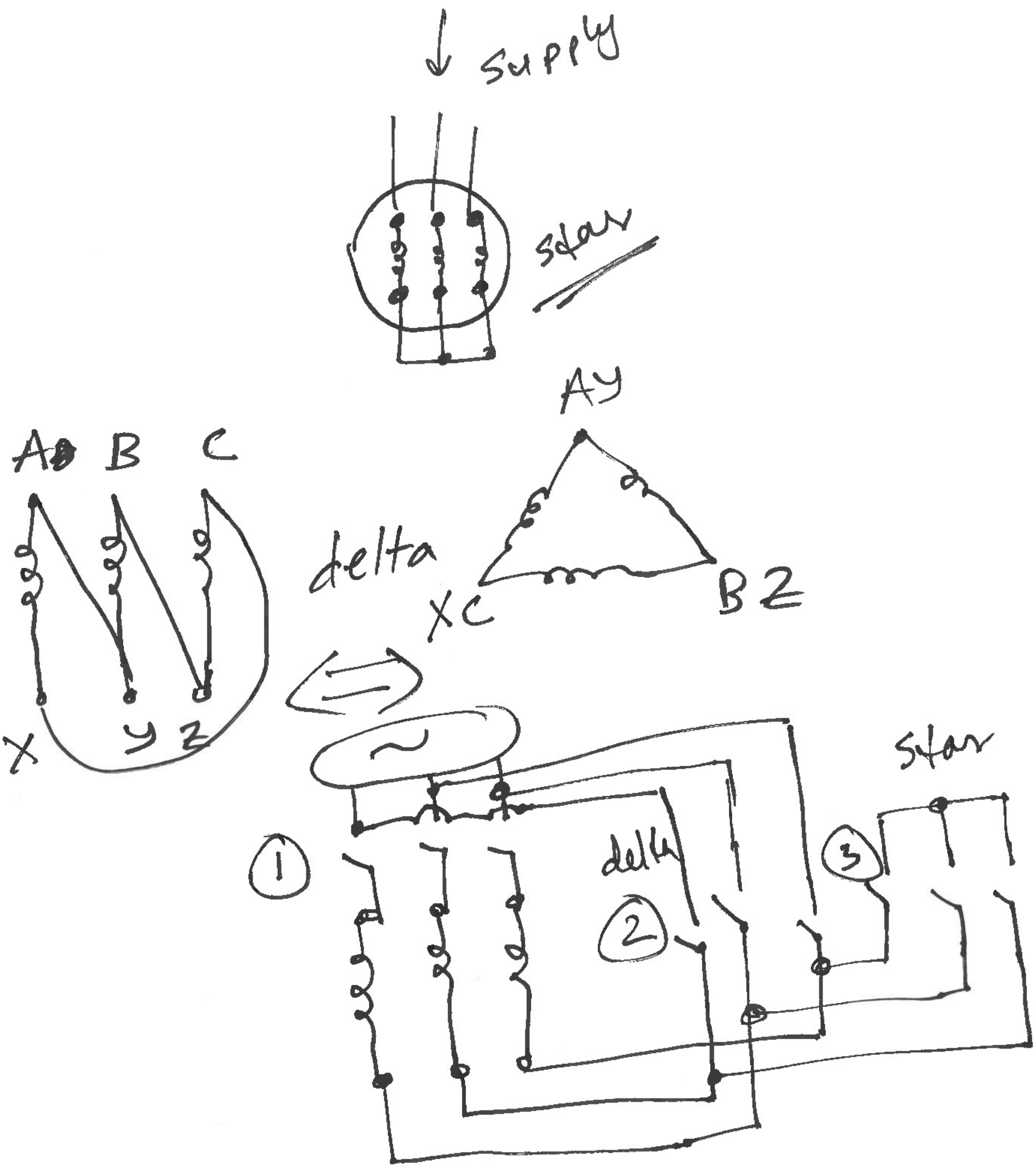
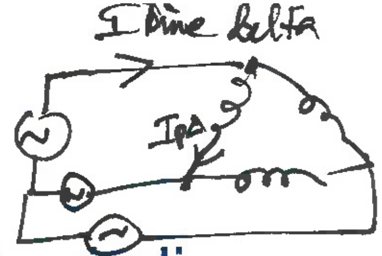

