PIE Tech

POLLACHI INSTITUTE OF ENGINEERING AND TECHNOLOGY

(Approved by **AICTE** and Affiliated to **Anna University**)

sky is the limit

Department of Electrical and Electronics Engineering

Regulation 2021

III Year – V Semester

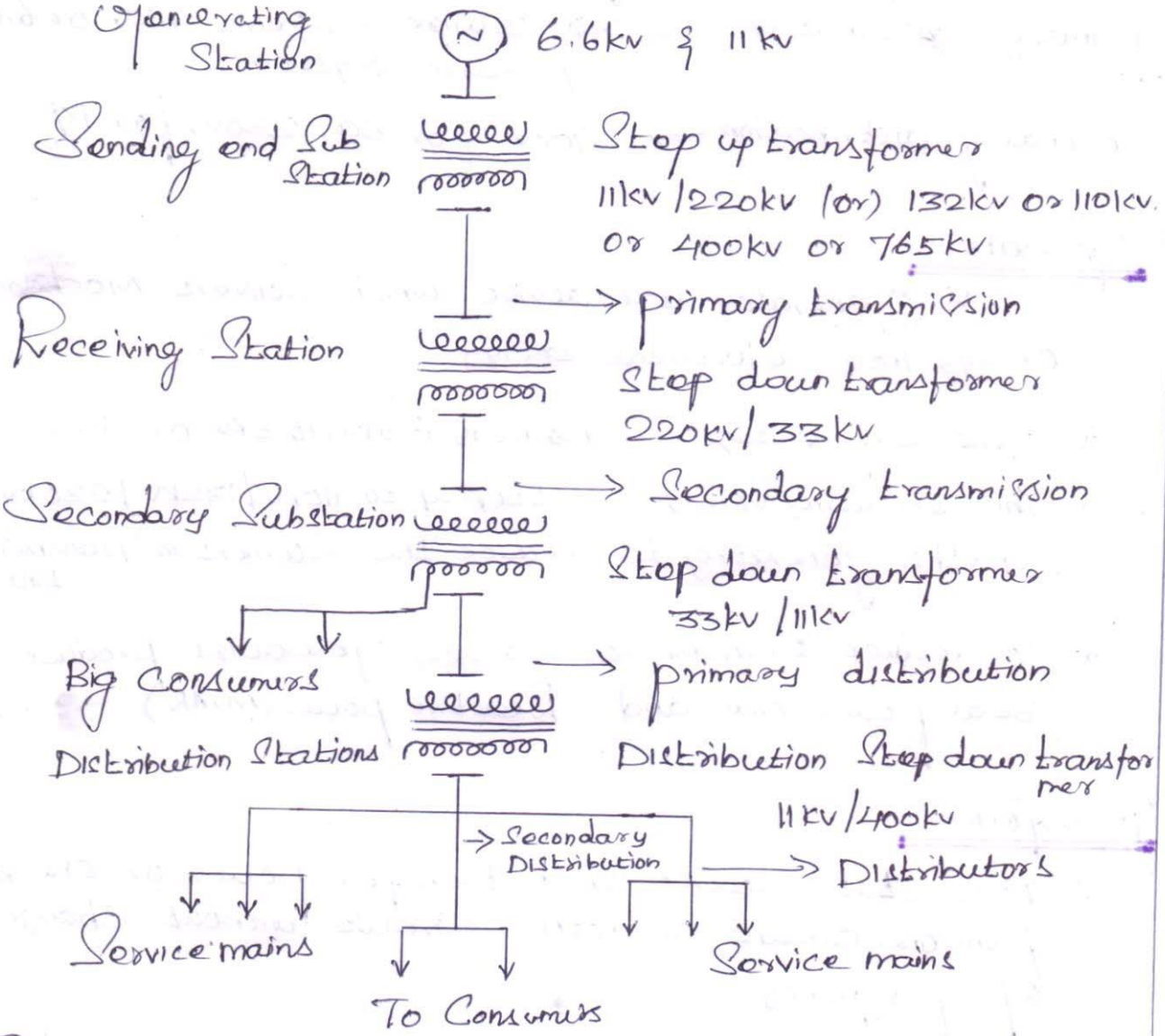
EE3501- Power System Analysis

Power System Analysis

Unit - Introduction

Part - B

① Explain Structure of modern power system with neat Sketch



Components of an Electric power System

* Generators → A device used to Convert one form of Energy into electrical energy
* Transformer → Transfer power (or) energy from one Circuit to other without change of frequency
* Transmission Lines → Transfer power from one Location to another.

Primary Transmission → 110kv, 132kv or 220kv or 400kv or 765kv high voltage Transmission 3φ 3 wire System.

