EE3015: Power Systems & Protection

Wang Peng

S2-B2C-104

6790-6856

Tutorial 1: Per Unit System I

1.1 A 3-phase generator <u>rated</u> 100MVA, 13.2kV, X=20% is connected through a Δ/Y transformer to a transmission line whose series reactance is 40 ohms per phase. Assume that the base values in the line circuit are 200MVA and 115kV.

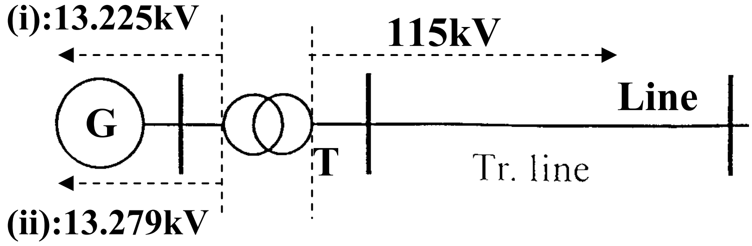
(a) Find the pu reactance of the transmission line.

(b) Find the generator and transformer reactances in pu for the following cases:

(i) The transformer is a 3-phase unit rated 100MVA, 13.8Δ/120Y kV, X = 8%

(ii) The transformer is composed of three single-phase units, <u>each</u> rated 35MVA, 13.8/69 kV, X=8%.

Solutions:



Base values:

S_{BN}=200MVA (Only one new base power through the calculation)

Two base voltages: (because of one transformer)

Base voltage of the line: (Given) V_{LBN}=115kV (line to line)

Base voltage of the generator: (Calculate) $V_{GBN} = V_{LBN} T_{ratio}$.

(a) pu reactance of the line: (Given: real impedance in Ω)

$$\text{Base impedance of line: } Z_{LBN} = \frac{V_{LBN}^2}{S_{BN}} = \frac{115^2}{200} = 66.125\,\Omega$$

$$\text{pu reactance of line: } X_{Lpu} = \frac{X_L}{Z_{LBN}} = \frac{40}{66.125} = 0.6049\text{pu}$$

(b) pu reactance of the generator and the transformer:

(i) The transformer in a 3-phase unit (Type 1).

Givens (rated): 100MVA (3-Φ); 13.8Δ/120Y kV

$$\mathbf{T_{ratio}}=\frac{V_{T\Delta}(\textit{rated} \quad \textit{line}-\textit{to}-\textit{line})}{V_{TY}(\textit{rated} \quad \textit{line}-\textit{to}-\textit{line})}=\frac{13.8kV}{120kV}$$ **(no calculation!!)**

Base voltage of generator: $\mathbf{V_{GBN} = V_{LBN}T_{ratio} = 115\frac{13.8}{120} = 13.225kV}$

Givens old bases: S_{TBO}=100MVA (3-Φ); V_{TBO}: 13.8Δ/120Y kV

New bases: S_{TBN}=200MVA (3-Φ); V_{TBN}: 13.225Δ/115Y kV

New pu impedances:

Transformer: $$\mathbf{X_{TNpu} = X_{TOpu}\frac{V_{TBO}^2}{V_{TBN}^2}\frac{S_{BN}}{S_{TBO}} = 0.08\frac{120^2}{115^2}\frac{200}{100} = 0.1742pu}$$

Generator: $$\mathbf{X_{GNpu} = X_{GOpu}\frac{V_{GBO}^2}{V_{GBN}^2}\frac{S_{BN}}{S_{BGO}} = 0.2\frac{13.2^2}{13.225^2}\frac{200}{100} = 0.3985pu}$$

(ii) The transformer consists of three single phase units (Type 2).

Givens (rated): S=35MVA and V=13.8/69 kV <u>for each unit</u>.

Three phase transformer (Ratio must be calculated!!!)

Y connection (side): $V_{TY} = \sqrt{3}\times 69 = 119.5kV$ **(line-line)**

Δ connection (side): $\mathbf{V_{T\Delta} = 13.8kV}$ **(line-line)**

$$\mathbf{T}_{ratio} = \frac{V_{T\Delta}}{V_{TY}} = \frac{\mathbf{13.8}}{\mathbf{119.5}}$$

S_{BTO}=3×35MVA=105 MVA V_{TBO}: 13.8Δ/119.5Y kV

New bases: S_{TBN}=200MVA (3-Φ); V_{TBN}: 13.275Δ/115Y kV

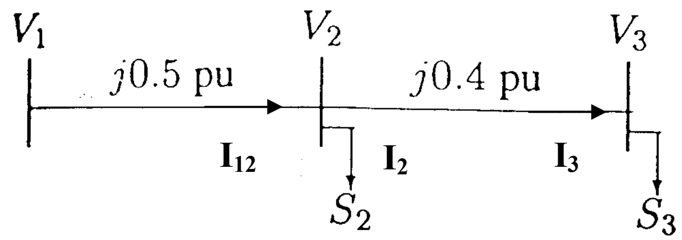
Base voltage at generator side: $\mathbf{V_{GBN} = V_{LBN}}T_{ratio} \mathbf{= 115\frac{13.8}{119.5} = 13.279kV}$

New pu impedances:

$$X_{TNpu} = X_{TOpu}\frac{V_{TBO}^2}{V_{TBN}^2}\frac{S_{BN}}{S_{TBO}} = 0.08\frac{119.5^2}{115^2}\frac{200}{105} = 0.1646pu$$

$$\mathbf{X_{GNpu} = X_{GOpu}\frac{V_{GBO}^2}{V_{GBN}^2}\frac{S_{BN}}{S_{GBO}} = 0.2\frac{13.2^2}{13.279^2}\frac{200}{100} = 0.3953pu}$$

1.2 The one-line diagram of a three-phase power system is shown below. The impedances marked are in per unit on a 100-MVA, 400-kV base. Given that loads S_2 = (15.93-j33.4) MVA, and S_3 = (77+j14) MVA, and that the voltage at bus 3 is maintained at 400kV, determine the magnitude of the voltage at bus 1.



