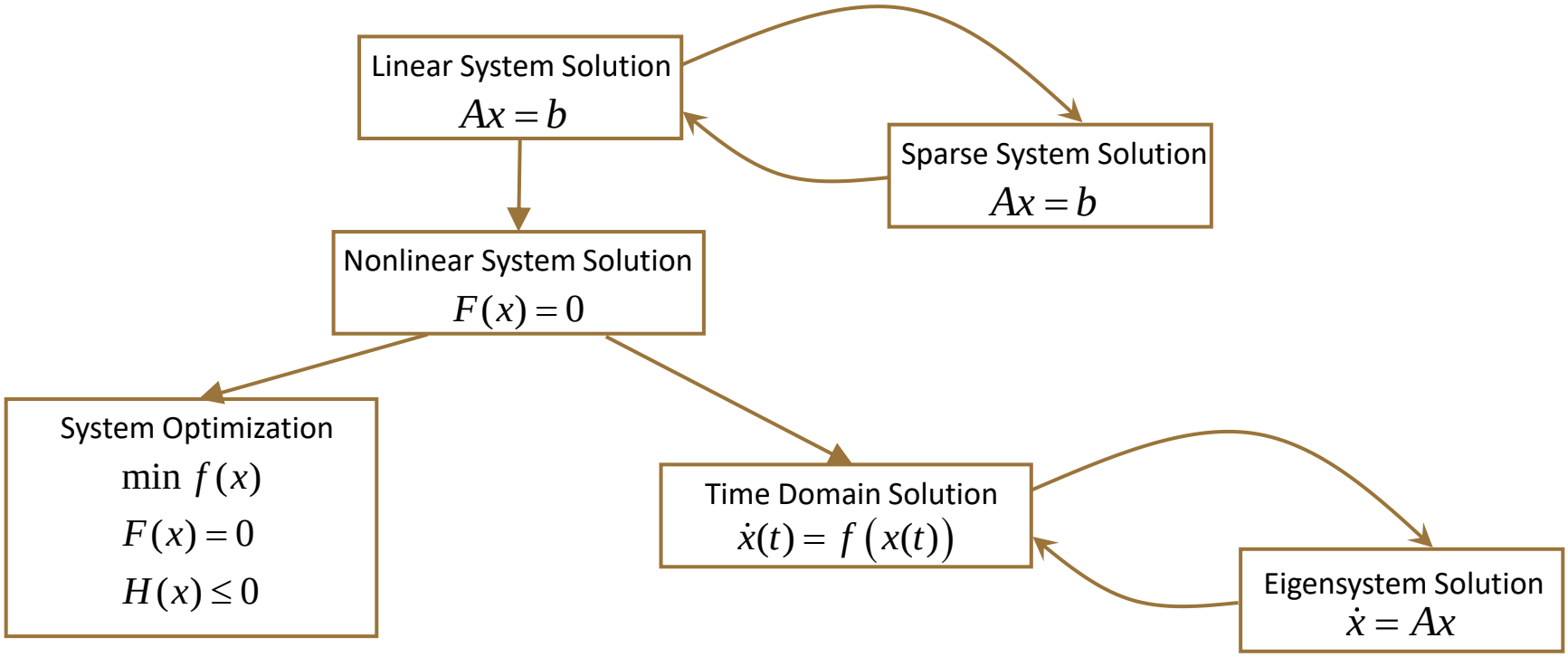
EE 521/ECE 582 – Analysis of Power systems

Class #2 – August 30, 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)

