EE 521/ECE 582 – Analysis of Power systems

Class #9 – September 22, 2022

Dr. Noel N. Schulz
Edmund O. Schweitzer III Chair in
Power Apparatus and Systems
Chief Scientist Joint Appointment, PNNL
Co-Director, PNNL/WSU Advanced Grid Institute (AGI)
Washington State University Pullman
Noel.Schulz@wsu.edu EME 35
509-335-0980 (o) and 509-336-5522 (c)

Student Hours

- Office Hours Friday & Next Week
  - **Fridays 1:30-2:30 pm** Zoom or EME 35 Pullman
  - **Tuesdays 4:30-5:30 pm (after class)** – Zoom or EME 35 Pullman
  - **Wednesdays 4-5 pm** Zoom or EME 35 Pullman
- Join from PC, Mac, Linux, iOS, or Android: https://wsu.zoom.us/j/8237216735 (Links to an external site.)
- Meeting ID: 823 721 6735

Or by request via email noel.Schulz@wsu.edu or phone 509-336-5522

Assignment Distribution (100% total):

Programming Projects: (80%)

1. Power Flow Project (20%)
   A. Y_{bus}, Jacobian matrices – Newton Raphson
   B. LU Factorization, Backward-Forward substitution for NR
   C. Fast Decoupled
   D. Q-limits, transformer taps
2. Sparse Power Flow Project (20%)
3. Continuation Power Flow Project (13%)
4. State Estimation Project (13%)
5. Optimal Power Flow Project (14%)

Other Assignments:

Article Set Discussions	10%
Paper/Presentation	10%

Over the Semester – Three Discussion Paper Sets

Name	Discussion #1	Discussion #2	Discussion #3
Liadi Akande	Q	S	
Noah Allison		Q	S
Ninad Gaikwad	S		Q
Jacob Hastings	Q	S	
Aryan Jha	S		Q
Annika Lawrence	S		Q
Sajjad Uddin Mahmud		Q	S
Ben McCornack	S		Q
Asif Iftekhar Omi	Q	S	
Sumanjali Pannala	Q	S	
Md. Samiul Islam Sagar		Q	S
Saeed Salimi Amiri		Q	S
Mauricio Silveira	S		Q
Leonardo Stringini		Q	S
Md Mehedi Hasan Tanim	Q	S	
Ke Wang		Q	S
Hassan Yazdani	Q	S	
Augusto Zanin Bertoletti	S		Q

S = Summary and Q = Questions

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 37, NO. 2, MARCH 2022 1363

A Basic AC Power Flow Based on the Bus Admittance Matrix Incorporating Loads and Generators Including Slack Bus

Roberto Benato, *Senior Member, IEEE*

1

IEEE Transactions on Power Systems, Vol. 3, No. 2, May 1988

A MODIFICATION TO THE FAST DECOUPLED POWER FLOW FOR NETWORKS WITH HIGH R/X RATIOS

Dragoslav Rajičić
Elektrotehnički Fakultet
Skopje, Yugoslavia

Anjan Bose
Arizona State University
Tempe, Arizona

2

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 37, NO. 3, MAY 2022 1695

Fast Newton-Raphson Power Flow Analysis Based on Sparse Techniques and Parallel Processing

Afshin Ahmadi, *Member, IEEE*, Melissa C. Smith, *Senior Member, IEEE*, Edward R. Collins, *Senior Member, IEEE*, Vahid Dargahi, *Member, IEEE*, and Shuangshuang Jin, *Senior Member, IEEE*

80s

800 JOURNAL OF MODERN POWER SYSTEMS AND CLEAN ENERGY, VOL. 10, NO. 3, May 2022

Data-driven Power Flow Method Based on Exact Linear Regression Equations

Yanbo Chen, Chao Wu, and Junjian Qi

IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 2, February 1985

SPARSE VECTOR METHODS

W.F. Tinney
Fellow, IEEE

V. Brandwajn
Member, IEEE

S.M. Chan
Member, IEEE

Consultant
9101 S.W. 8th Avenue
Portland, OR 97219

Systems Control, Inc.
1801 Page Mill Road
Palo Alto, CA 94304

5012 IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 34, NO. 6, NOVEMBER 2019

A Robust and Efficient Two-Stage Algorithm for Power Flow Calculation of Large-Scale Systems