Supply
star
A B C
X Y Z
delta
A Y
X C
B Z
star
delta
1
2
3

(2)

Motor-Starting Methods



- Without this starter, the motor will be turned on with winding connected in delta

$\Delta \Rightarrow I_{Line} = \sqrt{3} I_{\phi}$

$$I_{start-delta} = I_{line-delta} = \sqrt{3} \overbrace{I_{phase-delta}}^{I_{\phi\Delta}} = \frac{\sqrt{3}V_{line-to-line}}{Z_{motor}}$$

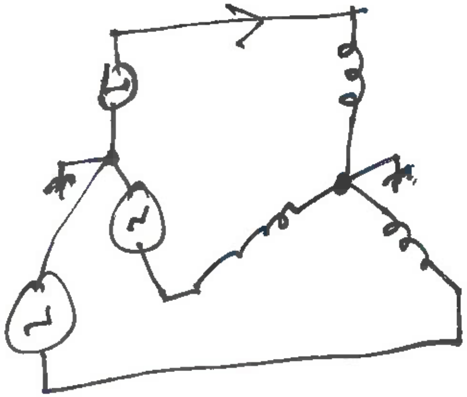
$$\frac{I_{start-delta}}{\sqrt{3}} = \frac{V_{LL}}{Z_{motor}}$$

- With delta-wye starter, the motor winding is connected in wye at starting

$V_{\phi} = \frac{V_{Line}}{\sqrt{3}}$

$$I_{start-wye} = I_{phase-wye} = \frac{V_{phase}}{Z_{motor}} = \frac{V_{line-to-line}/\sqrt{3}}{Z_{motor}}$$

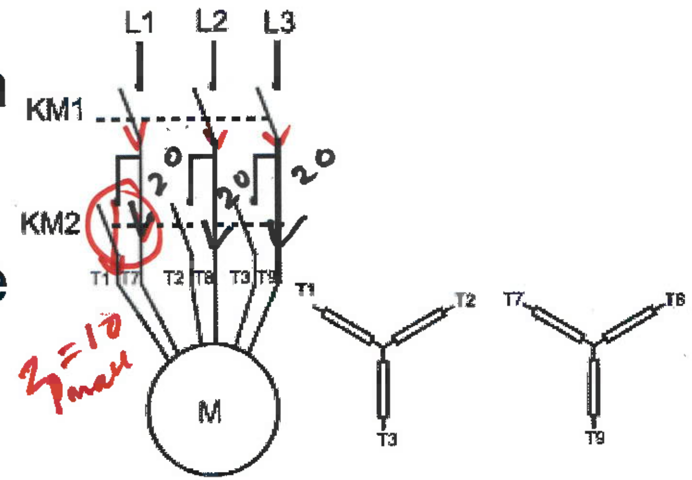
$$I_{start-wye} = \frac{I_{start-delta}}{\sqrt{3}\sqrt{3}} = \frac{I_{start-delta}}{3}$$



$$\therefore \frac{I_{start-wye}}{I_{start-delta}} = \frac{1}{3} \Rightarrow \beta_{start-wye} = \frac{\beta_{start-delta}}{3}$$

Motor-Starting Methods

- Part-Winding starter
  - ✓ Attractive for use with dual-rated motors (220/440 V or 230/460 V) (equivalent to two small motors with each half of motor ratings)
  - ✓ Stator has two windings that can be connected in parallel or series
  - ✓ Only one winding is connected at starting to limit starting current
  - ✓ Second winding is only connected after the motor has sped up and therefore, the inrush current would be small



lets assume initially when KM2 is OFF & KM1 is ON - The Impedance is 20 Ω

ONCE The motor has speed up KM2 is ON & the total impedance is 10 Ω

4 $1\,MVA = 1000\,kVA$

$\eta = \frac{S_{out}}{S_{in}} \Rightarrow S_{in} = \frac{S_{out}}{\eta}$

Exercise

- Example – An 50-kW, 0.8 p.f., 90% efficiency induction motor is started from a 11kV supply with 1 MVA short circuit capacity. The motor starting current is six times the nominal or full-load current. Calculate the amount of voltage sag at starting.