Organization of Course

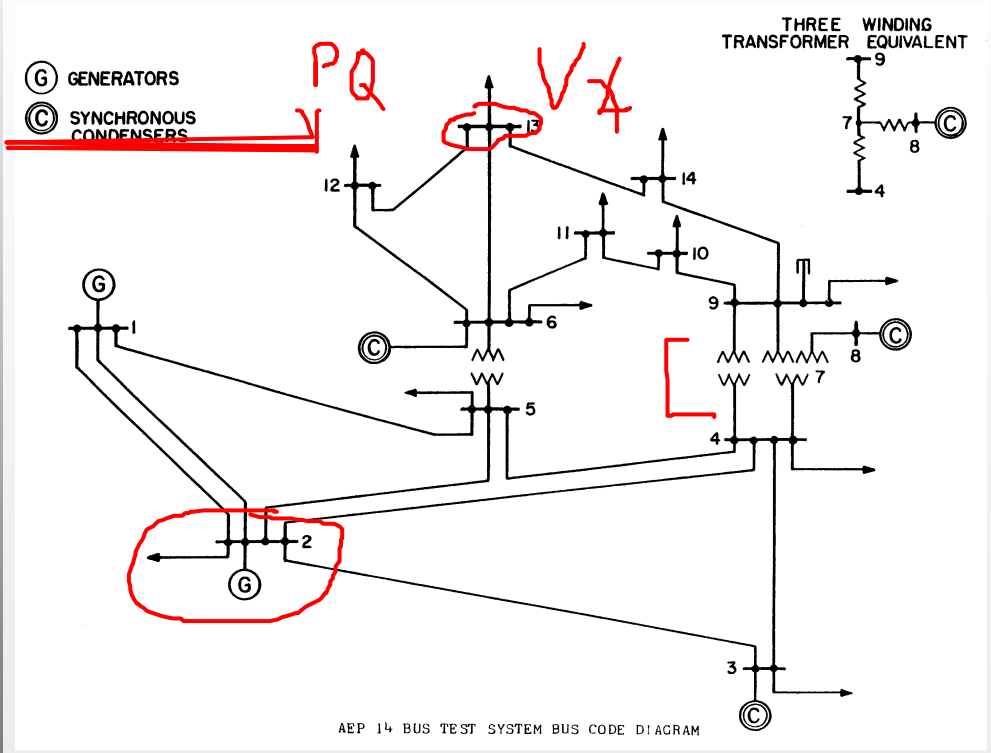


Programming Projects: (80%)

1. Power Flow Project (20%)
   A. Y_{bus}, Jacobian matrices – Newton Raphson
   B. 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%)

- Using IEEE 14 bus system as given, and I will provide a slightly modified version after you confirm the 14-bus system.
- Projects build on each other, adding different features
- In addition to getting the right answers, for each program we'll set up a session for you to describe your code to me.
- Copying code from a colleague or from on-line resources is not permitted.

Converting Physical System into Computer Models



What information do we need?

Solve for:
Voltages at bus
Current in the Line
P and Q for Generators
Information we have:
Buses, Connections, Generators, Syn Condensers, Transformers, Loads, Location

Converting Physical System into Computer Models

```
 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
BRANCH DATA FOLLOWS                         20 ITEMS
   1    2  1  1 1 0  0.01938   0.05917    0.0528    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   1    5  1  1 1 0  0.05403   0.22304    0.0492    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    3  1  1 1 0  0.04699   0.19797    0.0438    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    4  1  1 1 0  0.05811   0.17632    0.0340    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   2    5  1  1 1 0  0.05695   0.17388    0.0346    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   3    4  1  1 1 0  0.06701   0.17103    0.0128    0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   4    5  1  1 1 0  0.01335   0.04211    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   4    7  1  1 1 0  0.0       0.20912    0.0       0    0    0    0 0  0.978     0.0 0.0    0.0     0.0    0.0   0.0
   4    9  1  1 1 0  0.0       0.55618    0.0       0    0    0    0 0  0.969     0.0 0.0    0.0     0.0    0.0   0.0
   5    6  1  1 1 0  0.0       0.25202    0.0       0    0    0    0 0  0.932     0.0 0.0    0.0     0.0    0.0   0.0
   6   11  1  1 1 0  0.09498   0.19890    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   6   12  1  1 1 0  0.12291   0.25581    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   6   13  1  1 1 0  0.06615   0.13027    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   7    8  1  1 1 0  0.0       0.17615    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   7    9  1  1 1 0  0.0       0.11001    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   9   10  1  1 1 0  0.03181   0.08450    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
   9   14  1  1 1 0  0.12711   0.27038    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  10   11  1  1 1 0  0.08205   0.19207    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  12   13  1  1 1 0  0.22092   0.19988    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
  13   14  1  1 1 0  0.17093   0.34802    0.0       0    0    0    0 0  0.0       0.0 0.0    0.0     0.0    0.0   0.0
-999
LOSS ZONES FOLLOWS                    1 ITEMS
  1 IEEE 14 BUS
-99
INTERCHANGE DATA FOLLOWS                1 ITEMS
 1    2 Bus 2     HV    0.0  999.99  IEEE14  IEEE 14 Bus Test Case
-9
TIE LINES FOLLOWS                     0 ITEMS
-999
END OF DATA
```

