

Slack bus and slack generator



The Table below shows input data of each busbar in the system used to solve the power flow and the simulation result according to instruction described in question 1.

BUS

Input Data

[Simulation Result]

BUS 1

pu

P (load)

100 MW

Q (load)

0 Mvar

BUS 2

P (load)

200 MW

Q (load)

100 Mvar

CB of Generation

Open

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BUS 3

1 pu

P (Gen)

200 MW

P (load)

100 MW

Q (load)

50 Mvar

AVR

On

AGC

Off

Slack bus and slack generator

In power flow calculation, unique numerical solution cannot be calculated without reference voltage magnitude and angle due to unequal number of unknown variables and independent equations. The slack bus is the reference bus where its voltage is considered to be fixed voltage magnitude and angle ($1 \hat{=} 0^\circ$), so that the various voltage angle difference among the buses can be calculated respect. In addition, the slack generator supplies as much real power and reactive power as needed for balancing the power flow

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considering power generation, load demand and losses in the system while keep the voltage constant as $1 \hat{=} 0^\circ$. In real power system, when relatively weak system is linked to the larger system via a single bus, this bus can represent the large system with an equivalent generator keeping the voltage constant and generating any necessary power like slack bus. [1]

Bus type (PQ bus or PV bus)

BUS

Bus type

Comments

BUS 2

PQ Bus

Generator is disconnected to Bus 2

BUS 3

PV Bus

Generator is connected to Bus 3 and the magnitude of voltage of generator keep constant by using AVR

In general, each bus in the power system can be categorized into three bus types such as Slack Bus, Load (PQ) Bus, and Voltage Controlled (PV) Bus. The definition and difference between PQ Bus and PV Bus are described as follows; [2]

PV Bus (Generator Bus or Voltage Controlled Bus): It is a bus at which the magnitude of the bus voltage is kept constant by the generator. Even though the bus has several generators and load, if any generators connected to the bus regulate the bus voltage with AVR, then this bus is referred to PV Bus.

For PV bus, the magnitude of the bus voltage and real power supplied to the system are specified, and reactive power and angle of the bus voltage are accordingly determined. If a preset maximum and minimum reactive power limit is reached, the reactive output of the generator remains at the limited values, so the bus can be considered as PQ Bus instead of PV Bus. [2]

PQ Bus (Load Bus): It is a bus at which the voltage is changed depending on total net real power and reactive power of loads and generators without voltage regulator. Therefore, in the power simulation and calculation, the real power and reactive power of the loads are specified as input data and accordingly the voltage (magnitude and angle) is calculated based on the above input.

The following table specifies input and output of each bus type in the power system simulation and calculation.

Bus Type

P

Q

(Magnitude)

$\hat{\theta}$ (Angle)

PQ Bus

Input

Input

Output

Output

PV Bus

Input

Output

Input

Output

Slack Bus

Output

Output

Input

Input

System Balance

Total Generation & Load Demand

BUS

Real Power (MW)

Imaginary Power (Mvar)

Generation

Load

Generation

Load

BUS 1

204.093

100

56.240

0

BUS 2

0

200

0

100

BUS 3

200

100

107.404

50

Total

404.093

400

163.644

150

Difference

$$\mathbf{P_{gen} - P_{demand} = 4.093}$$

$$\mathbf{Q_{gen} - Q_{stored\ in\ load} = 13.644}$$

Reason: Real power loss due to resistance of transmission line and imaginary power storage due to reactance of transmission line are the reasons for the difference between power generation and load demand in the system.

P (Losses) & Q (Storage) over the transmission line

BUS

Real Power (MW)

Imaginary Power (Mvar)

Sending

Receiving

Losses

Sending

Receiving

Stored

BUS 1 - BUS 2

102.714

100.650

2.064

56.653

49.773

6.88

BUS 1 - BUS 3

1.379

1.378

0.001

0.4141)

0.4131)

0.001

BUS 3 – BUS 2

101.378

99.350

2.028

56.990

50.227

6.763

Total

Losses =

4.093

Q_{stored in load} =

13.644

1) Imaginary power flows from Bus 3 to Bus 1.

The summation of real power losses and imaginary power storage over the transmission line are exactly same with total difference between generation and load. Therefore, it is verified that the difference is shown over the transmission line.