Solutions: (Convert all parameters into pu values)

Base values: S_B=100MVA V_B=400 kV
pu voltage at bus 3 (as reference): $V_{3pu}=400/400=1\angle 0^o$

<u>pu power of loads</u>: (Load are given in the form of power S=P+jQ)

$S_2=(15.93-j33.4)=37.0044\angle -64.501^o$ (MVA)
$S_{2pu}=S_2/S_B=0.370044\angle -64.501^o$

$S_3=(77+j14)=78.262\angle 10.3^o$ (MVA)
$S_{3pu}=S_3/S_B=0.78262\angle 10.3^o$

pu voltages at bus 2 and bus 1:

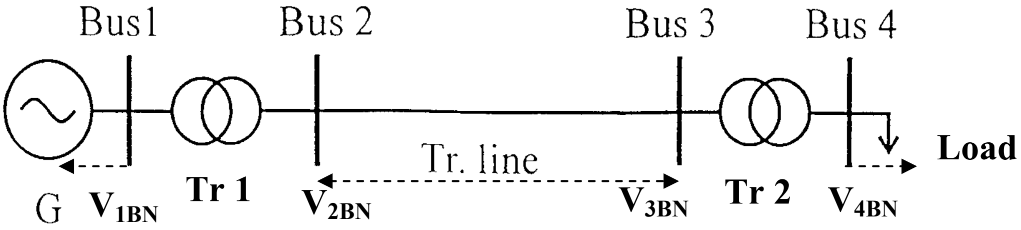
$I_{3pu}=(S_{3pu}/V_{3pu})^*=0.78262\angle -10.3^o$
KVL: $V_{2pu}=V_{3pu}+I_{3pu}\times j0.4=1.1\angle 16.26^o$

$I_{2pu}=(S_{2pu}/V_{2pu})^*=0.3364\angle 80.78^o$
KCL at bus 2: $I_{12pu}=I_{2pu}+I_{3pu}=0.846\angle 13.12^o$
KVL: $V_{1pu}=V_{2pu}+I_{12pu}\times j0.5=1.2\angle 36.87^o$

Absolute voltages: $|V_1|=|V_{1pu}|\times V_B=480\text{kV}$

$$|V_2|=440\text{kV}$$

1.3 Obtain the pu impedance diagram for the system without modeling the generator. Assume a base of 200MVA, 11kV in the generator circuit. The transmission line X=50 ohms and R=2.5 ohms; transformer ratings for Tr 1 are 50MVA, 11/132 kV, X=12%, R=2%, and for Tr 2 are 40MVA, 132/33 kV, X = 10%, R = 1%. The load connected at bus 4 is 40MW at 0.8 pf lag, at a voltage of 30kV.



Solutions:

Base Power (given): S_{BN}=200 MVA,

Base voltage at bus 1 (given): V_{1BN}=11kV,

Base voltage at bus 2: $V_{2BN} = V_{1BN} T_{1ratio} = 11\frac{132}{11} = 132\text{kV} = V_{3BN}$

Base voltage at bus 4: $V_{4BN} = V_{3BN} T_{2ratio} = 132\frac{33}{132} = 33\text{kV}$

Line pu impedance (given real impedance):

Base impedance: $Z_{BLN} = \frac{V_{BL}^2}{S_{BN}} = \frac{132^2}{200} = 87.12\,\Omega$

pu impedance: $Z_{Lpu} = \frac{Z_L}{Z_{BL}} = \frac{2.5 + j50}{81.12} = 0.0287 + j0.5739\text{pu}$

T1 pu impedance (given old pu impedance):

$$Z_{T1pu} = Z_{T1Opu}\frac{V_{2BO}^2}{V_{2BN}^2}\frac{S_{BN}}{S_{BT1O}} = (0.02 + j0.12)\frac{200}{50} = 0.08 + j0.48\text{pu}$$

T2 pu impedance (given old pu impedance):

$$Z_{T2pu} = Z_{T2Opu}\frac{S_{BN}}{S_{BT2O}} = (0.01 + j0.1)\frac{200}{40} = 0.05 + j0.50pu$$