Secondary Transmission → 3φ 3 wire System 33kv or 66kv feeders are used

primary distribution → 3φ 3 wire System, 11kv or 6.6kv 3φ 3 wire System

Secondary distribution → 400v for 3φ, 230v, for 1φ

Generators

* Generator is a device which Convert Mechanical energy into electrical energy.

* Generating voltage are normaly 6.6kv, 10.5kv (or) 11kv
* This generating voltage is Step up to 110kv / 132kv / 220kv at the generating to reduce the Current in Transmission Line
* To reduce transmission Losses, Generators produce real power (MW) and Reactive power (MVAR)

Transformers

* It is Static device which transfer power or energy from one circuit to another Circuit without change of frequency
* Main function of transformer are Step up voltage from the Lower generation level to the higher transmission voltage
* When we are increasing the transmission voltage, Current flowing through grid decreases, there by transmission Losses (I^2R) reduces.

Control Equipments

Circuit breaker: CB are used for opening or closing a circuit breaker under normal and abnormal fault conditions.

Isolators: Isolators are placed in Substations to isolate a part of system during maintenance.

Busbar: Busbar are used to Connect number of Line operating at the same voltage electrically.

It is made up Copper (or) aluminium,

Transmission System

* It Supplies only Large blocks of power to bulk power Station (or) very big Consumers.
* It interconnect the neighbouring generating Stations in to a power pool.
* Inter connection of two or more generating Stations.

primary Transmission

* Generated power is transmitted through transmission Line without stepping up the generated voltage
* The Line Current and powerLoss very high.
* Generated voltage is stepped up to higher value by using Step up transformer Located in Substation known as Sending end Substations to the receiving end Substations.

Secondary Transmission

* Receiving end Substation, the voltage is stepped down to value of 66 or 33 or 22kv using Step down transformers.
* It uses 3φ, 3 wire System and the Conductors used are called as feeders.

Distribution System

* The Component of an electrical power System Connecting all the Consumers in an area to the bulk power.
* A distribution Station distributes the power to domestic Commercial and relatively Small Consumers.
* It Can be divided into primary and Secondary distribution System.

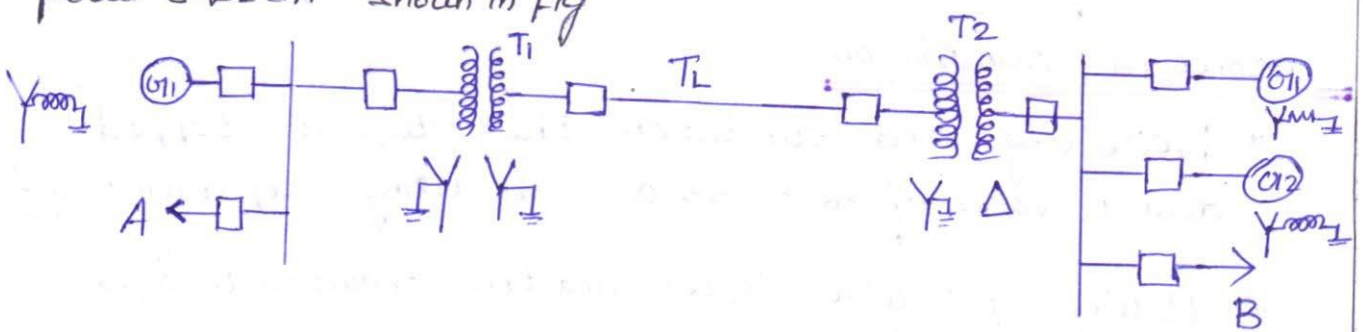
primary Distribution

* At the Secondary Substations, the voltage is Stepped down to 11kv or 6.6kv using Step down transformers.
* The primary distributors forms the link between Secondary Substations and distribution Substation.
* power is fed into the primary distribution System It uses 3ϕ, 3wire System.

Secondary Distribution

* At the distribution Substations the voltage is Stepped down to 400V, for (3ϕ) (or) 230V (1ϕ) using Stepdown transformers.
* It uses 3ϕ, 4wire System, Single phase Loads are Connected between one phase wire one neutral wire.