https://labs.ece.uw.edu/pstca/formats/cdf.txt

Converting Physical System into Computer Models

```
 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:
-----------------

Columns  1- 4   -999
```

Converting Physical System into Computer Models

```
BRANCH DATA FOLLOWS                                          20 ITEMS
   1    2  1  1 1 0  0.01938   0.05917    0.0528    0    0    0    0 0  0.0        0.0 0.0     0
   1    5  1  1 1 0  0.05403   0.22304    0.0492    0    0    0    0 0  0.0        0.0 0.0     0
   2    3  1  1 1 0  0.04699   0.19797    0.0438    0    0    0    0 0  0.0        0.0 0.0     0
   2    4  1  1 1 0  0.05811   0.17632    0.0340    0    0    0    0 0  0.0        0.0 0.0     0
   2    5  1  1 1 0  0.05695   0.17388    0.0346    0    0    0    0 0  0.0        0.0 0.0     0
   3    4  1  1 1 0  0.06701   0.17103    0.0128    0    0    0    0 0  0.0        0.0 0.0     0
   4    5  1  1 1 0  0.01335   0.04211    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   4    7  1  1 1 0  0.0       0.20912    0.0       0    0    0    0 0  0.978      0.0 0.0     0
   4    9  1  1 1 0  0.0       0.55618    0.0       0    0    0    0 0  0.969      0.0 0.0     0
   5    6  1  1 1 0  0.0       0.25202    0.0       0    0    0    0 0  0.932      0.0 0.0     0
   6   11  1  1 1 0  0.09498   0.19890    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   6   12  1  1 1 0  0.12291   0.25581    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   6   13  1  1 1 0  0.06615   0.13027    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   7    8  1  1 1 0  0.0       0.17615    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   7    9  1  1 1 0  0.0       0.11001    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   9   10  1  1 1 0  0.03181   0.08450    0.0       0    0    0    0 0  0.0        0.0 0.0     0
   9   14  1  1 1 0  0.12711   0.27038    0.0       0    0    0    0 0  0.0        0.0 0.0     0
  10   11  1  1 1 0  0.08205   0.19207    0.0       0    0    0    0 0  0.0        0.0 0.0     0
  12   13  1  1 1 0  0.22092   0.19988    0.0       0    0    0    0 0  0.0        0.0 0.0     0
  13   14  1  1 1 0  0.17093   0.34802    0.0       0    0    0    0 0  0.0        0.0 0.0     0
-999
LOSS ZONES FOLLOWS                          1 ITEMS
  1 IEEE 14 BUS
-99
INTERCHANGE DATA FOLLOWS                      1 ITEMS
 1    2 Bus 2      HV     0.0   999.99   IEEE14   IEEE 14 Bus Test Case
-9
TIE LINES FOLLOWS                           0 ITEMS
-999
END OF DATA
```

Branch data cards *:

Columns 1- 4 Tap bus number (I) *
For transformers or phase shifters, the side of the model the non-unity tap is on

Columns 6- 9 Z bus number (I) *
For transformers and phase shifters, the side of the model the device impedance is on.