****Load pu impedance (given real power, power factor and voltage):**

pu voltage: V_{4pu}=30/33=0.909$\angle 0^o$

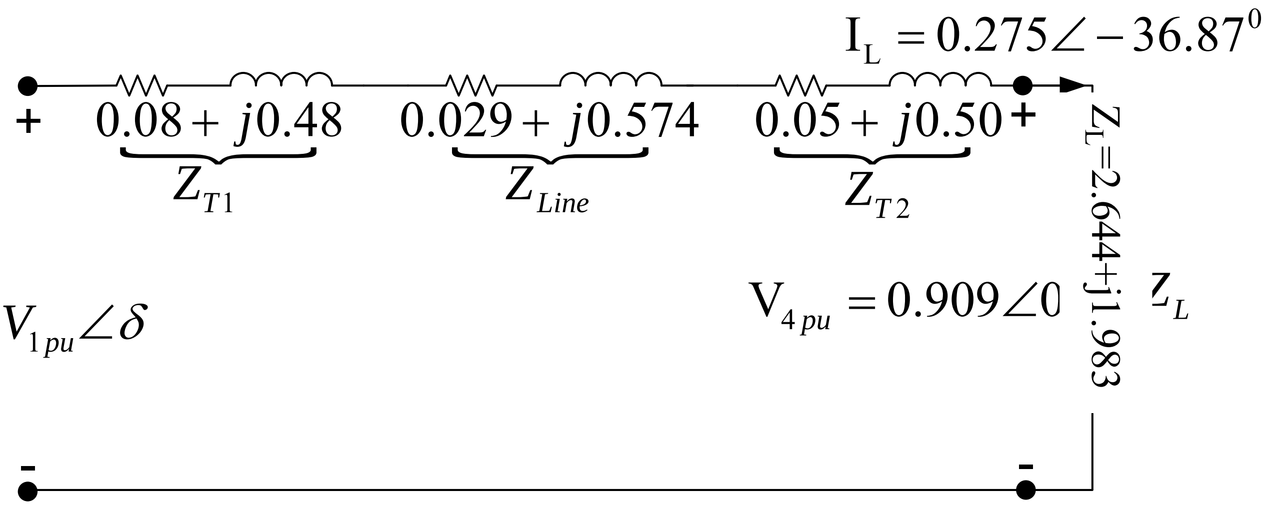
Load: S_L=40/0.8$\angle \cos^{-1}0.8$=50$\angle 36.87^o$ MVA (*power triangle)

pu load: S_{Lpu}=50/200$\angle 36.87^o$=0.25$\angle 36.87^o$ pu

pu current: I_{Lpu}= $(S_{Lpu}/ V_{4pu})^*$= 0.275 $\angle$-36.87^o ($S_{pu}=V_{pu}I_{pu}^*$)

pu load impedance: Z_{Lpu}= V_{4pu}/ I_{Lpu}=3.305$\angle 36.87^o$=2.644+j1.983

pu impedance diagram:



Tutorial 2: PU System II

2.1 The system below has the following component ratings:

G1: 12 kV, 50 MVA, X = 8%;

G2: 12 kV, 40 MVA, X = 8%

T1: 3 single-phase units, each rated 13/80kV, 15MVA, X=9%

T2: 3 single-phase units, each rated 6.9/39.8kV, 25MVA, X=8%

T3: 3 single-phase units, each rated 70/80kV, 25MVA, X=13%

T4: 12/138 kV, 80 MVA, X = 12%

L1: X=30Ω/phase;

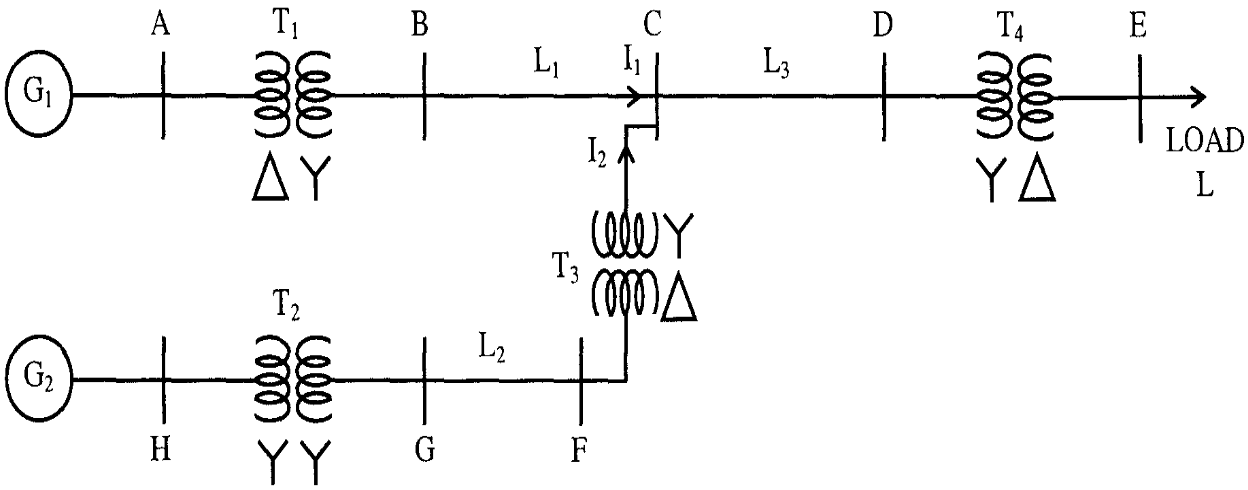
L2: X=30 Ω /phase;

L3: X=50 Ω /phase

Load: 60MW, 0.9pf lag at 11kV

a) Selecting bases of 100MVA and 140kV in L3 draw the per unit impedance diagram.

b) Assume that current phasors I_1 and I_2 are equal under the load. Calculate the magnitude of the voltage at the terminals of each generator.



Solutions:

a)

Given bases: S_{BN}=100MVA, V_{BN}=140 kV (base voltage at L3)

Step 1: Determine other base voltages(*Transformer types!)

Base voltage at buses B, C and D: $V_{BN}^{B} = V_{BN}^{C} = V_{BN}^{D} = 140kV$

Base voltage at bus A (T1: type 2 transformer):

$$T_{1ratio} = \frac{13}{\sqrt{3}\times 80} = \frac{13}{138.564}$$

$$V_{BN}^{A} = V_{BN}^{C} \times T_{1ratio} = 140 \times \frac{13}{\sqrt{3}\times 80} = 13.1347kV$$

Base voltage at bus E:

$$V_{BN}^{E} = V_{BN}^{D} \times T_{4ratio} = 140 \times \frac{12}{138} = 12.1739kV$$

Base voltage at buses F and G (T2 and T3: type 2):

$$V_{BN}^{F} = V_{BN}^{G} = V_{BN}^{C} \times T_{3ratio} = 140 \times \frac{70}{\sqrt{3}\times 80} = 70.7254kV$$