$P_{motor} = S_m \cos\phi$ ($\cos\phi = 0.8$)

$$S_{motor} = \frac{50\,\text{kW}}{0.8 \times 0.9} = 69.44\,\text{kVA}$$

$V_{sag} = \frac{S_{source}}{S_{source} + \beta S_{motor}}$

$$V_{sag} = \frac{1000\ \text{kVA}}{1000 + 6 \times 69.44} = 0.706 = 70.6\,\% \quad \Rightarrow \quad \Delta V = 1 - V_{sag} = 29.4\%$$

- If the motor is fed through a dedicated 33/11kV transformer of the same power rating as the motor and with a leakage impedance of 10%. Assuming that the short circuit capacity at PCC remains unchanged,

ε

$V_{sag} = \frac{(1+\beta\varepsilon)\,S_{source}}{(1+\beta\varepsilon)\,S_{source} + \beta S_{motor}}$

$$V_{sag} = \frac{(1 + \underbrace{6}_{\beta} \times \underbrace{0.1}_{\varepsilon}) \times 1000}{(1 + \underbrace{6}_{\beta} \times \underbrace{0.1}_{\varepsilon}) \times 1000 + 6 \times 69.44} = 0.793 = 79.3\,\%$$

$$\Rightarrow \quad \Delta V = 1 - V_{sag} = 20.7\%$$

5

Exercise

- If delta-star starter is used instead,

$$V_{sag} = \frac{1000}{1000+(6/3)\times 69.44} = 0.878 = 87.8\,\%$$

$$\Delta V = 1 - V_{sag} = 12.2\%$$

6

Minimum SCC to Maintain Voltage

- Employing specific motor-starting method alone may not be sufficient to solve the problem as the voltage may still remain low.
  - ✓ What is needed is a stronger supply, also termed higher short circuit ratio (see page 31)
  - ✓ To limit the voltage drop at the motor terminal to V_{min}, the source strength needs to be (assuming the desirable voltage is 1 pu, set $V_{sag} = V_{min}$ shown on page 9):

