{\partial Q_2}{\partial V_N} \\ \cdot & & & \cdot & \cdot & & & \cdot \\ \cdot & & & \cdot & \cdot & & & \cdot \\ \frac{\partial Q_N}{\partial \delta_2} & \cdot & \cdot & \frac{\partial Q_N}{\partial \delta_N} & \frac{\partial Q_N}{\partial V_2} & \cdot & \cdot & \frac{\partial Q_N}{\partial V_N} \end{array}\right] \\ \begin{array}{cc} \quad 3 \quad & \quad 4 \quad \end{array} \end{array}$$

- **Jacobian Entries:**

For n≠k:

$$J1_{kn} = \frac{\partial P_k}{\partial \delta_n} = |V_k||Y_{kn}||V_n|\sin(\delta_k - \delta_n - \theta_{kn})$$

$$J2_{kn} = \frac{\partial P_k}{\partial V_n} = |V_k||Y_{kn}|\cos(\delta_k - \delta_n - \theta_{kn})$$

$$J3_{kn} = \frac{\partial Q_k}{\partial \delta_n} = -|V_k||Y_{kn}||V_n|\cos(\delta_k - \delta_n - \theta_{kn})$$

$$J4_{kn} = \frac{\partial Q_k}{\partial V_n} = |V_k||Y_{kn}|\sin(\delta_k - \delta_n - \theta_{kn})$$

For n=k:

$$J1_{kk} = \frac{\partial P_k}{\partial \delta_k} = -|V_k|\sum_{\substack{n=1\\n\neq k}}^{N}|Y_{kn}||V_n|\sin(\delta_k - \delta_n - \theta_{kn})$$

$$J2_{kk} = \frac{\partial P_k}{\partial V_k} = |V_k||Y_{kk}|\cos\theta_{kk} + \sum_{n=1}^{N}|Y_{kn}||V_n|\cos(\delta_k - \delta_n - \theta_{kn})$$

$$J3_{kk} = \frac{\partial Q_k}{\partial \delta_k} = |V_k|\sum_{\substack{n=1\\n\neq k}}^{N}|Y_{kn}||V_n|\sin(\delta_k - \delta_n - \theta_{kn})$$

cos

*

$$J4_{kk} = \frac{\partial Q_k}{\partial V_k} = -|V_k||Y_{kk}|\sin\theta_{kk} + \sum_{n=1}^{N}|Y_{kn}||V_n|\sin(\delta_k - \delta_n - \theta_{kn})$$

PV Buses:

Omit V_K term from x vector.

Omit the Q_K term from y vector.

In [J] omit columns corresp to $\frac{\partial}{\partial V_K}$

and omit row corresponding to partials of

row corresponding V_K

- Use Newton Raphson to solve:

Previous

New/current

1) Use P & Q equations to calculate $\Delta y(i)$:

$$\Delta y(i) = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix} = \begin{bmatrix} P - P[x(i)] \\ Q - Q[x(i)] \end{bmatrix}$$

where:

$$x(i) = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix}$$

If Convergence criteria is met, quit.

2) Calculate the Jacobian.

iteration index = i

3) Use LU Factorization to solve:

$$\left[\begin{array}{c|c} J1(i) & J2(i) \\ \hline J3(i) & J4(i) \end{array}\right] \begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix} = \begin{bmatrix} \Delta P(i) \\ \Delta Q(i) \end{bmatrix}$$

4) Compute:

$$x(i+1) = \begin{bmatrix} \delta(i+1) \\ V(i+1) \end{bmatrix} = \begin{bmatrix} \delta(i) \\ V(i) \end{bmatrix} + \begin{bmatrix} \Delta\delta(i) \\ \Delta V(i) \end{bmatrix}$$

5) Goto 1.

Calc Q at each voltage controlled bus.

- Compare to min/max limits
- If limit exceeded, set Q to limit & change to PQ bus.

~~Check Q against lim~~

- Check Q on later iterations to see if PQ can be changed back to PV bus.