Columns 11-12 Load flow area (I)

Columns 13-14 Loss zone (I)

Column 17 Circuit (I) * (Use 1 for single lines)

Column 19 Type (I) *
0 - Transmission line
1 - Fixed tap
2 - Variable tap for voltage control (TCUL, LTC)
3 - Variable tap (turns ratio) for MVAR control
4 - Variable phase angle for MW control (phase shifter)

Columns 20-29 Branch resistance R, per unit (F) *

Columns 30-40 Branch reactance X, per unit (F) * No zero impedance lines

Columns 41-50 Line charging B, per unit (F) * (total line charging, +B)

Columns 51-55 Line MVA rating No 1 (I) Left justify!

Columns 57-61 Line MVA rating No 2 (I) Left justify!

Columns 63-67 Line MVA rating No 3 (I) Left justify!

Columns 69-72 Control bus number

Column 74 Side (I)
0 - Controlled bus is one of the terminals
1 - Controlled bus is near the tap side
2 - Controlled bus is near the impedance side (Z bus)

Columns 77-82 Transformer final turns ratio (F)

Columns 84-90 Transformer (phase shifter) final angle (F)

Columns 91-97 Minimum tap or phase shift (F)

Columns 98-104 Maximum tap or phase shift (F)

Columns 106-111 Step size (F)

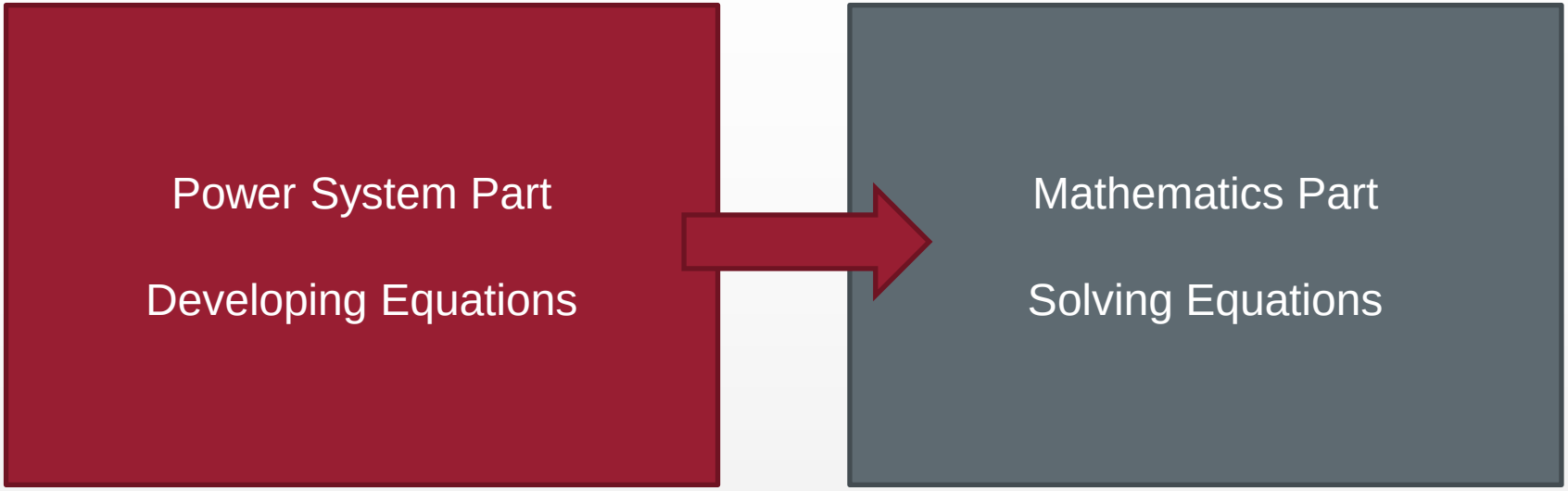
Columns 113-119 Minimum voltage, MVAR or MW limit (F)

Columns 120-126 Maximum voltage, MVAR or MW limit (F)

Section end card:

Columns 1- 4 -999

What's the process for power flow?