Kunjie Tang, *Student Member, IEEE*, Shufeng Dong, Jie Shen, Chengzhi Zhu, and Yonghua Song, *Fellow, IEEE*

Paper Discussion Set #1

EE 521/ECE 582 Discussion Paper Set #1
Assignment with Deadlines – 9/30, 10/4 and 10/11, 11:59 pm

1. Read at least three of the papers listed in Assignment – Discussion Assignment Paper Set #1. Two from papers #1-4 and 1 from papers #5-6.
2. Students listed below provide a summary of their article on discussion board by 9/30.
3. Students listed below provide a list of at least three questions for class members to answer.
4. All students should provide answers to the questions or add to the discussions for at least three papers.

Assignment #1	Column A: Summarize (150 to 200 word summary of article)	Column B: List of three questions for class to answer?	Column C: Answer the Questions or Add to Discussions (Each response should be between 25 and 100 words)
See Canvas for Papers	Due: 9/30	Due: 10/4	Due: 10/11
Paper #1	Ninad Gaikwad	Liadi Akande	All students in class should respond to three of these papers.
Paper #2	Aryan Jha	Jacob Hastings	All students in class should respond to three of these papers.
Paper #3	Annika Lawrence	Asif Iftekhar Omi	All students in class should respond to three of these papers.
Paper #4	Ben McCornack	Sumanjali Pannala	All students in class should respond to three of these papers.
Paper #5	Mauricio Silveira	Md Mehedi Hasan Tanim	All students in class should respond to three of these papers.
Paper #6	Augusto Zanin Bertoletti	Hassan Yazdani	All students in class should respond to three of these papers.

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Final Paper and Presentation

- Pick one of the topics related to the class and find at least five IEEE journal papers (four of the papers must be in the last 15 years) that discuss different research or work on that topic. One paper can be from the discussion sets.
- Write a paper that summarizes these journal papers and discusses the how they relate to topics covered in class.
- During the last two weeks of class (after Thanksgiving Break), present a 10-12 minute presentation on your topic summarizing the papers and discussing how it relates to the class. There will be peer review of presentations.

Steps	Activity	Due Date:
Pick a Topic	Upload Topic on Canvas	Oct 14
Presentations	10-12 min presentation with Q&A	Nov 29, Dec 1,6 & 8
Paper	4-5 pages – Summary & how topic relates to class	Dec 9

Ref

Paper

Topic ← why?

5 paragraphs

Compare + Contrast ←

How does it relate

Refs → 5 Other Refs

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   D. Q-limits, transformer taps
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4. State Estimation Project (13%)
5. Optimal Power Flow Project (14%)

Finishing Each Assignment:

1. Demonstration with Dr. Schulz
   a. Explaining Code
   b. Results with Changed Input
2. Executive Summary and Code
   a. One-to-Two page summary including iterations or other key metrics
   b. Appendix with final results
   c. Submission of code

Final Deadlines:

- Dec 13 for meeting with Dr. Schulz
- Dec 15 for final reports

Power Flow Project (20%)

Assignment

A. Y_{bus}, Jacobian matrices – Newton Raphson
B. LU Factorization, Backward-Forward substitution for NR
C. Fast Decoupled
D. Q-limits, transformer taps

Results:

- Methods
    - Y_{bus}
    - Jacobian
    - LU Factorization
    - Backward-Forward substitution
- Full Newton-Raphson
    - Without Taps
    - With Taps
    - With Q limits
- Fast Decoupled
    - Without Taps
    - With Taps

Finishing Each Assignment:

1. Demonstration with Dr. Schulz
    a. Explaining Code
    b. Results with Changed Input
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    a. One-to-Two page summary including iterations or other key metrics
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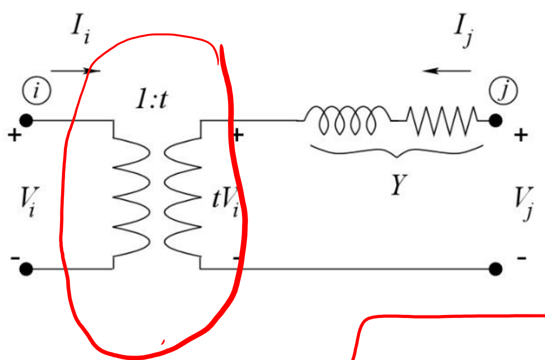
Project #1

- Remaining ones – Friday
- Y-bus Numbers for without taps and with taps are posted in announcements
- First Iteration of Jacobian to be posted Friday for both
- Need to program Ybus, Jacobian, LU factorization and backward-forward yourself (important for Sparsity aspects)
- Questions

Regulating Transformers in Power Flow



$$I_j = \left(V_j - tV_i\right)Y$$

$$I_i = -t^* I_j$$

Put in admittance matrix form:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} |t|^2 Y & -t^* Y \\ -tY & Y \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix}$$

$Y(i,j)$

add to $Y(i,i)$

$Y(j,j)$ no change

$Y(j,i)$

$Y_{\text{No taps}}$

Y_{taps}

If the voltage at bus j is regulated, the voltage magnitude $V_j = \hat{V}$ becomes a known value and the tap setting t is now the unknown.

1. Set $t = t_0$
2. Run a power flow to calculate V_j
3. Is $V_j > \hat{V}$? If yes, then $t = t + \Delta t$ and go to step 2.
4. Is $V_j < \hat{V}$? If yes, then $t = t + \Delta t$, and go to step 2.
5. Done

Another approach is to let directly solve for t from the Newton-Raphson. All partial derivatives with respect to V_j are replaced with derivatives with respect to t

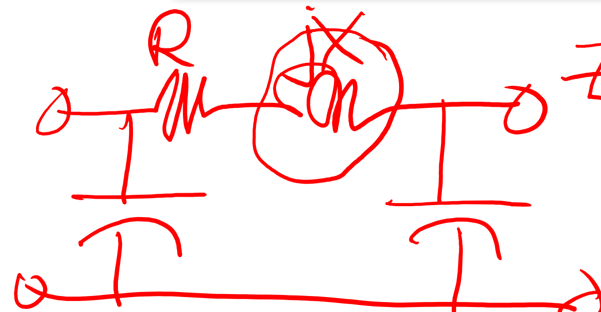
Pros and Cons for each approach?

$|Z| = \sqrt{R^2 + X^2} \approx X$

$Z = R + jX$

$X >> R$

$|Z| \to X$



$Z = jX = X\angle 90^\circ$

$Y\angle 90^\circ$

Decoupled Power Flow

Recall that the Jacobian does not need to be exact for the NR to still converge rapidly.

Consider the power flow Jacobian: $\begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \cancel{\frac{\partial \Delta P}{\partial V}} \\ \cancel{\frac{\partial \Delta Q}{\partial \theta}} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix}$

$\begin{bmatrix} J_{11} & 0 \\ 0 & J_{22} \end{bmatrix}$

The generic form of $\frac{\partial \Delta P_i}{\partial V_j}$ is $\frac{\partial \Delta P_i}{\partial V_j} = V_i Y_{ij} \boxed{\cos(\cancel{\theta_i} - \cancel{\theta_j} - \varphi_{ij})}$

small 90°

$\approx 0 \quad 0$

The generic form of $\frac{\partial \Delta Q_i}{\partial \theta_j}$ is $\frac{\partial \Delta Q_i}{\partial \theta_j} = V_i V_j Y_{ij} \boxed{\cos(\theta_i - \theta_j - \varphi_{ij})}$