Base voltage at bus H:

$$V_{BN}^{H} = V_{BN}^{G} \times T_{2ratio} = 70.7254 \times \frac{\sqrt{3}\times 6.9}{\sqrt{3}\times 39.8} = 12.2614kV$$

Step 2: determine pu impedance

Generator pu impedances: (given old pu impedance)

$$X_{G1Npu} = Z_{G1Opu}\frac{S_{BN}}{S_{G1BO}}\left(\frac{V_{G1BO}}{V_{BN}^{A}}\right)^2 = 0.08\frac{100}{50}\left(\frac{12}{13.1347}\right)^2 = 0.1335pu$$

$$X_{G2Npu} = Z_{G2Opu}\frac{S_{BN}}{S_{G2BO}}\left(\frac{V_{G2BO}}{V_{BN}^{H}}\right)^2 = 0.08\frac{100}{40}\left(\frac{12}{12.2614}\right)^2 = 0.1916pu$$

Transformer pu impedances: (given old pu impedance)

$$\mathbf{X_{T1Npu} = Z_{T1Opu}\frac{S_{BN}}{S_{T1BO}}\left(\frac{V^{B}_{T1BO}}{V^{B}_{BN}}\right)^{2} = 0.09\frac{100}{45}\left(\frac{\sqrt{3}\times 80}{140}\right)^{2} = 0.1959pu}$$

$$\mathbf{X_{T2Npu} = Z_{T2Opu}\frac{S_{BN}}{S_{T2BO}}\left(\frac{V^{H}_{T2BO}}{V^{H}_{BN}}\right)^{2} = 0.08\frac{100}{75}\left(\frac{\sqrt{3}\times 6.9}{12.2614}\right)^{2} = 0.1013pu}$$

$$\mathbf{X_{T3Npu} = Z_{T3Opu}\frac{S_{BN}}{S_{T3BO}}\left(\frac{V^{C}_{T3BO}}{V^{C}_{BN}}\right)^{2} = 0.13\frac{100}{75}\left(\frac{\sqrt{3}\times 80}{140}\right)^{2} = 0.1698pu}$$

$$\mathbf{X_{T4Npu} = Z_{T4Opu}\frac{S_{BN}}{S_{T4BO}}\left(\frac{V^{C}_{T4BO}}{V^{C}_{BN}}\right)^{2} = 0.12\frac{100}{80}\left(\frac{138}{140}\right)^{2} = 0.1457pu}$$

Line pu impedances: (given real impedance in Ω)

Base impedance: $$\mathbf{Z_{L1B} = Z_{L3B} = \frac{\left(V^{B}_{BN}\right)^{2}}{S_{BN}} = \frac{140^{2}}{100} = 196\,\Omega}$$

$$\mathbf{X_{L1pu} = \frac{X_{L1}}{Z_{L1B}} = \frac{30}{196} = 0.1531pu}$$

$$\mathbf{X_{L3pu} = \frac{X_{L3}}{Z_{L3B}} = \frac{50}{196} = 0.2551pu}$$

Base impedance: $$\mathbf{Z_{L2B} = \frac{\left(V^{F}_{BN}\right)^{2}}{S_{BN}} = \frac{70.7254^{2}}{100} = 50.021\,\Omega}$$

$$\mathbf{X_{L2pu} = \frac{X_{L2}}{Z_{L2B}} = \frac{30}{50.021} = 0.5998pu}$$

Load pu impedance: (Given P, power factor and voltage)

$$\mathbf{V_{Lpu} = 11/V_{BN}^{E} = 11/12.1739 = 0.9036pu}$$

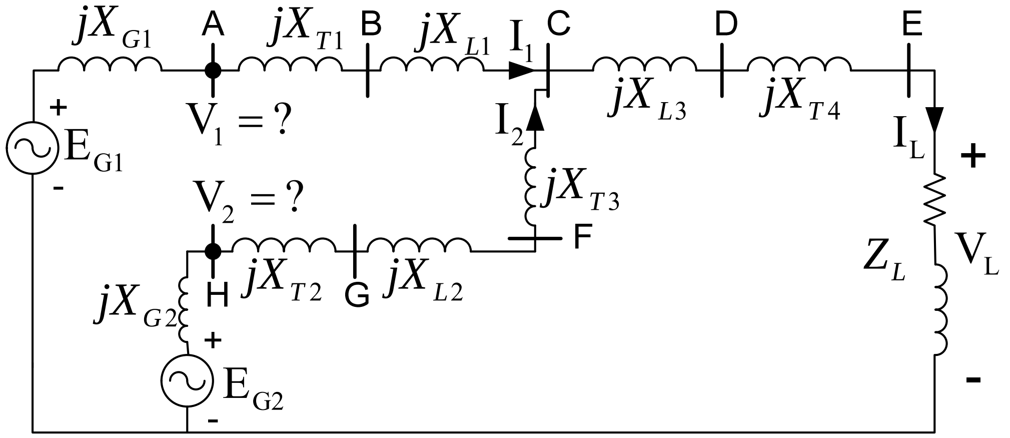
$$\mathbf{S_L = \frac{P}{pf}\angle\theta = \frac{60}{0.9}\angle\cos^{-1}0.9 = 66.6667\angle 25.8419^o\,MVA}$$

$$\mathbf{S_{Lpu} = 0.666667\angle 25.8419^o\,pu}$$

$$\mathbf{I_{Lpu} = \left(\frac{S_{Lpu}}{V_{Lpu}}\right)^* = 0.7378\angle -25.8419^o\,pu}$$

$$\mathbf{Z_{Lpu} = \frac{V_{Lpu}}{I_{Lpu}} = 1.2247\angle 25.8419^o = 1.1022 + j0.5338pu}$$