‘ Kirchoff’ balance as each bus [4]

Bus1

$$\hat{\Sigma} P_1 = + P_{gen1} - P_{load1} - P_{12} - P_{13} = 204.093 - 100 - 102.714 - 1.379 = 0$$

$$\hat{\Sigma} Q_1 = + Q_{gen1} - Q_{load1} - Q_{12} - Q_{13} = 56.24 - 0 - 56.653 + 0.413 = 0$$

Bus2

$$\hat{\Sigma} P_2 = + P_{gen2} - P_{load2} - P_{21} - P_{23} = 0 - 200 + 100.65 + 99.35 = 0$$

$$\hat{\Sigma} Q_2 = + Q_{gen2} - Q_{load2} - Q_{21} - Q_{23} = 0 - 100 + 49.773 + 50.227 = 0$$

BUS3

$$\hat{\Sigma} P_3 = + P_{gen3} - P_{load3} - P_{31} - P_{32} = 200 - 100 + 1.378 - 101.378 = 0$$

$$\hat{\Sigma} Q_3 = + Q_{gen3} - Q_{load3} - Q_{31} - Q_{32} = 107.404 - 50 - 0.414 - 56.99 = 0$$

According to the calculation above, as summation of incoming & outgoing real power and imaginary power at each bus become zero, it is verified that each busbar obeys a ‘ Kirchoff’ balance. In addition, the total power system is completely balanced, because total generation power (real & imaginary) are equal to summation of total load demand and real power loss & stored

imaginary power over the transmission (i. e. $P_{gen} - P_{demand} = P_{losses}$, $Q_{gen} - Q_{stored\ in\ load} = Q_{stored\ in\ system}$) as shown above.

Voltage Angle and Angle Difference

As a result of the Powerworld, the voltage angle and angle difference are shown in the table below.

BUS

Voltage Angle

Voltage Angle Difference

BUS1

$$\hat{\theta}'_1 = 0.00^\circ$$

BUS1- BUS2

$$\hat{\theta}'_1 - \hat{\theta}'_2 = 0.00^\circ - (-2.5662^\circ) = 2.5662^\circ$$

BUS2

$$\hat{\theta}'_2 = -2.5662^\circ$$

BUS2- BUS3

$$\hat{\theta}'_2 - \hat{\theta}'_3 = -2.5662^\circ - (-0.043^\circ) = -2.5232^\circ$$

BUS3

$$\hat{\theta}'_3 = -0.043^\circ$$

BUS3- BUS1

$$\hat{\delta}_3 - \hat{\delta}_1 = -0.043^\circ - 0.00^\circ = -0.043^\circ$$

Power System Analysis -1

The table below summarizes generation and voltage angle variation at each bus as generation at Bus 3 varies from 0 MW to 450 MW by 50MW.

Simulation Results and Observation

P3 = 0 MW

P3 = 50 MW

P3 = 100 MW

P3 = 150 MW

P3 = 250 MW

P3 = 300 MW

P3 = 350 MW

P3 = 400 MW

P3 = 450 MW

Reactive Power Generation at Bus 3: It is found that reactive power generation $Q_3(\text{gen})$ decrease while real power generation $P_3(\text{gen})$ increase because Bus 3 as a PV Bus regulates the constant bus voltage magnitude by controlling excitation of the generation through the AVR.

Power Generation at Bus 1: It is found that $P_1(\text{gen})$ decreases and $Q_1(\text{gen})$ increases simultaneously, while $P_3(\text{gen})$ increases and $Q_3(\text{gen})$ decrease. As <https://assignbuster.com/slack-bus-and-slack-generator/>

the total load demand in the system keeps constant (i. e. $P_{total}(load) = 400$ MW, $Q_{total}(load) = 150$ Mvar), any necessary real power and reactive power for the system balance need to be supplied by generator (slack generator) at Bus 1. Therefore, power generation $P_1(gen)$ and $Q_1(gen)$ at Bus 1 change reversely compared to power generation change at Bus 3.

Voltage Angle Difference: In general, real power flow is influenced by voltage angle difference between sending bus and receiving bus according to $P_R =$. Therefore, it is observed that as real power generation $P_3(gen)$ increases real power flow from Bus 3 to Bus2 increase, accordingly voltage angle difference ($\hat{\delta}_3 - \hat{\delta}_2$) between Bus 3 and Bus 2 increases. However, decrease in real power from Bus 1 to Bus 2 due to increase of $P_3(gen)$ result in decrease of voltage angle difference ($\hat{\delta}_1 - \hat{\delta}_2$). In addition, Real power between Bus 1 and Bus 3 flows from Bus 1 to Bus 3 until $P_3(gen)$ reach to 200 MW and as $P_3(gen)$ increase more than 200 MW the real power flows from Bus 3 to Bus 1. So, it is also observed that voltage angle difference ($\hat{\delta}_3 - \hat{\delta}_1$) is negative angle when $P_3(gen)$ is less than 200MW and the difference increase while $P_3(gen)$ increase.

Power System Analysis -2

The table below summarizes the variation of power generation and voltage angle difference at each bus when the load demand at Bus 3 varies by 50MW and 25Mvar.