$$S_{source} = \beta S_{motor} \times \frac{V_{min}}{1 - V_{min}}$$

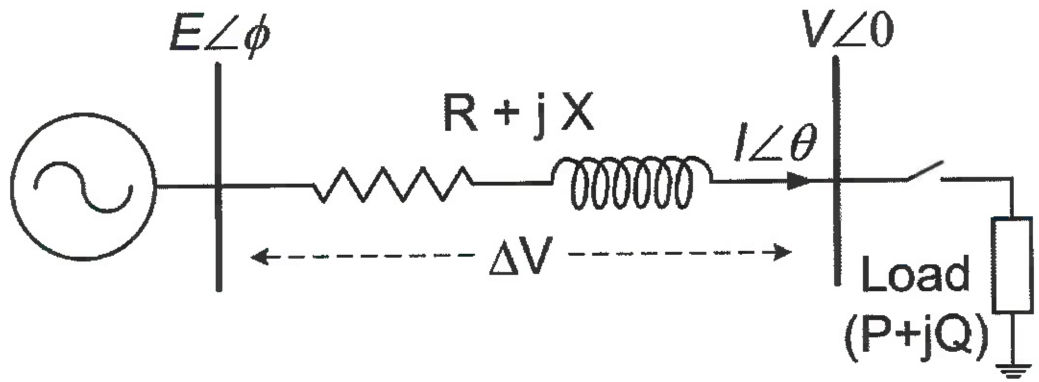
$V_{sag} = V_{min}$

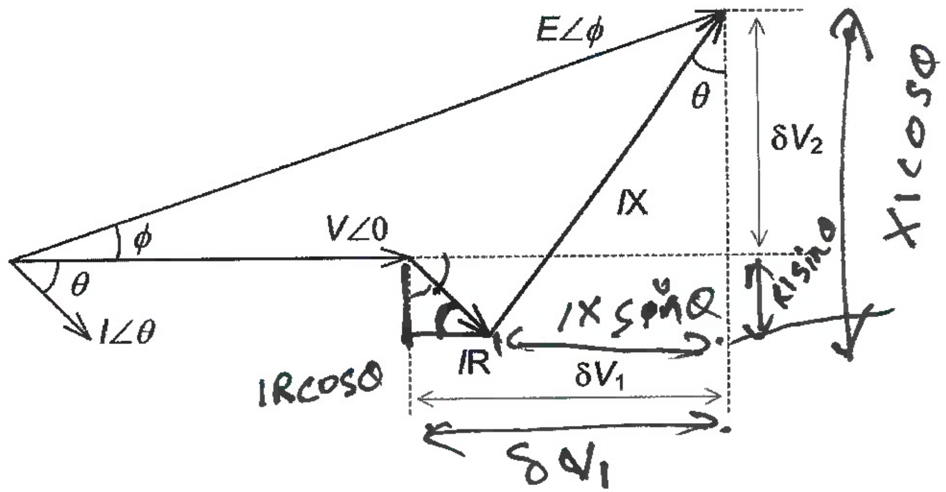
$$V_{sag} = \frac{S_{source}}{S_{source} + \beta S_{motor}}$$

$$V_{min} = \frac{S_{source}}{S_{source} + \beta S_{motor}}$$

(7)

System Voltage Response





- Before switch is closed, V=E
- When switch is closed, there is a sudden increase in the flow of power and current to the load
  - ✓ Drop in voltage magnitude and shift in voltage phase angle as load current flows through the system impedance

$$E^2 = (V + \delta V_1)^2 + \delta V_2{}^2$$

$$E^2 = (V + RIcos\theta + XIsin\theta)^2 + (XIcos\theta - RIsin\theta)^2$$

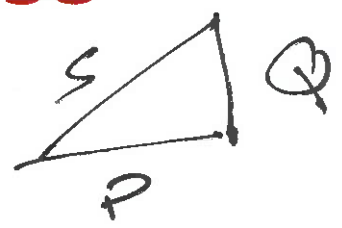
$$E^2 = (V + RIcos\theta + XIsin\theta)^2$$

$$E = V + RIcos\theta + XIsin\theta$$

Last expression is approximate: valid for small shift in voltage angle delta

(8)

System Voltage Response



$$E = V + RIcos\theta + XIsin\theta$$

$$E = V + \frac{\cancel{R}VIcos\theta}{V} + \frac{\cancel{X}VIsin\theta}{V} \quad Q$$

$$E = V + \frac{RP}{V} + \frac{XQ}{V}$$

note: $\begin{Bmatrix} P = VIcos\theta \\ Q = VIsin\theta \end{Bmatrix}$

- Energizing the load results in a change in load terminal voltage ΔV of

$$\Delta V \approx E - V = \frac{RP}{V} + \frac{XQ}{V} = \frac{RP+XQ}{V} = \frac{XQ}{V} \text{ for } X \gg R$$

$\downarrow \Delta V = \frac{Q}{S_{cc}} \uparrow$

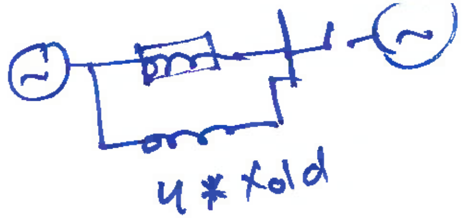
$$\frac{\Delta V}{V} \approx \frac{XQ}{V^2} = \frac{Q}{V^2/X} = \frac{Q}{S_{SCC}} \text{ as } S_{SCC} = \frac{V^2}{X}$$

$\frac{\Delta V}{V} = \frac{Q}{S_{cc}}$

✓ where Δ V / V is the percentage voltage variation at load terminal

✓ The amount of change in voltage magnitude can be estimated by comparing the load reactive demand against system short circuit capacity