- **Calculating Ybus**
- **Jacobian Matrices**
- **Setting Up Equations**
- **Determining Knowns and Unknowns**
- **Determine limits**

- **Matrix mathematics using computers**
- **Factorization**
- **Backward-Forward substitution for Newton Raphson**
- **Calculate the unknowns**

Power System Information Have & Impact

Types of Buses –

- P, Q – Load Bus – Unknowns V, angle
- PV – Generator Bus – Unknowns are angle and Q
- Swing Bus (know V and angle) – Unknowns are P, Q

Lines –

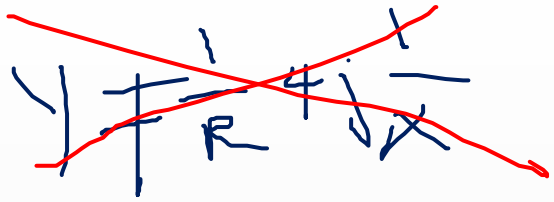
R, X, B
Transformer Tap information
Connections

Limits –

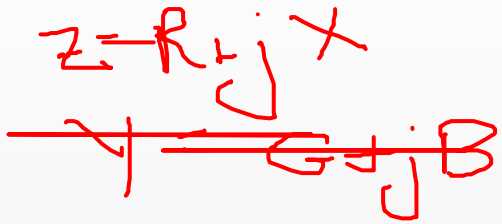
P and Q limits on Generators, Swing

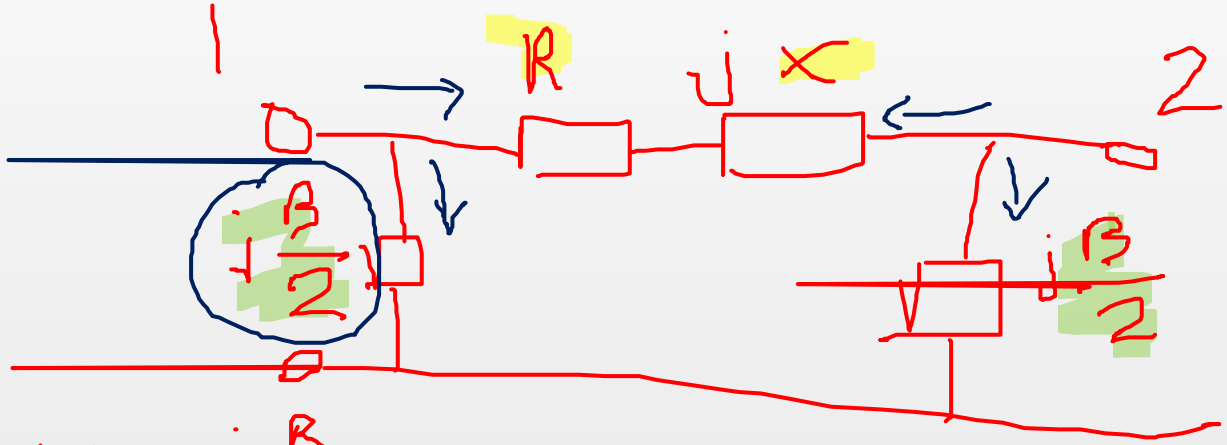
Calculating the Ybus

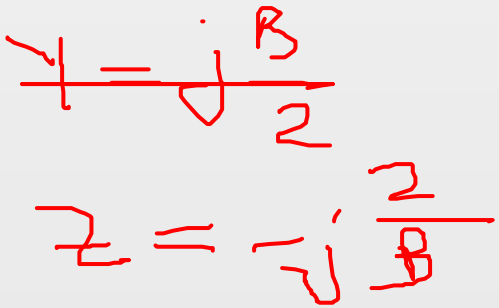
[Ybus] * [V] = [I]