Simulation Results and Observation

$P_2 = 0$ MW $Q_2 = 0$ MW

$P_2 = 50$ MW $Q_2 = 25$ MW

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$$P_2 = 100 \text{ MW } Q_2 = 50 \text{ MW}$$

$$P_2 = 150 \text{ MW } Q_2 = 75 \text{ MW}$$

$$P_2 = 250 \text{ MW } Q_2 = 125 \text{ MW}$$

$$P_2 = 300 \text{ MW } Q_2 = 150 \text{ MW}$$

$$P_2 = 350 \text{ MW } Q_2 = 175 \text{ MW}$$

$$P_2 = 400 \text{ MW } Q_2 = 200 \text{ MW}$$

$$P_2 = 450 \text{ MW } Q_2 = 225 \text{ MW}$$

Power Generation at Bus 1 and Bus 3: It is observed that as the total load demand in the system increases due to increase of load demand $P_2(\text{load})$ & $Q_2(\text{load})$ at Bus 2, any necessary real power for the system balance is supplied by generator (slack generator) at Bus 1 considering constant $P_3(\text{gen})$, so $P_1(\text{gen})$ increases. In addition, any necessary reactive power for the system balance is supplied from Bus 1 as well as Bus 3, so both $Q_1(\text{gen})$ and $Q_3(\text{gen})$ increase.

Voltage Angle Difference: It is found that real power flow increase both from Bus 1 to Bus 2 and from Bus 3 to Bus 2 due to increase of load demand at Bus 2. Accordingly, both voltage angle difference $\hat{\delta}'_1 - \hat{\delta}'_2$ and $\hat{\delta}'_3 - \hat{\delta}'_2$ increase when the power flow P_{12} and P_{32} increase. In addition, when $P_2(\text{load})$ is less than 200 MW, $P_{1\text{gen}}$ is relatively low. Therefore real power between Bus 3 and Bus 1 flows from Bus 3 to Bus 1 at lower $P_2(\text{load})$ (less than 200MW). On the other hand, while $P_2(\text{load})$ increase more than 200 MW, the real power flow direction changes (Bus 1 to Bus 3) and the real

power flow increases. Accordingly, the voltage angle difference $\hat{V}_1 - \hat{V}_3$ change from negative to positive and increase.

Voltage Magnitude at Bus 2: It is observed that magnitude of bus voltage at Bus2 drops due to increase of the load demand at Bus 2.

Question 2

System Model & Admittance Matrix

In order to construct the admittance matrix of Powerworld B3 case, single phase equivalent circuit can be drawn as below;

$$z = r + jx \quad (r = 0, x = 0.05)$$

$$z_{12} = z_{21} = j0.05 \text{ pu}, y_{12} = 1/z_{12} = 1/j0.05 = -j20 \text{ pu} = y_{21}$$

$$z_{13} = z_{31} = j0.05 \text{ pu}, y_{13} = 1/z_{13} = 1/j0.05 = -j20 \text{ pu} = y_{31}$$

$$z_{23} = z_{32} = j0.05 \text{ pu}, y_{23} = 1/z_{23} = 1/j0.05 = -j20 \text{ pu} = y_{32}$$

Admittance matrix can be defined as follows;

BUS =

Diagonal elements $Y(i, i)$ of the admittance matrix, called as the self-admittance [lecture slide] [6], are the summation of all admittance connected with BUS i .

$$= y_{12} + y_{13} = -j20 - j20 = -j40 \text{ pu}$$

$$= y_{21} + y_{23} = -j20 - j20 = -j40 \text{ pu}$$

$$= y_{31} + y_{32} = -j20 - j20 = -j40 \text{ pu}$$

Off diagonal elements $Y(i, j)$ of the admittance matrix, called as the mutual admittance [lecture slide] [6], are negative admittance between BUS i and BUS j .

$$= -y_{12} = -(-j20) = j20 \text{ pu} = -y_{13} = -(-j20) = j20 \text{ pu}$$

$$= -y_{21} = -(-j20) = j20 \text{ pu} = -y_{23} = -(-j20) = j20 \text{ pu}$$

$$= -y_{31} = -(-j20) = j20 \text{ pu} = -y_{32} = -(-j20) = j20 \text{ pu}$$

Therefore, the final admittance matrix BUS is;

$$\text{BUS} = =$$

The following figure shows the BUS of the Powerworld B3 case and it is verified that the calculated admittance matrix is consistent with the result of the Powerworld.

Power Flow Calculation

Nodal equation with the admittance matrix can be used to calculate voltage at each bus if we know all the current (i. e. total generation power and load demand at each BUS) and finally the power flow can be calculated accordingly.