Exercise



9

- A single-phase 200kW induction motor, rated with full load efficiency of 90% and power factor of 0.85 lagging, has a starting current, which is 6 times its full load value. The voltage dip at the motor terminals during motor starting is 30%.
- In order to enhance the security of supply to the motor, a second incoming source with a source impedance 4 times the source impedance of the original supply is connected.

a) Find the short circuit capacity at the motor terminals before and after the supply reinforcement

b) After the enforcement, determine the amount of voltage variations at the motor terminals when the motor is switched on and switched off

10

Exercise

Solution (a)

Before Reinforcement

Induction motor capacity, P=200kW (1ph)

Rated full-load efficiency,η =90%

Rated power factor = 0.85

Since S = VphxIph

Therefore Iph = S/(Vph)

Since motor starting current is 6 times of its full load value, therefore

Iph(starting) = 6 x Iph = (6x200x1000)/(0.85 x 0.90 x Vph)

Where S=P/(eff x pf)

Since ΔV=Q/SCC

Assuming starting current is purely reactive

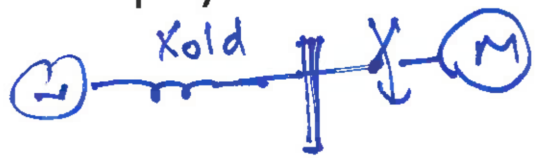
(i.e. Sstarting = 0+jQstarting)

ΔV=Vph x Iph(starting)/SCC

$\eta = \frac{S_{out}}{S_{in}}$

$S_{in} = \frac{S_{out}}{\eta}$

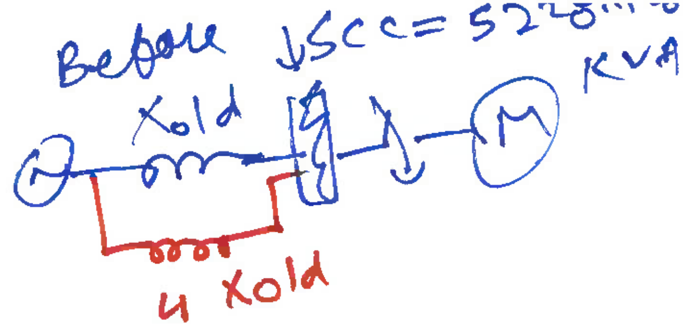
$P = \underbrace{|V_p I_p|}_{S} \cos\phi$



$S_{start} = \cancel{P}^{\,0} + j\,Q_{starting}$

(11)

Exercise



Given ΔV = 30%

SCC= $\cancel{V_{ph}}$ x 6 x 200 x 1000/(0.85 x 0.90 x $\cancel{V_{ph}}$ x 0.3) = 5228.758kVA (1 Ph)

$Scc = \frac{1}{X}$

After Reinforcement

X_{old} = 1/ SCC_{old} = 1/5228.75=0.1913μΩ

X_{new}= [4 x $(X_{old})^2$]/(5x X_{old})=4 x X_{old}/5

SCC_{new}=1/ X_{new}=$\cancel{7}$ 5/($\cancel{6}$ 4 x X_{old})= 5 /(4 x 0.1913 x 10^{-6})=6534.24kVA (1 Ph)

$\frac{1}{X_{new}} = \frac{1}{X_{old}} + \frac{1}{4X_{old}}$

$\frac{1}{X_{new}} = \frac{4+1}{4X_{old}}$

$X_{new} = \frac{4X_{old}}{5}$

$Scc_{new} = \frac{1}{X_{new}} = \frac{5}{4X_{old}}$

12

Exercise

b) When the motor is switched on,

$\Delta V = Q/SCC = [V_{ph} \times 6 \times 200 \times 1000/(0.85 \times 0.9 \times V_{ph} \times 6534.24 \times 1000)] \times 100$

$\Delta V = 24\%$ (DIP)

When motor is switched off,

The motor reactive power changes from rated Q to 0, during this time

$Q_{rated} = 200 \times 1000 \times \sin(\cos^{-1}(0.85)) / (0.9 \times 0.85) \approx 137.721\text{kVAr}$