Step 3: pu impedance diagram



b): System voltage calculations:

$$\mathbf{V_{pu}^{C} = V_{Lpu} + I_{Lpu}(jX_{T4pu} + jX_{L3pu}) = 1.0662\angle 14.45^o}$$

$$\mathbf{I_{1pu} = I_{2pu} = 0.5I_{Lpu} = 0.3689\angle -25.8419^o}$$

$$\mathbf{V_{1pu} = V_{pu}^{A} = V_{pu}^{C} + I_{1pu}\times j(X_{T1pu} + X_{L1pu}) = 1.1536\angle 19.335^o\,pu}$$

$$\mathbf{V_{2pu} = V_{pu}^{H} = V_{pu}^{C} + I_{2pu}\times j(X_{T2pu} + X_{T3pu} + X_{L2pu}) = 1.2973\angle 25.34^o\,pu}$$

$$\mathbf{|V_1| = |V_{1pu}|\times V_{BN}^{A} = 15.1527kV}$$

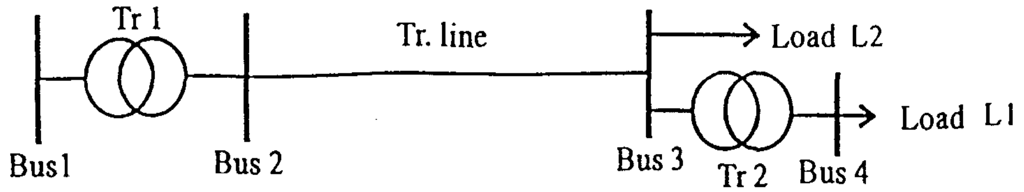
$$\mathbf{|V_2| = |V_{2pu}|\times V_{B}^{H} = 15.9066kV}$$

2.2 The system shown has the following component ratings:

Line: X = 7.2 Ω/phase; R=1.5 Ω/phase
Load L1: Y-connected R=32 Ω/phase
Load L2: 4 MW, 0.8pf lag, 22kV
T1: 10MVA, 230/22kV, Z=(2 +j8)%
T2: 5MVA, 22/12 kV, Z=(1.2 +j6)%

a) Sketch the pu impedance diagram. Assume 10MVA and 22kV as base values in the transmission line circuit.

b) If the voltage at bus 3 is maintained at 22kV, calculate the voltages at Buses 2 and 1.



Solutions:

a) Given base values: S_{BN}=10MVA, V_{2BN}=22kV at line circuit

Step1: determine other base voltages

Base voltage at buses 2 and 3: $V_{2BN} = V_{3BN} = 22\text{kV}$

Base voltage at bus 1: $V_{1BN} = V_{2BN}\dfrac{230}{22} = 230\text{kV}$

Base voltage at bus 4: $V_{4BN} = V_{3BN}\dfrac{12}{22} = 12\text{kV}$

Step2: determine new pu impedances

Transformer impedances (given old pu impedance):

T1: $Z_{T1Npu} = 0.02 + j0.08\text{pu}$ **(new bases are the same with the old)**

$$\text{T2:}\ Z_{T2Npu} = Z_{T2Opu}\frac{S_{BN}}{S_{T2BO}} = (0.012 + j0.06)\frac{10}{5} = 0.024 + j0.12\text{pu}$$

Line impedances (real impedance is given):

$$\mathbf{Z_{liB} = \frac{V_{2BN}^2}{S_{BN}} = \frac{22^2}{10} = 48.4\,\Omega}$$

$$\mathbf{Z_{llpu} = \frac{Z_l}{Z_{llB}} = \frac{1.5 + j7.2}{48.4} = 0.03099 + j0.1487pu}$$

Load impedances:
Load L1: (given real power, pf and voltage)

$$\mathbf{V_{3pu} = 22/V_{3BN} = 1pu}$$

$$\mathbf{S_{L2} = \frac{4}{0.8}\angle\cos^{-1}0.8 = 5\angle 36.87^o\,MVA = 0.5\angle 36.87^o\,pu}$$

$$\mathbf{I_{L2pu} = \left(\frac{S_{L2pu}}{V_{3pu}}\right)^* = 0.5\angle -36.87^o\,pu}$$

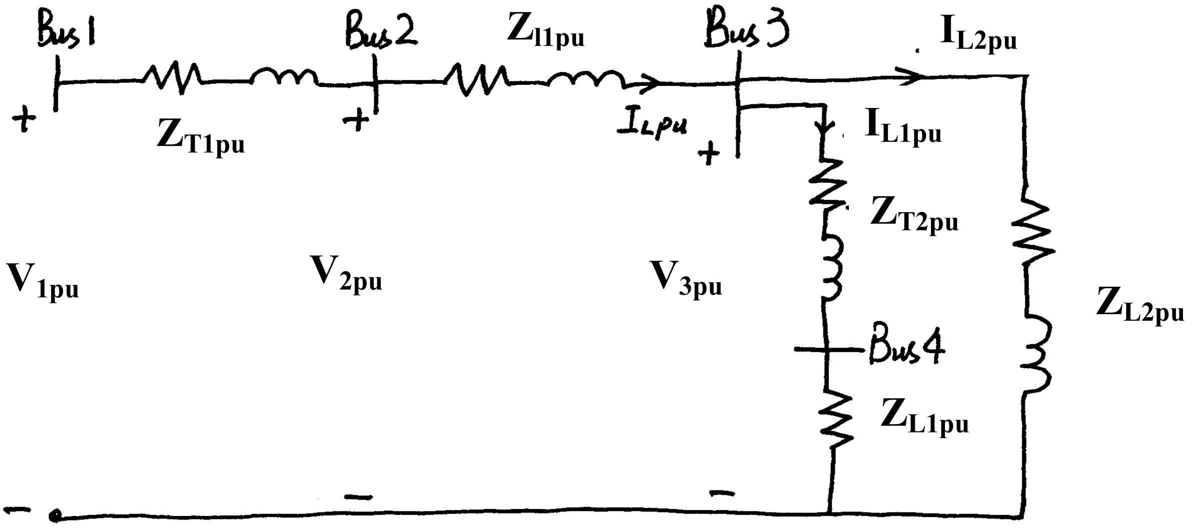
$$\mathbf{Z_{L2pu} = \frac{V_{3pu}}{I_{L2pu}} = 2\angle 36.87^o\,pu = 1.6 + j1.2pu}$$