, therefore,

In this question, however, simulation results of the voltage at each bus from the Powerworld are used for the power flow calculation as follows;

[Simulation result]

Voltage at each Bus and Voltage Difference

$V_1 = 1 \hat{\angle} 0.00^\circ \text{ pu}$ (BUS1) $V_2 = 1 \hat{\angle} -0.48^\circ \text{ pu}$ (BUS2) $V_3 = 1 \hat{\angle} 0.48^\circ \text{ pu}$ (BUS 3)

Voltage difference between BUS 1 and BUS 2

$V_{12} = V_1 - V_2 = 1 \hat{\angle} 0.00^\circ - 1 \hat{\angle} -0.48^\circ = 3.5 \times 10^{-5} + j 8.38 \times 10^{-3} = 8.38 \times 10^{-3} \hat{\angle} 89.76^\circ \text{ pu}$

$V_{21} = V_2 - V_1 = -V_{12} = -3.5 \times 10^{-5} - j 8.38 \times 10^{-3} = 8.38 \times 10^{-3} \hat{\angle} -90.24^\circ \text{ pu}$

Voltage difference between BUS 3 and BUS 2

$V_{32} = V_3 - V_2 = 1 \hat{\angle} 0.48^\circ - 1 \hat{\angle} -0.48^\circ = j 16.76 \times 10^{-3} = 16.76 \times 10^{-3} \hat{\angle} 90^\circ \text{ pu}$

$V_{23} = V_2 - V_3 = -V_{32} = -j 16.76 \times 10^{-3} = -16.76 \times 10^{-3} \hat{\angle} -90^\circ \text{ pu}$

Voltage difference between BUS 3 and BUS 1

$V_{31} = V_3 - V_1 = 1 \hat{\angle} 0.48^\circ - 1 \hat{\angle} 0.00^\circ = -3.5 \times 10^{-5} + j 8.38 \times 10^{-3} = 8.38 \times 10^{-3} \hat{\angle} 90.24^\circ \text{ pu}$

$V_{13} = V_1 - V_3 = -V_{31} = 3.5 \times 10^{-5} - j 8.38 \times 10^{-3} = 8.38 \times 10^{-3} \hat{\angle} -89.76^\circ \text{ pu}$

Line Current

Current flow from BUS i and BUS j can be calculated by using voltage difference and interconnected admittance of the line between buses. $[I_{ij} = y_{ij} * (V_i - V_j)]$

Line current between BUS 1 and BUS 2

$$I_{12} = y_{12} \times (V_1 - V_2) = -j20 \times 8.38 \times 10^{-3} \hat{}^{89.76^\circ} = 167.6 \times 10^{-3} \hat{}^{-0.24^\circ} \text{ pu (BUS 1 } \hat{} \text{ BUS 2)}$$

$$I_{21} = y_{21} \times (V_2 - V_1) = -j20 \times 8.38 \times 10^{-3} \hat{}^{-90.24^\circ} = 167.6 \times 10^{-3} \hat{}^{-180.24^\circ} \text{ pu (BUS 2 } \hat{} \text{ BUS 1)}$$

Line current between BUS 3 and BUS 2

$$I_{32} = y_{32} \times (V_3 - V_2) = -j20 \times 16.76 \times 10^{-3} \hat{}^{90^\circ} = 335.2 \times 10^{-3} \hat{}^{0.00^\circ} \text{ pu (BUS 3 } \hat{} \text{ BUS 2)}$$

$$I_{23} = y_{23} \times (V_2 - V_3) = -j20 \times 16.76 \times 10^{-3} \hat{}^{-90^\circ} = 335.2 \times 10^{-3} \hat{}^{180^\circ} \text{ pu (BUS 2 } \hat{} \text{ BUS 3)}$$

Line current between BUS 3 and BUS 1

$$I_{31} = y_{31} \times (V_3 - V_1) = -j20 \times 8.38 \times 10^{-3} \hat{}^{90.24^\circ} = 167.6 \times 10^{-3} \hat{}^{0.24^\circ} \text{ pu (BUS 3 } \hat{} \text{ BUS 1)}$$

$$I_{13} = y_{13} \times (V_1 - V_3) = -j20 \times 8.38 \times 10^{-3} \hat{}^{-89.76^\circ} = 167.6 \times 10^{-3} \hat{}^{-179.76^\circ} \text{ pu (BUS 1 } \hat{} \text{ BUS 3)}$$

Apparent Power Flow

Apparent flow from BUS i and BUS j can be calculated by voltage at the sending bus and line current. [$S_{ij} = V_i \times I_{ij}^*$]

Apparent Power from BUS 1 to BUS 2

$$S_{12} = V_1 \times I_{12}^* = 1 \hat{}^{0.00^\circ} \times 167.6 \times 10^{-3} \hat{}^{0.24^\circ} = 167.6 \times 10^{-3} \hat{}^{0.24^\circ} = 0.1676 + j 7.02 \times 10^{-4} \text{ pu}$$

Apparent Power from BUS 2 to BUS 1

$$S_{21} = V_2 \cdot I_{21}^* = 1 \angle -0.48^\circ \times 167.6 \times 10^{-3} \angle 180.24^\circ = 167.6 \times 10^{-3} \angle 179.76^\circ = -0.1676 + j7.02 \times 10^{-4} \text{ pu}$$