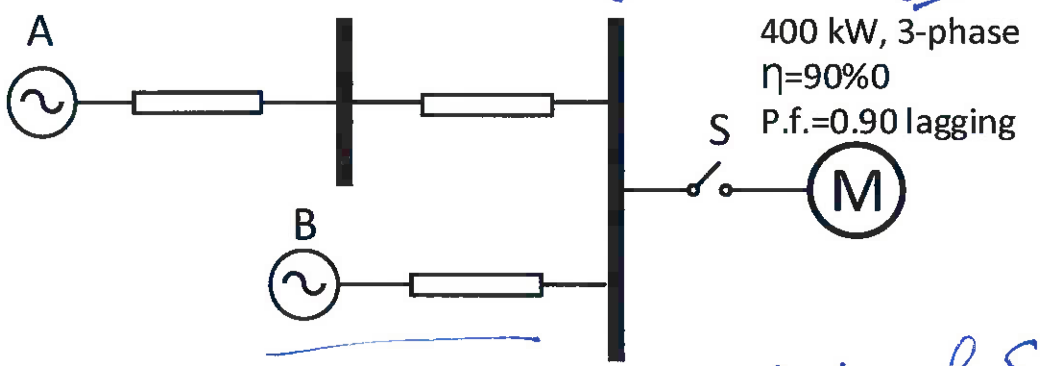
$\Delta V = Q/SCC = 137.721 \times 1000 \times 100 / (6534.24 \times 1000) \approx 2.1\%$ (Swell)

13

Two sources A and B supply an induction motor shown in Figure. The short circuit capacity is 10000 kVA and the voltage dip during the motor start is 0.3. The voltage dip during the motor starting is thrice when source B is taken out.

Calculate the short circuit capacity at the bus connected to the motor M in the absence of source B.

↓ 10000kVA
0.3



$$\Delta V = \frac{\beta S_{motor}}{S_{cc}}$$

Solution:

(i) Overall voltage dip, $\Delta V = \beta\, S_{motor}/10000$

Voltage dip when source B is taken out, $\Delta V_A = \beta\, S_{motor}/S_A$

$$\Delta V = \frac{\beta S_{motor}}{10000\text{kVA}}$$

$\Delta V_A/\Delta V = 3 = 10000/S_A$

Therefore, SCC in absence of source B, $S_A = 10000/3 = 3333.3$kVA

$$\Delta V_A = \frac{\beta S_{motor}}{S}$$

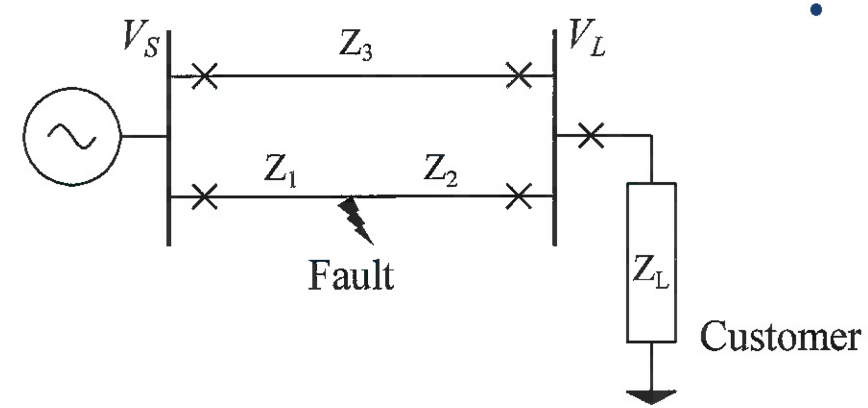
$$\frac{\Delta V_A}{\Delta V} = \frac{3\cancel{\Delta V}}{\cancel{\Delta V}} = \frac{\dfrac{\cancel{\beta S_{motor}}}{\cancel{10000\text{kVA}}\, S}}{\dfrac{\cancel{\beta S_{mo}}}{10000\text{kVA}}}$$