Load L2: (given real impedance)

$$\mathbf{Z_{L1B} = \frac{V_{4BN}^2}{S_{BN}} = \frac{12^2}{10} = 14.4\,\Omega}$$

$$\mathbf{Z_{L1pu} = \frac{Z_{L1}}{Z_{L1B}} = \frac{32}{14.4} = 2.2222pu}$$

Step 3: pu impedance diagram



b) Voltage calculation

$$\mathbf{I_{L1pu}} = \frac{\mathbf{V_{3pu}}}{\mathbf{Z_{L1pu}} + \mathbf{Z_{T1pu}}} = \mathbf{0.4446\angle -3.058^{o}\,pu}$$

$$\mathbf{I_{L2pu}} = \left(\frac{\mathbf{S_{L2pu}}}{\mathbf{V_{3pu}}}\right)^{*} = \mathbf{0.5\angle -36.87^{o}\,pu\,(from\ part\ a)}$$

$$\mathbf{I_{Lpu}} = \mathbf{I_{L1pu}} + \mathbf{I_{L2pu}} = \mathbf{0.904\angle -20.985^{o}\,pu}$$

$$\mathbf{V_{2pu}} = \mathbf{V_{3pu}} + \mathbf{I_{Lpu}} \times \mathbf{Z_{llpu}} = \mathbf{1.0805\angle 6.134^{o}\,pu}$$

$$\mathbf{V_{1pu}} = \mathbf{V_{2pu}} + \mathbf{I_{Lpu}} \times \mathbf{Z_{T1pu}} = \mathbf{1.13095\angle 8.98^{o}\,pu}$$

$$\left|\mathbf{V_2}\right| = \mathbf{23.77kV}$$

$$\left|\mathbf{V_1}\right| = \mathbf{260.12kV}$$

2.3 The component ratings for the system are as follows:

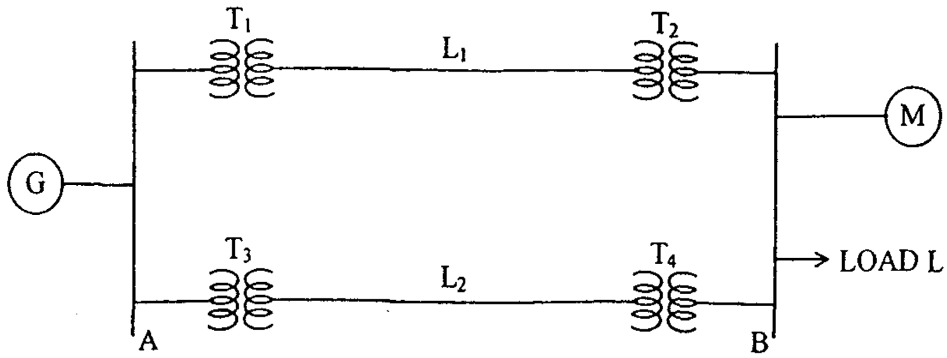
G: 90MVA, 22kV, X=18%
T1: 50MVA, 220/22kV, X=10%
T2: 40MVA, 11/220kV, X=6%
T3: 40MVA, 110/22kV, X=6.4%
T4: 40MVA, 11/110kV, X=8%
M: 66.5MVA, 10.45kV, X=18.5%
Load L: 57MVA, 0.6pf lag, 10.45kV (R & X in series)
L1: X=48.4 ohms per phase
L2: X=65.43 ohms per phase

a) Selecting a base of 100MVA and 22kV in the generator circuit, sketch the per unit impedance diagram of the system.

b) Assuming that the motor M operates at full-load 0.8 pf leading at a terminal voltage of 10.45kV, find

i) the voltage at the generator bus

ii) the generator and motor internal emfs.



Solutions:

a) pu impedance diagram

Given Bases: S_{BN}=100MVA, $V_{GBN} = 22kV$ at generator side

Step1: determine other base voltages

Base voltage at line L_1: $V_{L1BN} = V_{GBN}\dfrac{220}{22} = 220kV$

Base voltage at line L_2: $V_{L2BN} = V_{GBN}\dfrac{110}{22} = 110kV$

Base voltage at motor bus: $V_{MBN} = V_{L1BN}\dfrac{11}{220} = 11kV$

(Old and New voltage for all transformers are the same)**

Step2: determine pu impedance

Transformer pu impedances (given old pu impedance):

$$T1: Z_{T1Npu} = Z_{T1Opu}\frac{S_{BN}}{S_{T1BO}} = 0.1\frac{100}{50} = j0.2pu$$

$$T2: Z_{T2Npu} = Z_{T2Opu}\frac{S_{BN}}{S_{T2BO}} = 0.06\frac{100}{40} = j0.15pu$$

$$T3: Z_{T3Npu} = Z_{T3Opu}\frac{S_{BN}}{S_{T3BO}} = 0.064\frac{100}{40} = j0.16pu$$

$$T4: Z_{T4Npu} = Z_{T4Opu}\frac{S_{BN}}{S_{T4BO}} = 0.08\frac{100}{40} = j0.2pu$$