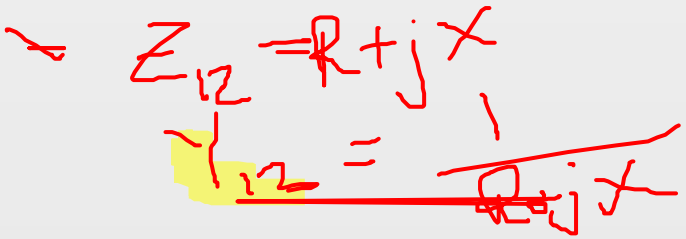


Given in Common Data File –
R, X and B

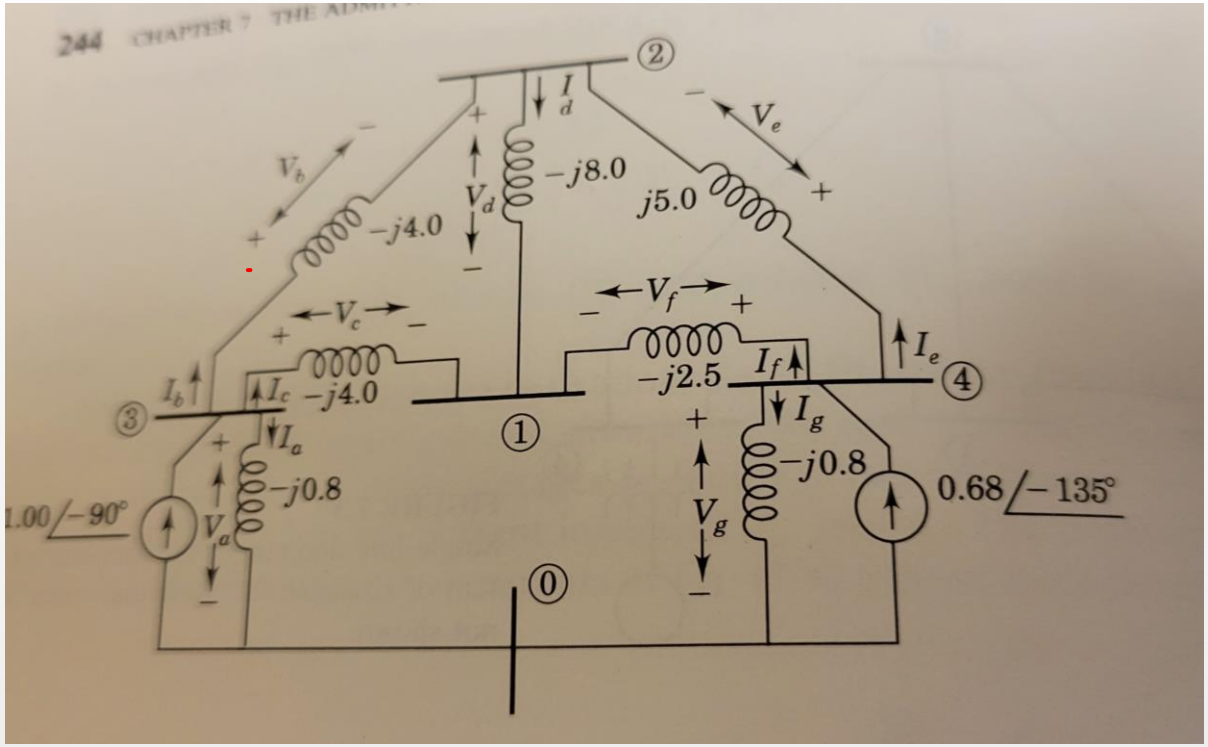




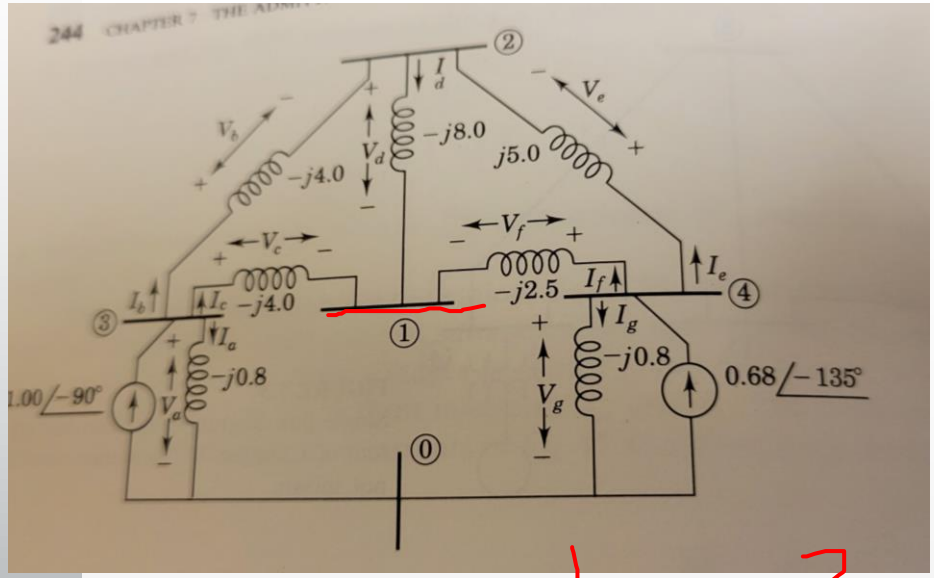




Calculating the Ybus



Calculating the Ybus



$$Y_{ii} = \sum_{j=1,\, j\neq i}^{N} y_{ij} + \frac{B}{2} y_{io}$$