$$3 = \frac{10000\text{kVA}}{S_A}$$

$$S_A = \frac{10000\text{k}}{3} = 3333.3\ \text{kVA}$$

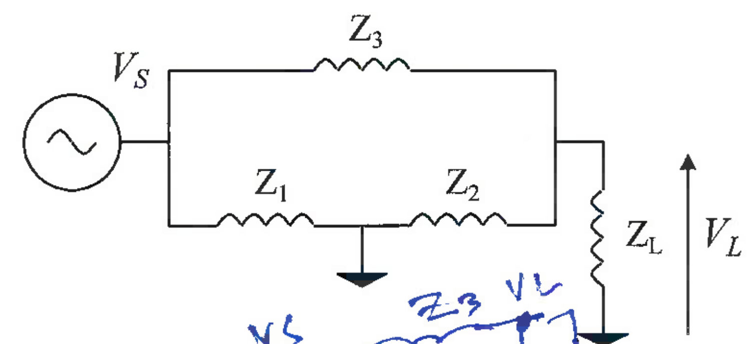
Voltage sags caused by system faults

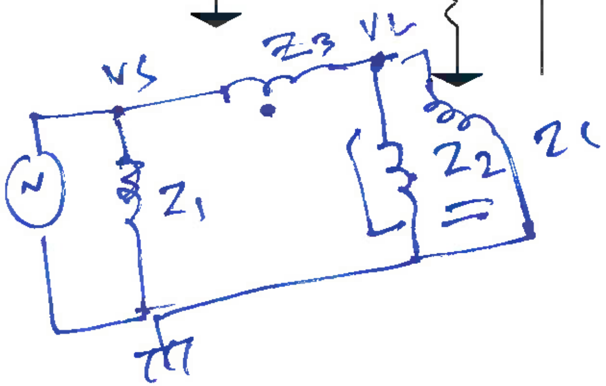
System connection



- Fault occurs on the transmission or distribution system such as a cable fault

Equivalent circuit during fault





- In general, Z_1, Z_2 and $Z_3 << Z_L$

$$V_L = V_S \times \frac{Z_2}{Z_3 + Z_2}$$

$$V_L = \frac{Z_2}{Z_2 \times Z_3} * V_S$$

2. In Figure 2, the radial distribution consist of three-phase supply system is shown, the short circuit capacity (SCC) of the source is 2 MVA. Bus A is connected with sensitive loads and a transformer of 100 kVA, X=4%. Bus B is connected with sensitive loads and a transformer of 75 kVA, X=3%. A three-phase fault occurs at Bus C.

   a) Calculate the SCC at **Bus B** and **Bus C**, **Assuming base power of 50 kVA.**

   b) What is the percentage of voltage dip experienced by the sensitive loads connected to **Bus A** and **Bus B**, in the event of a three-phase fault occurring at **Bus C**?