≈ 0

If the transmission lines are primarily reactive, then φ_{ij} is ≈ 90°. Furthermore, adjacent bus angles are usually within a few degrees,

$$\Rightarrow \cos(\theta_i - \theta_j - \varphi_{ij}) \approx 0$$

Therefore $\frac{\partial \Delta Q_i}{\partial \theta_j} \approx 0$ and $\frac{\partial \Delta P_i}{\partial V_j} \approx 0$

28

28

$$\begin{bmatrix} \boxed{14\times14}^{LU} & 0 \\ 0 & \boxed{14\times14}_{LU} \end{bmatrix}$$

Therefore

$$\theta^{k+1} = \theta^{k} - \left[\frac{\partial \Delta P}{\partial \theta}\right]^{-1} \Delta P$$

$$V^{k+1} = V^{k} - \left[\frac{\partial \Delta Q}{\partial V}\right]^{-1} \Delta Q$$

Accuracy

Time

Advantages:

- Matrices are smaller, therefore decreasing LU factorization effort
- V and θ iterations are performed separately and may converge independently (i.e. different number of iterations)

Disadvantages:

- Convergence may be slow if system is not well-conditioned (i.e. zero assumption is not valid)

Many commercial programs have the option to switch between full and decoupled NR iterations.

Revisit previous example:

$$J=\begin{bmatrix} \frac{\partial \Delta P_2}{\partial \theta_2} & \frac{\partial \Delta P_2}{\partial \theta_3} & \frac{\partial \Delta P_2}{\partial V_3} \\ \frac{\partial \Delta P_3}{\partial \theta_2} & \frac{\partial \Delta P_3}{\partial \theta_3} & \frac{\partial \Delta P_3}{\partial V_3} \\ \frac{\partial \Delta Q_3}{\partial \theta_2} & \frac{\partial \Delta Q_3}{\partial \theta_3} & \frac{\partial \Delta Q_3}{\partial V_3} \end{bmatrix} = \begin{bmatrix} -13.2859 & 9.9010 & 0.9901 \\ 9.9010 & -20.000 & -1.9604 \\ -0.9901 & 2.0000 & -19.4040 \end{bmatrix}$$

Is smaller than this

This

This

Is smaller than this

ΔJ_{21}

Separate solutions:

$$\begin{bmatrix} -13.2859 & 9.9010 \\ 9.9010 & -20.000 \end{bmatrix}\begin{bmatrix} \theta_2^1 - 0 \\ \theta_3^1 - 0 \end{bmatrix} = \begin{bmatrix} 0.5044 \\ -1.1802 \end{bmatrix}$$

$$\begin{bmatrix} -19.4040 \end{bmatrix}\begin{bmatrix} V_3^1 - 1 \end{bmatrix} = \begin{bmatrix} -0.2020 \end{bmatrix}$$

$$\begin{bmatrix} \theta_2^1 \\ \theta_3^1 \\ V_3^1 \end{bmatrix} = \begin{bmatrix} -0.0095 \\ -0.0637 \\ 0.9896 \end{bmatrix}$$

Very close to full NR!
Continue until convergence…

Fast Decoupled Power Flow

In the previous decoupled power flow, the Jacobian was updated at every iteration. If the Jacobian is held constant at every iteration, the method is known as the "Very Dishonest Newton's Method." This method still requires at least one Jacobian evaluation.

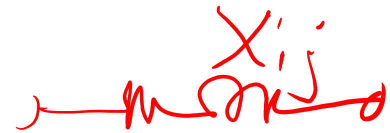
However, another approach in which the Jacobian is a constant matrix is called the fast decoupled power flow. In this case, the Jacobian is approximated based on the line parameters.

$$\left[\frac{\Delta P^k}{V}\right] = [B'][\Delta\theta^{k+1}]$$

$$\left[\frac{\Delta Q^k}{V}\right] = [B''][\Delta V^{k+1}]$$

Variations include the XB, BX, XX, and BB methods.

The XB and BX are the most common.