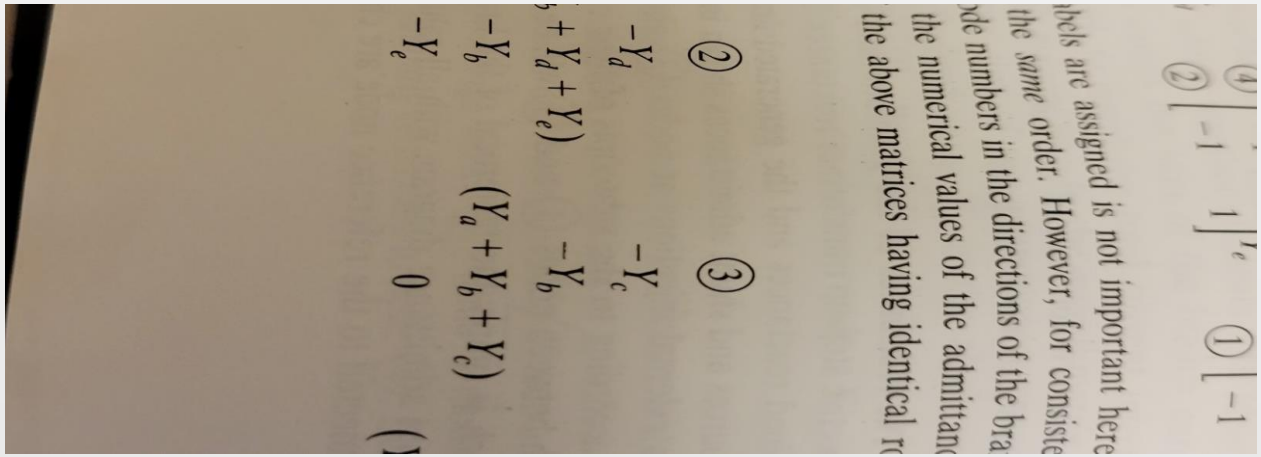
$$\frac{1}{R+jX}$$

$$\begin{bmatrix} y_c+y_d+y_f & -y_d & -y_c & -y_f \\ -y_d & y_b+y_d+y_e & y_b & -y_e \\ -y_c & -y_b & y_c+y_b+y_a & 0 \\ -y_f & -y_e & 0 & y_f+y_e \end{bmatrix}$$