(2.) Obtain the per unit impedance and Reactance diagram for the power System Shown in fig



(4)

Generator no 1: 30 MVA 10.5 kV $x'' = 1.6$ ohm

Generator no 2: 15 MVA 6.6 kV $x'' = 1.2$ ohm

Generator no 3: 25 MVA 6.6 kV $x'' = 0.56$ ohm

Transformer T_1 (3φ): 15 MVA 33/11 kV $X = 15.2$ ohm per phase on high tension side

Transformer T_2 (3φ): 15 MVA 33/6.2 kV $X = 16$ ohm per phase on high tension side

Transmission Line : 20.5 ohms/phase

Load A : 15 MW 11 kV 0.9 pf Lagging

Load B : 40 MW 6.6 kV 0.85 pf Lagging

Solution: High tension side of T_1 and high tension side of T_2 is specified so we start from transmission line

Transmission Line: Assume $\text{Base MVA}_{new} = 30$ MVA

$\text{Base kv}_{new} = 33$ kV

Actual impedance $= j20.5\ \Omega/\text{ph}$

$$\text{pu impedance} = \frac{\text{Actual impedance}}{\text{Base impedance}}$$

$$= \frac{\text{Actual impedance}}{(kv_b)^2} \times MVA_b$$

$$= \frac{j20.5}{(33)^2} \times 30 = j0.565 \text{ pu}$$

Transformer T_1 (referred to Secondary Side or HT Side

$kv_{b\,new} = 33$ kV

$$Z_{pu} = \frac{Z_{actual}}{(kv_b)^2} \times MVA \Rightarrow \frac{j15.2}{(33)^2} \times 30 = j0.418$$

$$= j0.418 \text{ pu}$$

Generator 1: Transformer T_1 primary side change occurs so Calculate kvb_{new}

$$kvb_{new} = kvb_{old} \times \frac{LT \text{ side voltage Rating of } T_1}{HT \text{ Side voltage Rating of } T_1}$$

$$= \frac{33 \times 11}{33} = 11 kV$$

$$Z_{pu} = \frac{Z_{actual}}{(kV_b)^2} \times MVA_b \Rightarrow \frac{j1.6 \times 30}{(11)^2} = j0.397 pu$$

Load A

$kvb_{new} = 11kV$ $P = 15MW$, 0.9 pf Lag

$$S_L = 15 \angle \cos^{-1} 0.9 = 13.5 + j6.54 \text{ MVA}$$

Actual impedance $Z_L = \frac{kV_b^2}{S_L^*} = \frac{11^2}{13.5 + j6.54}$

$\cos^{-1} 0.9 = 25.84$
Convert to Rectangle form
$15 \angle 25.84 \Rightarrow 13.5 + 6.54$

$$= 7.259 + j3.52 \Omega$$

$$Z_{pu} = \frac{Z_L}{Z_{base}} = \frac{Z_L}{kV_{b\,new}^2} \times MVA$$

$$= \frac{7.259 + j3.52}{11^2} \times 30 \Rightarrow 1.8 + j0.87 \text{ pu}$$

Transformer T_2 (referred to primary or HT side)

kvb_{new} = kV_b of Transmission Line = 33kV

$$Z_{pu} = \frac{Z_{actual}}{kV_{b\,new}^2} \times MVA_{b\,new} = \frac{j16 \times 30}{33^2} =$$

$$= j0.44 pu$$

Generator 2 : Transformer T_2 Secondary Side change occurs

So calculate $KV_{b\,new}$ as

$$KV_{b\,new} = KV_{b\,old} \times \frac{\text{LT Side voltage rating of } T_2}{\text{HT Side voltage rating of } T_2}$$

$$= 33 \times \frac{6.2}{33} = 6.2\,kV$$

$$Z_{pu} = \frac{Z_{actual}}{KV_{b\,new}^2} \times MVA_{new} \Rightarrow j\frac{1.2 \times 30}{(6.2)^2}$$

$$\Rightarrow j0.936\,pu$$

Generator 3

$$Z_{pu} = \frac{Z_{actual}}{KV_{b\,new}^2} \times MVA_{new} \Rightarrow \frac{j0.56 \times 30}{(6.2)^2}$$