XB version:

$$B'_{ij} = \frac{1}{X_{ij}}$$
$$B'_{ii} = \boxed{-\sum_{j \neq i} B'_{ij}}$$

Approximation to $\left[\frac{\partial \Delta P}{\partial \theta}\right]$

$$B''_{ij} = B_{ij}$$
$$B''_{ii} = 2B_i - \sum_{j \neq i} B''_{ij}$$

Approximation to $\left[\frac{\partial \Delta Q}{\partial V}\right]$

where $B_{ij} = \frac{-X_{ij}}{R_{ij}^2 + X_{ij}^2}$ and B_i is the shunt susceptance at bus i

$$B_i = \frac{B_R}{2}$$

Revisit previous example again:

$$Y = \begin{bmatrix} 13.1505\angle -84.7148^\circ & 3.3260\angle 93.8141^\circ & 9.9504\angle 95.7106^\circ \\ 3.3260\angle 93.8141^\circ & 13.1505\angle -84.7148^\circ & 9.9504\angle 95.7106^\circ \\ 9.9504\angle 95.7106^\circ & 9.9504\angle 95.7106^\circ & 19.8012\angle -84.2606^\circ \end{bmatrix}$$

$\rightarrow$

imag

$$\boxed{B} = \cancel{\mathrm{real}}(Y) = \begin{bmatrix} -13.0946 & 3.3186 & 9.9010 \\ 3.3186 & -13.0946 & 9.9010 \\ 9.9010 & 9.9010 & -19.7020 \end{bmatrix}$$

Line data

i	j	R_{ij}	X_{ij}	B_{ij}
1	2	0.02	0.3	0.15
1	3	0.01	0.1	0.1
2	3	0.01	0.1	0.1

$$B' = \begin{bmatrix} -\left(\frac{1}{X_{21}} + \frac{1}{X_{23}}\right) & \frac{1}{X_{23}} \\ \frac{1}{X_{23}} & -\left(\frac{1}{X_{31}} + \frac{1}{X_{32}}\right) \end{bmatrix} = \begin{bmatrix} -13.3332 & 10 \\ 10 & -20 \end{bmatrix}$$

$$B'' = [2B_3 - (B_{31} + B_{32})] = [2(0.05 + 0.05) - (9.9010 + 9.9010)] = -19.6020$$

$R + jX$

$Y = \cancel{B}\ G + jB$

Compare sub-Jacobians:

Fast Decoupled   Sub-Jacobian at Flat Start

$$\begin{bmatrix} -13.3332 & 10 \\ 10 & -20 \end{bmatrix} \Rightarrow \begin{bmatrix} -13.2859 & 9.9010 \\ 9.9010 & -20 \end{bmatrix}$$

$$[-19.6020] \Rightarrow [-19.4040]$$

Iterate:

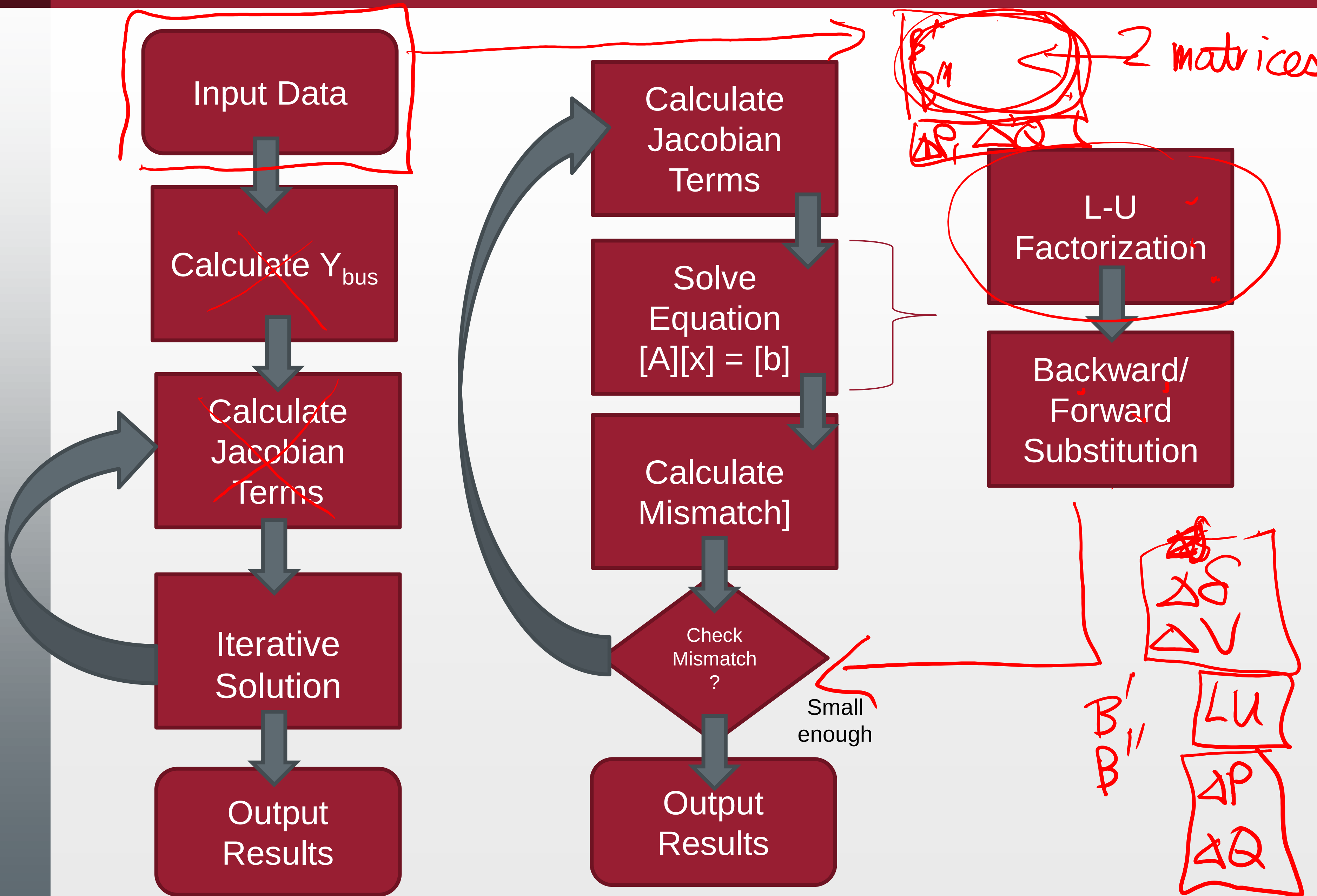
$$\begin{bmatrix} -13.3332 & 10 \\ 10 & -20.000 \end{bmatrix} \begin{bmatrix} \theta_2^1 - 0 \\ \theta_3^1 - 0 \end{bmatrix} = \begin{bmatrix} 0.5044 \\ -1.1802 \end{bmatrix}$$

$$[-19.6020][V_3^1 - 1] = [-0.2020]$$

$$\Rightarrow \begin{bmatrix} \theta_2^1 \\ \theta_3^1 \\ V_3^1 \end{bmatrix} = \begin{bmatrix} -0.0103 \\ -0.0642 \\ 0.9897 \end{bmatrix}$$

Very close to full NR!
Continue until convergence…

Fast Decoupled Power Flow -> What changes?