Apparent Power from BUS 3 to BUS 2

$$S_{32} = V_3 \cdot I_{32}^* = 1 \angle 0.48^\circ \times 335.2 \times 10^{-3} \angle 0.00^\circ = 335.2 \times 10^{-3} \angle 0.48^\circ = 0.3352 + j2.81 \times 10^{-3} \text{ pu}$$

Apparent Power from BUS 2 to BUS 3

$$S_{23} = V_2 \cdot I_{23}^* = 1 \angle -0.48^\circ \times 335.2 \times 10^{-3} \angle 180^\circ = 335.2 \times 10^{-3} \angle 179.76^\circ = -0.3352 + j2.81 \times 10^{-3} \text{ pu}$$

Apparent Power from BUS 3 to BUS 1

$$S_{31} = V_3 \cdot I_{31}^* = 1 \angle 0.48^\circ \times 167.6 \times 10^{-3} \angle -0.24^\circ = 167.6 \times 10^{-3} \angle 0.24^\circ = 0.1676 + j7.02 \times 10^{-4} \text{ pu}$$

Apparent Power from BUS 1 to BUS 3

$$S_{13} = V_1 \cdot I_{13}^* = 1 \angle 0.00^\circ \times 167.6 \times 10^{-3} \angle 179.76^\circ = 167.6 \times 10^{-3} \angle 179.76^\circ = -0.1676 + j7.02 \times 10^{-4} \text{ pu}$$

Comparison with simulation results

The unit of the above calculation results is pu value, so in order to compare the results with simulation results pu value of current and power flow need to be converted to actual values by using the following equation considering $S_{base} = 100\text{MVA}$ and $V_{line_base} = 345\text{kV}$. [3]

$$S_{actual} = S_{base} \tilde{A} \tilde{S}_{pu} = 100 \text{ MVA} \tilde{A} \tilde{S}_{pu}$$

$$I_{actual} = I_{base} \tilde{A} \tilde{I}_{pu} = \tilde{A} \tilde{I}_{pu} = \tilde{A} \tilde{I}_{pu} = 167.3479 \text{ A} \tilde{A} \tilde{I}_{pu}$$

Calculation Result and Simulation Result

Flow direction & Value

Calculation Result

Simulation Result

BUS 1 ↔ BUS 2

| S12|

0.1676 Å- 100 = 16.76 MVA

16.67 MVA

P12

16.76 MW

16.67 MW

Q12

0.0702 Mvar

0.07 Mvar

| I12|

0.1676 Å- 167.3479 = 28.0475 A

27.89 A

BUS 3 ↔ BUS 2

| S32|

$$0.3352 \text{ \AA} - 100 = 33.52 \text{ MVA}$$

33.33 MVA

P32

33.52 MW

33.33 MW

Q32

0.281 Mvar

0.28 Mvar

|I32|

$$0.3352 \text{ \AA} - 167.3479 = 56.0950 \text{ A}$$

55.78 A

BUS 3 † BUS 1

|S31|

$$0.1676 \text{ \AA} - 100 = 16.76 \text{ MVA}$$

16.67 MVA

P31

16.76 MW

16.67 MW

Q31

0.0702 Mvar

0.07 Mvar

|I31|

$0.1676 \text{ \AA} - 167.3479 = 28.0475 \text{ A}$

27.89 A

BUS 2 † BUS 1

|S21|

$0.1676 \text{ \AA} - 100 = 16.76 \text{ MVA}$

16.67 MVA

P21

-16.76 MW

-16.67 MW

Q21

0.0702 Mvar

0.07 Mvar

|I21|

$0.1676 \text{ \AA} - 167.3479 = 28.0475 \text{ A}$

27. 89 A

BUS 2 † BUS 3

| S23|

$$0.3352 \text{ \AA} - 100 = 33.52 \text{ MVA}$$

33.33 MVA

P23

-33.52 MW

-33.33 MW

Q23

0.281 Mvar

0.28 Mvar

| I23|

$$0.3352 \text{ \AA} - 167.3479 = 56.0950 \text{ A}$$

55.78 A

BUS 1 † BUS 3

| S13|

$$0.1676 \text{ \AA} - 100 = 16.76 \text{ MVA}$$

16.67 MVA

P13

-16.76 MW

-16.67 MW

Q13

0.0702 Mvar

0.07 Mvar

|I13|

0.1676 Å- 167.3479 = 28.0475 A

27.89 A

It is found that calculation results of current flow and apparent power flows (i. e. 28.0475 A and 56.0950 A / 33.52 MVA and 16.76MVA) are about 0.5 % higher than simulation result (i. e. 27.89 A and 55.78 A / 33.33 MVA and 16.67 MVA) which can be considered slightly different. Difference of the voltage angle at each bus between calculation (0.48°) and simulation (0.4775°) could be the reason for this minor difference.