Generator pu impedance (given old pu impedance):

$$Z_{GNpu} = Z_{GOpu}\frac{S_{BN}}{S_{GBO}} = 0.18\frac{100}{90} = j0.2pu$$

Motor new pu impedance (given old pu impedance):

$$Z_{MNpu} = Z_{MOpu} \frac{V_{MBO}^2}{V_{MBN}^2} \frac{S_{BN}}{S_{MBO}} = 0.185 \frac{10.45^2}{11^2} \frac{100}{66.5} = j0.251pu$$

Line pu impedances (given real impedance):

$$\text{L1: } Z_{L1B} = \frac{V_{L1BN}^2}{S_{BN}} = \frac{220^2}{100} = 484\,\Omega$$

$$Z_{L1Npu} = \frac{Z_{L1}}{Z_{L1B}} = j\frac{48.4}{484} = j0.1pu$$

$$\text{L2: } Z_{L2B} = \frac{V_{L2BN}^2}{S_{BN}} = \frac{110^2}{100} = 121\,\Omega$$

$$Z_{L2Npu} = \frac{Z_{L2}}{Z_{L2B}} = j\frac{65.43}{121} = j0.541pu$$

Load pu impedance (given real power, pf and voltage):

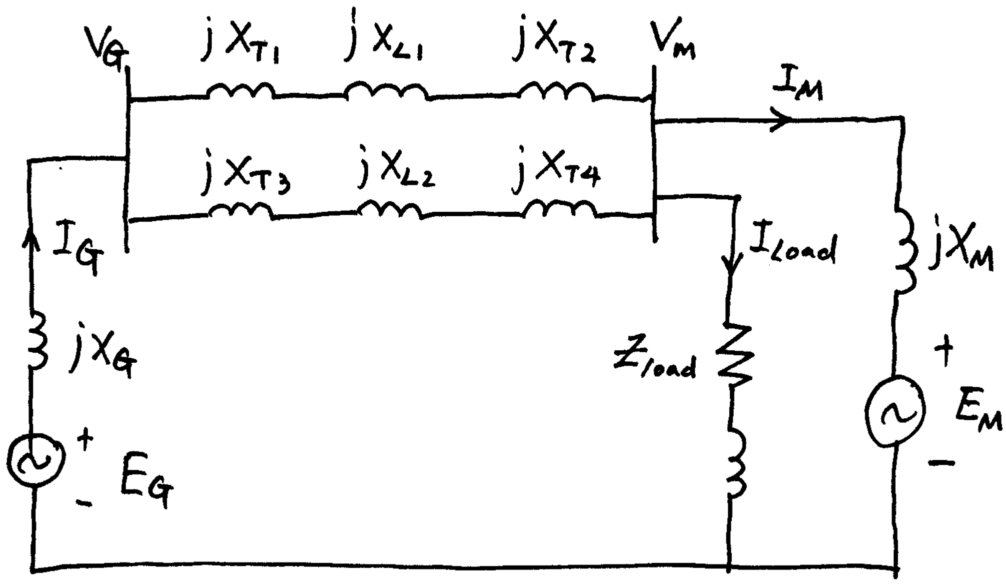
$$S_{loadpu} = \frac{57}{100}\angle\cos^{-1}0.6 = 0.57\angle 53.13^{o}\,pu$$

$$V_{Mpu} = V_{loadpu} = \frac{V_M}{V_{BMN}} = \frac{10.45}{11} = 0.95\angle 0^{o}\,pu$$

$$I_{loadpu} = \left(\frac{S_{loadpu}}{V_{Mpu}}\right)^{*} = 0.6\angle -53.13^{o}\,pu$$

$$Z_{loadpu} = \frac{V_{loadpu}}{I_{loadpu}} = 1.583\angle 53.13^{o} = 0.9498 + j1.2664pu$$

Step 3: pu impedance diagram:



b) Voltage calculations

$$\mathbf{V_{Mpu} = \frac{V_M}{V_{BMN}} = \frac{10.45}{11} = 0.95\angle 0^o\,pu}$$

$$\mathbf{S_{Mpu} = \frac{66.5}{100}\angle -\cos^{-1}0.8 = 0.665\angle -36.87^o\,pu}$$

$$\mathbf{I_{Mpu} = \left(\frac{S_{Mpu}}{V_{Mpu}}\right)^* = 0.7\angle 36.87^o\,pu}$$

$$\mathbf{I_{Gpu} = I_{Mpu} + I_{loadpu} = 0.9219\angle -3.73^o\,pu}$$

$$\mathbf{V_{Gpu} = V_{Mpu} + I_{Gpu} \times j(X_{T1pu} + X_{L1pu} + X_{T2pu})//j(X_{T1pu} + X_{L1pu} + X_{T2pu})}$$

$$\mathbf{= 1.0066\angle 15.917^o\,pu}$$

$$\mathbf{E_{Gpu} = V_{Gpu} + I_{Gpu} \times jX_{Gpu} = 1.0826\angle 25.15^o\,pu}$$

$$\mathbf{E_{Mpu} = V_{Mpu} - I_{Mpu} \times jX_{Mpu} = 1.065\angle -7.589^o\,pu}$$

Summary

Basic Values and equations in per unit system:

Base MVA $S_{B3\text{-}\Phi} = S_B$ (<u>Only select one</u> for an entire system)