$$\boxed{|Y| = |B| \quad \theta \pm 90^\circ}$$

$\boxed{X}$

Q-Limits

V θ P Q P Q MVAR Min VAR G B
L L G G

```
 08/19/93 UW ARCHIVE            100.0  1962 W IEEE 14 Bus Test Case
BUS DATA FOLLOWS                          14 ITEMS
   1 Bus 1      HV  1  1  3 1.060    0.0     0.0     0.0   232.4   -16.9     0.0 1.060    0.0     0.0   0.0   0.0        0
   2 Bus 2      HV  1  1  2 1.045  -4.98    21.7    12.7    40.0    42.4     0.0 1.045   50.0   -40.0   0.0   0.0        0
   3 Bus 3      HV  1  1  2 1.010 -12.72    94.2    19.0     0.0    23.4     0.0 1.010   40.0     0.0   0.0   0.0        0
   4 Bus 4      HV  1  1  0 1.019 -10.33    47.8    -3.9     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
   5 Bus 5      HV  1  1  0 1.020  -8.78     7.6     1.6     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
   6 Bus 6      LV  1  1  2 1.070 -14.22    11.2     7.5     0.0    12.2     0.0 1.070   24.0    -6.0   0.0   0.0        0
   7 Bus 7      ZV  1  1  0 1.062 -13.37     0.0     0.0     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
   8 Bus 8      TV  1  1  2 1.090 -13.36     0.0     0.0     0.0    17.4     0.0 1.090   24.0    -6.0   0.0   0.0        0
   9 Bus 9      LV  1  1  0 1.056 -14.94    29.5    16.6     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.19       0
  10 Bus 10     LV  1  1  0 1.051 -15.10     9.0     5.8     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
  11 Bus 11     LV  1  1  0 1.057 -14.79     3.5     1.8     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
  12 Bus 12     LV  1  1  0 1.055 -15.07     6.1     1.6     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
  13 Bus 13     LV  1  1  0 1.050 -15.16    13.5     5.8     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
  14 Bus 14     LV  1  1  0 1.036 -16.04    14.9     5.0     0.0     0.0     0.0 0.0      0.0     0.0   0.0   0.0        0
-999
```

```
Bus data cards *:
-----------------

Columns  1- 4   Bus number (I) *
Columns  7-17   Name (A) (left justify) *
Columns 19-20   Load flow area number (I) Don't use zero! *
Columns 21-23   Loss zone number (I)
Columns 25-26   Type (I) *
                 0 - Unregulated (load, PQ)
                 1 - Hold MVAR generation within voltage limits, (PQ)
                 2 - Hold voltage within VAR limits (gen, PV)
                 3 - Hold voltage and angle (swing, V-Theta) (must always
                   have one)
Columns 28-33   Final voltage, p.u. (F) *
Columns 34-40   Final angle, degrees (F) *
Columns 41-49   Load MW (F) *
Columns 50-59   Load MVAR (F) *
Columns 60-67   Generation MW (F) *
Columns 68-75   Generation MVAR (F) *
Columns 77-83   Base KV (F)
Columns 85-90   Desired volts (pu) (F) (This is desired remote voltage if
                this bus is controlling another bus.
Columns 91-98   Maximum MVAR or voltage limit (F)
Columns 99-106  Minimum MVAR or voltage limit (F)
Columns 107-114 Shunt conductance G (per unit) (F) *
Columns 115-122 Shunt susceptance B (per unit) (F) *
Columns 124-127 Remote controlled bus number

Section end card:
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Columns  1- 4   -999
```

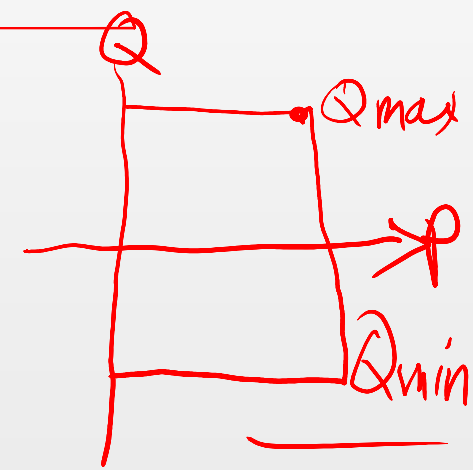

$Q > Q_{max}$

$Q < Q_{min}$

What happens if you hit a Q limit?

PV 1 eq

Q_{limit}

P

$P = P_{lt}$

$Q = Q_{limit}$

PQ 2 eq

$Q_{min} < Q < Q_{max}$

$\Delta V = 0$

J:

13x13	13x9
9x13	9x9
13x13	13x10
10x13	10x10

Announcements

- Start Reading Chapter 4
- Extra Video will drop soon