Question 3

Admittance Matrix and Nodal Equation

Admittance between two buses

$$y_{12} = y_{21} = -j8 \text{ pu} \quad y_{13} = y_{31} = -j4 \text{ pu} \quad y_{14} = y_{41} = -j2.5 \text{ pu}$$

$$y_{23} = y_{32} = -j4 \text{ pu} \quad y_{24} = y_{42} = -j5 \text{ pu}$$

$$y_{30} = -j0.8 \text{ pu (BUS3-Neutral BUS)} \quad y_{40} = -j0.8 \text{ pu (BUS4-Neutral BUS)}$$

Admittance Matrix

Ybus (Admittance Matrix) =

Diagonal elements $Y(i, i)$ of the admittance matrix, called as the self-admittance [2] [4], are the summation of all admittance connected with BUS i.

$$= y_{12} + y_{13} + y_{14} = -j8 -j4 - j2.5 = -j14.5$$

$$= y_{21} + y_{23} + y_{24} = -j8 -j4 - j5 = -j17$$

$$= y_{30} + y_{31} + y_{32} = -j0.8 -j4 - j4 = -j8.8$$

$$= y_{40} + y_{41} + y_{42} = -j0.8 -j2.5 - j5 = -j8.3$$

Off diagonal elements $Y(i, j)$ of the admittance matrix, called as the mutual admittance [2] [4], are negative admittance between BUS i and BUS j.

$$= -y_{12} = -(-j8) = j8 \text{ pu} = -y_{13} = -(-j4) = j4 \text{ pu} = -y_{14} = -(-j2.5) = j2.5 \text{ pu}$$

$$= -y_{21} = -(-j8) = j8 \text{ pu} = -y_{23} = -(-j4) = j4 \text{ pu} = -y_{24} = -(-j5) = j5 \text{ pu}$$

$$= -y_{31} = -(-j4) = j4 \text{ pu} = -y_{32} = -(-j4) = j4 \text{ pu} = -y_{34} = 0 \text{ pu}$$

$$= -y_{41} = -(-j2.5) = j2.5 \text{ pu} = -y_{42} = -(-j5) = j5 \text{ pu} = -y_{43} = 0 \text{ pu}$$

Therefore, admittance matrix Ybus is as follows;

Ybus = =

Power Flow Analysis

Power flow ignoring transmission line capacitance

Nodal Equation

Current from the neutral bus to each bus are given and admittance matrix (Ybus) is calculated above. Therefore, final nodal equation is as follows;

$$I_{bus} = Y_{bus} * V_{bus} \hat{=} V_{bus} = Y^{-1}_{bus} * I_{bus}$$

$$= Y_{bus} \hat{=} =$$

=

Voltage Analysis

Voltage at each bus can be derived from the equation ($V_{bus} = Y^{-1}_{bus} * I_{bus}$) and Matlab was used for calculate matrix division. (Source code is attached in Appendix-1)

Vbus ==

$$V_{12} = 0.0034 + j 0.0031 \text{ pu} \quad V_{13} = -0.0277 - j 0.0257 \text{ pu} \quad V_{14} = 0.0336 + j 0.0311 \text{ pu}$$

$$V_{21} = -0.0034 - j 0.0031 \text{ pu} \quad V_{23} = -0.0311 - j 0.0288 \text{ pu} \quad V_{24} = 0.0302 + j 0.0280 \text{ pu}$$

$$V_{31} = 0.0277 + j 0.0257 \text{ pu} \quad V_{32} = 0.0311 + j 0.0288 \text{ pu}$$

$$V_{41} = -0.0336 - j 0.0311 \text{ pu} \quad V_{42} = -0.0302 - j 0.0280 \text{ pu}$$

Current flow in the system

Current flow from BUS i and BUS j can be calculated by using voltage difference and interconnected admittance of the line between buses. [$I_{ij} = y_{ij} * (V_i - V_j)$] The calculation result from Matlab is as follows;

$$I_{12} = 0.0249 - j 0.0269 \text{ pu} \quad I_{13} = -0.1026 + j 0.1108 \text{ pu} \quad I_{14} = 0.0777 - j 0.0840 \text{ pu}$$

$$I_{21} = -0.0249 + j 0.0269 \text{ pu} \quad I_{23} = -0.1151 + j 0.1243 \text{ pu} \quad I_{24} = 0.1399 - j 0.1511$$

$$I_{31} = 0.1026 - j 0.1108 \text{ pu} \quad I_{32} = 0.1151 - j 0.1243 \text{ pu} \quad I_{34} = 0 \text{ pu}$$

$$I_{41} = -0.0777 + j 0.0840 \text{ pu} \quad I_{42} = -0.1399 + j 0.1511 \text{ pu} \quad I_{43} = 0 \text{ pu}$$