1 2 3 4

Calculating the Ybus

```
BRANCH DATA FOLLOWS                                  20 ITEMS
   1     2  1   1 1 0  0.01938    0.05917     0.0528      0     0     0     0 0  0.0        0.0 0.0     0
   1     5  1   1 1 0  0.05403    0.22304     0.0492      0     0     0     0 0  0.0        0.0 0.0     0
   2     3  1   1 1 0  0.04699    0.19797     0.0438      0     0     0     0 0  0.0        0.0 0.0     0
   2     4  1   1 1 0  0.05811    0.17632     0.0340      0     0     0     0 0  0.0        0.0 0.0     0
   2     5  1   1 1 0  0.05695    0.17388     0.0346      0     0     0     0 0  0.0        0.0 0.0     0
   3     4  1   1 1 0  0.06701    0.17103     0.0128      0     0     0     0 0  0.0        0.0 0.0     0
   4     5  1   1 1 0  0.01335    0.04211     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   4     7  1   1 1 0  0.0        0.20912     0.0         0     0     0     0 0  0.978      0.0 0.0     0
   4     9  1   1 1 0  0.0        0.55618     0.0         0     0     0     0 0  0.969      0.0 0.0     0
   5     6  1   1 1 0  0.0        0.25202     0.0         0     0     0     0 0  0.932      0.0 0.0     0
   6    11  1   1 1 0  0.09498    0.19890     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   6    12  1   1 1 0  0.12291    0.25581     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   6    13  1   1 1 0  0.06615    0.13027     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   7     8  1   1 1 0  0.0        0.17615     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   7     9  1   1 1 0  0.0        0.11001     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   9    10  1   1 1 0  0.03181    0.08450     0.0         0     0     0     0 0  0.0        0.0 0.0     0
   9    14  1   1 1 0  0.12711    0.27038     0.0         0     0     0     0 0  0.0        0.0 0.0     0
  10    11  1   1 1 0  0.08205    0.19207     0.0         0     0     0     0 0  0.0        0.0 0.0     0
  12    13  1   1 1 0  0.22092    0.19988     0.0         0     0     0     0 0  0.0        0.0 0.0     0
  13    14  1   1 1 0  0.17093    0.34802     0.0         0     0     0     0 0  0.0        0.0 0.0     0
-999
LOSS ZONES FOLLOWS                          1 ITEMS
  1 IEEE 14 BUS
-99
INTERCHANGE DATA FOLLOWS                    1 ITEMS
 1     2 Bus 2      HV     0.0   999.99   IEEE14   IEEE 14 Bus Test Case
-9
TIE LINES FOLLOWS                           0 ITEMS
-999
END OF DATA
```



Calculating the Ybus

```
BRANCH DATA FOLLOWS                                  20 ITEMS
   1     2   1   1 1 0  0.01938    0.05917     0.0528
   1     5   1   1 1 0  0.05403    0.22304     0.0492
   2     3   1   1 1 0  0.04699    0.19797     0.0438
   2     4   1   1 1 0  0.05811    0.17632     0.0340
   2     5   1   1 1 0  0.05695    0.17388     0.0346
   3     4   1   1 1 0  0.06701    0.17103     0.0128
```

Announcements

- Remember to do introduction on Canvas discussion
- Remember 14 Bus paper for Discussion
- AGI Day 2021 – August 31 – virtual
- Read Chapter 1 and start on Chapter 2 (through at least 2.4)
- Pull out your power systems book and review power flow modeling
- Start working with MATLAB
  - Input the CDF file
  - Start working on building the Ybus