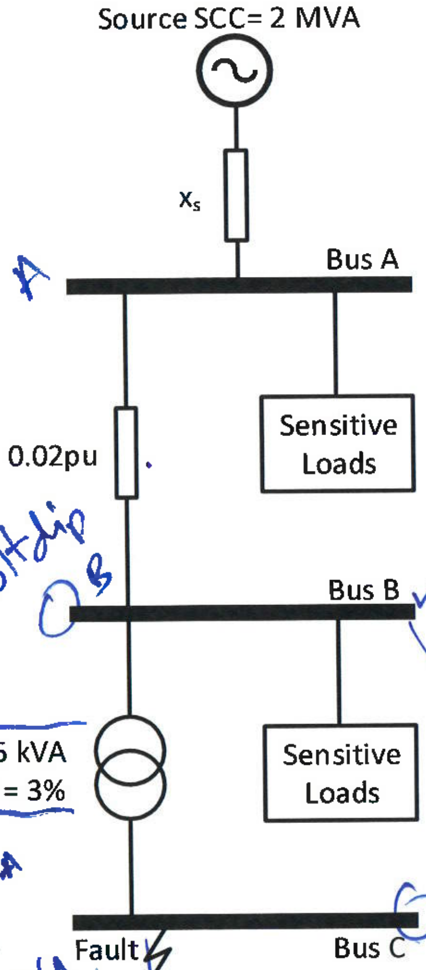


Figure 2

$X_{sc} = \frac{1}{Sc} = \frac{1}{\frac{2\,MVA}{50\,kVA}}$

$X_{sc} = \frac{50\,kVA}{2\,MVA}$

$X_{sc} = 0.025$

$X_{tran} = \frac{0.03 \times 1}{\frac{75\,kVA}{50\,kVA}}$

$X_{tran} = \frac{0.03 \times 50\,kVA}{75\,kVA}$

$X_{tran} = 0.02$ p.u

$Scc_{Bus\,C} = \frac{1}{X_s + \cancel{0.04}}$

0.02

$Scc_C = \frac{1}{\cancel{X_s} + 0.02 + 0.02}$

0.025

$= \frac{1}{0.025 + 0.02 + 0.02}$

15.4 pu

$Scc_B = \frac{1}{0.02 + 0.025}$

$Scc_B = 22.2\,pu$

(i) $S_{base} = 50$ kVA

$SCC_{A,pu} = 2000kVA/50kVA = 40$ pu.

$X_{s,pu} = 1/ SCC_{A,pu} = 1/40 = 0.025pu$

$X_{A,pu} = 0.02$ pu

$X_{Btrans,pu}=0.03*50\ kVA/75kVA = 0.02$ pu

$SCC_{B,pu}=1/ (X_{s,pu}+ X_{A,pu})=\cancel{1/(0.025+0.02)\approx 22.2pu}$

$SCC_{C,pu}=1/ (X_{s,pu}+ X_{A,pu}+ X_{Btrans,pu})=1/(0.025+0.02+0.02)\approx 15.4pu$

(ii) $V_A = (X_{A,pu} + X_{Btrans,pu})/(X_{A,pu} + X_{Btrans,pu}+ X_{s,pu})$

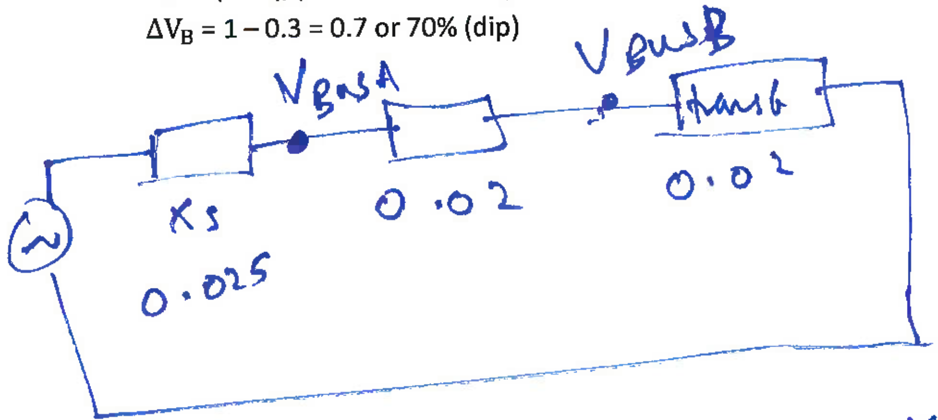
$VA = (0.02+0.02)/(0.025+0.02+0.02) \approx 0.6$

$\Delta V_A = 1 - 0.6 = 0.4$ or 40% (dip)

$VB = (X_{Btrans,pu})/(X_{A,pu} + X_{Btrans,pu}+ X_{s,pu})$

$V_B = (0.02)/(0.025+0.02+0.02) \approx 0.3$

$\Delta V_B = 1 - 0.3 = 0.7$ or 70% (dip)



$$V_{BusA} = \frac{0.02+0.02}{0.02+0.02+0.5} * 1 = 0.6$$

$$\Delta V_A = 1 - 0.6 = 40\%$$

$$V_{BusB} = \frac{0.02}{0.02+0.02+0.025} * 1 = 0.3$$

$$\Delta V_{busB} = 1 - V_{BusB} = 70\%.$$