Power flow in the system

Apparent flow from BUS i and BUS j can be calculated by voltage at the sending bus and line current. [$S_{ij} (\text{pu}) = V_i * I_{ij}^* = P_{ij} + jQ_{ij}$] The calculation result from Matlab is as follows;

$$S_{12} = 0.0311 + j 0.0175 \text{ pu} \quad S_{13} = -0.1283 - j 0.0723 \text{ pu} \quad S_{14} = 0.0972 + j 0.0548 \text{ pu}$$

$$S_{21} = -0.0311 - j 0.0174 \text{ pu} \quad S_{23} = -0.1438 - j 0.0803 \text{ pu} \quad S_{24} = 0.1749 + j 0.0977 \text{ pu}$$

$$S_{31} = 0.1283 + j 0.0780 \text{ pu} \quad S_{32} = 0.1438 + j 0.0875 \text{ pu} \quad S_{34} = 0 \text{ pu}$$

$$S_{41} = -0.0972 - j 0.0496 \text{ pu} \quad S_{42} = -0.1749 - j 0.0892 \text{ pu} \quad S_{44} = 0 \text{ pu}$$

Admittance Matrix considering transmission line capacitance

According to the instruction of the Question 3, power system model can be drawn by using the equivalent circuit of the lines with capacitive shunt admittance (y_c) of 0.1 pu at each side as shown below.

Admittance Matrix

Contrary to equivalent model in Question 3-1, the current flow through the capacitor in the transmission line needs to be considered to find the admittance matrix. Therefore, considering the capacitors the current equation with Kirchhoff's current law at each bus is as follows; [2] [5]

$$\text{Bus 1: } I_1 = I_{12} + I_{13} + I_{14} + I_{c12} + I_{c13} + I_{c14} \quad I_1 = y_{12}(V_1 - V_2) + y_{13}(V_1 - V_3) + y_{14}(V_1 - V_4) + y_{c12}V_1 + y_{c13}V_1 + y_{c14}V_1$$

$$\text{Bus 2: } I_2 = I_{21} + I_{23} + I_{24} + I_{c21} + I_{c23} + I_{c24} \quad I_2 = y_{21}(V_2 - V_1) + y_{23}(V_2 - V_3) + y_{24}(V_2 - V_4) + y_{c21}V_2 + y_{c23}V_2 + y_{c24}V_2$$

$$\text{Bus 3: } I_3 = I_{30} + I_{31} + I_{32} + I_{c31} + I_{c32} \quad I_3 = y_{30}V_3 + y_{31}(V_3 - V_1) + y_{32}(V_3 - V_2) + y_{c31}V_3 + y_{c32}V_3$$

$$\text{Bus 4: } I_4 = I_{40} + I_{41} + I_{42} + I_{c41} + I_{c42} \quad I_4 = y_{40}V_4 + y_{41}(V_4 - V_1) + y_{42}(V_4 - V_2) + y_{c41}V_4 + y_{c42}V_4$$

Equation above can be rearranged to separate and group individual products by voltage.

$$\text{Bus 1: } I_1 = (y_{12} + y_{13} + y_{14} + y_{c12} + y_{c13} + y_{c14})V_1 - y_{12}V_2 - y_{13}V_3 - y_{14}V_4 = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4$$

$$\text{Bus 2: } I_2 = (y_{21} + y_{23} + y_{24} + y_{c21} + y_{c23} + y_{c24})V_2 - y_{21}V_1 - y_{23}V_3 - y_{24}V_4 = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4$$

$$\text{Bus 3: } I_3 = (y_{30} + y_{31} + y_{32} + y_{c31} + y_{c32})V_3 - y_{31}V_1 - y_{32}V_2 = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4$$

$$\text{Bus 4: } I_4 = (y_{40} + y_{41} + y_{42} + y_{c41} + y_{c42})V_4 - y_{41}V_1 - y_{42}V_2 = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4$$

Finally, Diagonal elements $Y(i, i)$ and off diagonal elements $Y(i, j)$ of the admittance matrix are calculated as follows;

$$= y_{12} + y_{13} + y_{14} + y_{c12} + y_{c13} + y_{c14} = -j8 -j4 - j2.5 + j0.1 + j0.1 + 0.1j = -j14.2 \text{ pu}$$

$$= y_{21} + y_{23} + y_{24} + y_{c21} + y_{c23} + y_{c24} = -j8 -j4 - j5 + j0.1 + j0.1 + 0.1j = -j16.7 \text{ pu}$$

$$= y_{30} + y_{31} + y_{32} + y_{c31} + y_{c32} = -j0.8 -j4 - j4 + j0.1 + 0.1j = -j8.6 \text{ pu}$$

$$= y_{40} + y_{41} + y_{42} + y_{c41} + y_{c42} = -j0.8 -j2.5 - j5 + j0.1 + 0.1j = -j8.1 \text{ pu}$$

$$= -y_{12} = -(-j8) = j8 \text{ pu} = -y_{13} = -(-j4) = j4 \text{ pu} = -y_{14} = -(-j2.5) = j2.5 \text{ pu}$$

$$= -y_{21} = -(-j8) = j8 \text{ pu} = -y_{23} = -(-j4) = j4 \text{ pu} = -y_{24} = -(-j5) = j5 \text{ pu}$$

$$= -y_{31} = -(-j4) = j4 \text{ pu} = -y_{32} = -(-j4) = j4 \text{ pu} = -y_{34} = 0 \text{ pu}$$

$$= -y_{41} = -(-j2.5) = j2.5 \text{ pu} = -y_{42} = -(-j5) = j5 \text{ pu} = -y_{43} = 0 \text{ pu}$$