Base voltage $V_{BL\text{-}L} = V_B$ (<u>different at two sides</u> of a transformer)
Select V_B at one side of transformer.
Calculate others: $V_{B2} = T_{ratio} \times V_{B1}$ $\quad T_{ratio} = V_{B2rated} / V_{B1rated}$.

$$\mathbf{S_B} = \sqrt{3}\mathbf{V}_B \times \boldsymbol{I}_B^*$$

Base Current (phase): $\mathbf{I_B^*} = \mathbf{S}_B / \left(\sqrt{3}\boldsymbol{V}_B\right)$

Base impedance $\mathbf{Z_B} = \dfrac{\mathbf{V}_{B\Phi}}{\boldsymbol{I}_B} = \dfrac{\boldsymbol{V}_B^2}{\boldsymbol{S}_B}$ **(per phase)**

Per unit values:

$S_{pu} = S/S_B$; $V_{pu} = V/V_B$; $I_{pu} = I/I_B$;

$S_{pu} = V_{pu} I_{pu}^*$; $Z_{pu} = V_{pu}/I_{pu}$

Given real impedance (absolute value) $Z(\Omega)$:
pu impedance: $Z_{pu} = Z(\Omega)/Z_B(\Omega)$;

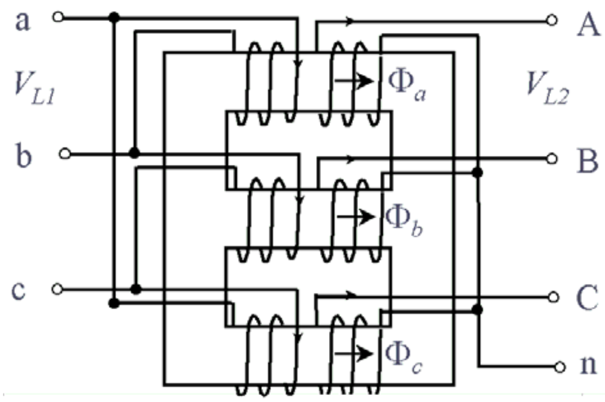
Given pu impedance (Z_{Opu}) based on rated S_{BO} and rated voltage V_{BO}:
New pu impedance Z_{Npu} based on new S_{BN} and new V_{BN}:

$$\mathbf{Z_{Npu}} == \frac{\mathbf{V_{BO}^2}}{\mathbf{V_{BN}^2}} \frac{\mathbf{S_{BN}}}{\mathbf{S_{BO}}} \mathbf{Z_{Opu}}$$

Given power and power factor and voltage?
Find S using power triangle and power factor
Find Spu $\Rightarrow$ Find $V_{pu} \Rightarrow$ Find $I_{pu} = (S_{pu}/V_{pu}) \Rightarrow$ Find $Z_{pu} = V_{pu}/I_{pu}$

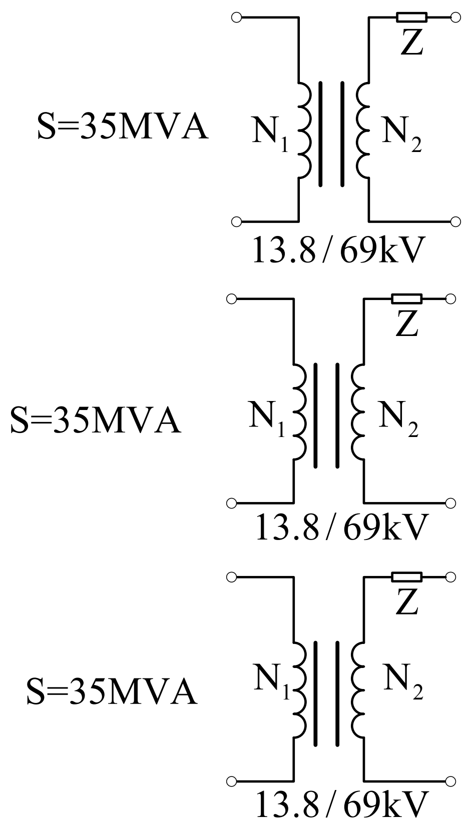
Two types of three-phase transformers:

a) A Δ/Y connected transformer (<u>in a 3-phase unit Type 1</u>)

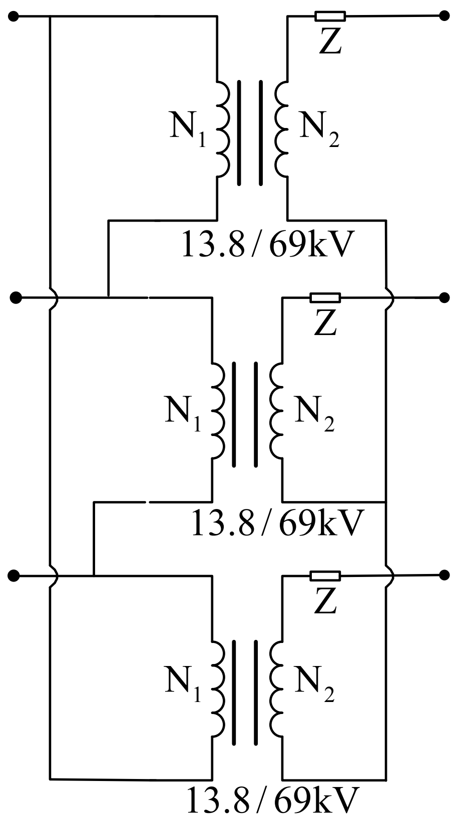


Line to line voltage ratio are given!!!

b) A transformer (constructed by <u>three single-phase units Type 2</u>)



Three single-phase transformers



Δ/Y connection

Line to line voltage ratio $= 13.8\text{kV} / (69\sqrt{3})\text{k}$

S=3×35=115MVA