Therefore, admittance matrix Y_{bus} is as follows;

Ybus = =

Annex-1: Matlab source code and Calculation results with Matlab

Matlab Source Code

```
% define self admittance and mutual admittance by using admittance
between
```

```
% the buses (y12= y21=-j8, y13= y31=-j4, y14= y41=-j2. 5, y23= y32=-j4,
```

```
% y24= y42=-j5, y34= 0, y43= 0, y30=-j0. 8, y40=-j0. 8
```

```
y12=-8i; y21=-8i; y13=-4i; y31=-4i; y14=-2. 5i; y41=-2. 5i; y23=-4i; y32=-
4i;
```

```
y24=-5i; y42=-5i; y34= 0; y43= 0; y30=-0. 8i; y40=-0. 8i;
```

```
Y11=-8i-4i-2. 5i; Y12= 8i; Y13= 4i; Y14= 2. 5i;
```

```
Y21= 8i; Y22=-8i-4i-5i; Y23= 4i; Y24= 5i;
```

```
Y31= 4i; Y32= 4i; Y33=-0. 8i-4i-4i; Y34= 0;
```

```
Y41= 2. 5i; Y42= 5i; Y43= 0; Y44=-5i-2. 5i-0. 8i;
```

```
%Bus 3 and Bus 4 is not connected, so admittance Y34 and Y43 are equal to
zero
```

```
% define the 4x4 admittance matrix (Ybus)
```

```
Ybus=[Y11 Y12 Y13 Y14; Y21 Y22 Y23 Y24; Y31 Y32 Y33 Y34; Y41 Y42 Y43
Y44];
```

<https://assignbuster.com/slack-bus-and-slack-generator/>

% In order to define the nodal equation ($I = Y_{bus} * V$), the given I needs to be defined.

```
i1= 0; i2= 0; i3=-i; i4=-0.4808-0.4808i;
```

```
lbus=[i1; i2; i3; i4];
```

% Each bus voltage can be calculated by using matrix division ($V = Y_{bus}^{-1} * I$)

```
Vbus= Ybus\lbus;
```

```
v1= Vbus(1, 1); v2= Vbus(2, 1); v3= Vbus(3, 1); v4= Vbus(4, 1);
```

% Calculate voltage difference between buses

```
v12= v1-v2; v13= v1-v3; v14= v1-v4;
```

```
v21= v2-v1; v23= v2-v3; v24= v2-v4;
```

```
v31= v3-v1; v32= v3-v2; v34= v3-v4;
```

```
v41= v4-v1; v42= v4-v2; v43= v4-v3;
```

% current flow between buses can be calculated by $i_{12} = y_{12} * (v_1 - v_2)$

```
i12= y12*v12; i13= y13*v13; i14= y14*v14;
```

```
i21= y21*v21; i23= y23*v23; i24= y24*v24;
```

```
i31= y31*v31; i32= y32*v32; i34= y34*v34;
```

```
i41= y41*v41; i42= y42*v42; i43= y43*v43;
```

% apparent power can be calculated by $s_{12} = v_1 * conj(i_{12})$

<https://assignbuster.com/slack-bus-and-slack-generator/>


```
s12= v1*conj(i12); s13= v1*conj(i13); s14= v1*conj(i14);
```

```
s21= v2*conj(i21); s23= v2*conj(i23); s24= v2*conj(i24);
```

```
s31= v3*conj(i31); s32= v3*conj(i32); s34= v3*conj(i34);
```

```
s41= v4*conj(i41); s42= v4*conj(i42); s43= v4*conj(i43);
```

```
% Real power and Reactive power can be derived by following
```

```
p12= real(s12); p13= real(s13); p14= real(s14);
```

```
q12= imag(s12); q13= imag(s13); q14= imag(s14);
```

```
p21= real(s21); p23= real(s23); p24= real(s24);
```

```
q21= imag(s21); q23= imag(s23); q24= imag(s24);
```

```
p31= real(s31); p32= real(s32); p34= real(s34);
```

```
q31= imag(s31); q32= real(s32); q34= imag(s34);
```

```
p41= real(s41); p42= real(s42); p43= real(s43);
```

```
q41= imag(s41); q42= real(s42); q43= imag(s43); % end
```

Matlab Calculation Results