$$\Rightarrow j0.437\,pu$$

Load B

$KV_{b\,new} = 6.2\,kV$

$P = 40\,MW \quad 0.85\,pf\ Lagging$

$= 40 \angle \cos^{-1} 0.85$ $\quad \cos^{-1} 0.85 = 31.78$

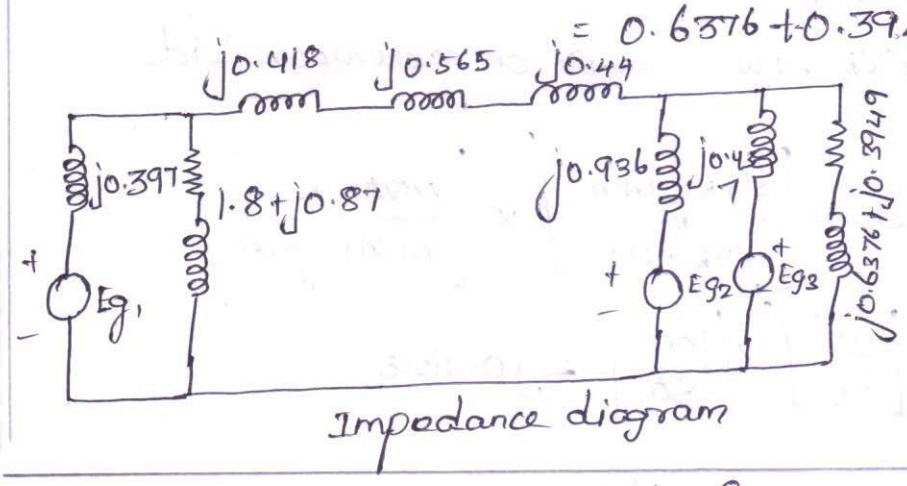
$= 40 \angle 31.78$

$= 34 + j21.06$

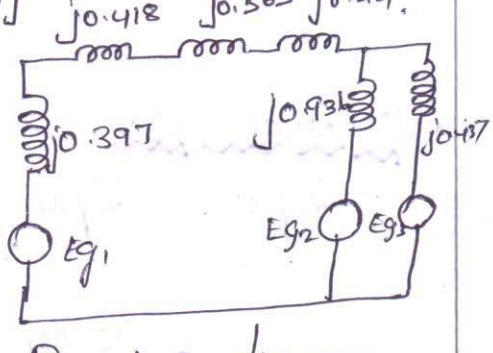
$$Z_L = \frac{KV_b^2}{S_L^*} = \frac{6.2^2}{34 - 21.06} = 0.817 + j0.506$$

$$Z_{pu} = \frac{Z_L}{KV_{b\,new}^2} \times MVA_{new} = \frac{0.817 + j0.506}{(6.2)^2} \times 30$$

$$= 0.6576 + 0.3949j$$

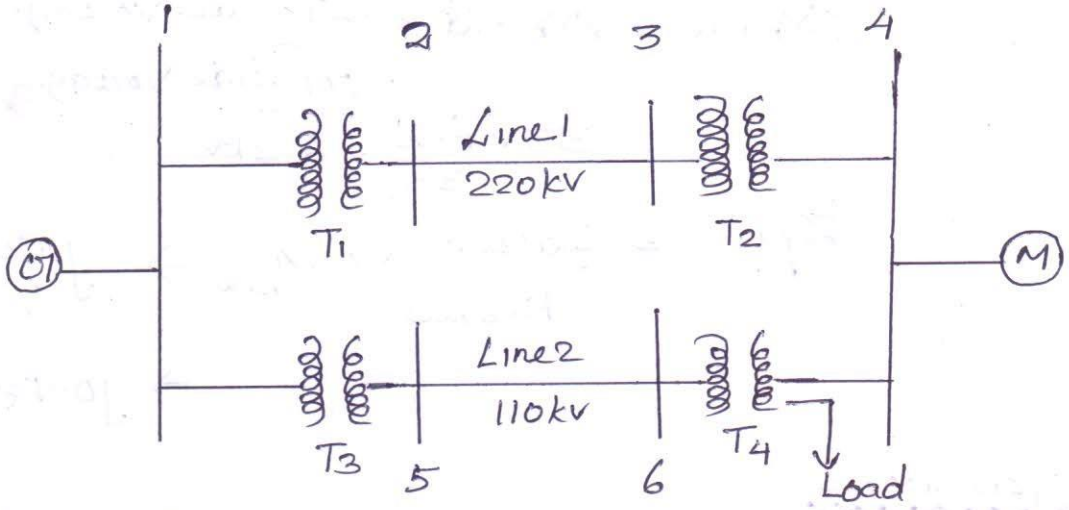


Impedance diagram



Reactance diagram

(3) The one Line diagram of a power system is shown in fig. three phase power and Line - Line ratings are given below



Generator :	80 MVA	22kV	$X = 9\%$
Transformer 1 :	50 MVA	22/220kV	$X = 10\%$
Transformer 2 :	40 MVA	220/22 kV	$X = 6\%$
Transformer 34 :	40 MVA	22/110 kV	$X = 6.4\%$
Line 1 :		200 kV	$X = 121\ \Omega$
Line 2 :		110kV	$X = 42.35\ \Omega$
Motor :	68.85 MVA	20kV	$X = 22.5\%$
Load :	10 MVAR	4kV	Δ Connected Capacitor

Draw an impedance diagram showing all impedance in per unit on a 100MVA base choose 22kV as the voltage base for generator

Solution

MVA_b new = 100 MVA

kV_b new = 22kV on generator side

Generator G1

$$Z_{pu} = Z_{pu\ given} \times \left[\frac{kV_{b\ given}}{kV_{b\ new}}\right]^2 \times \left[\frac{MVA_{b\ new}}{MVA_{b\ given}}\right]$$

$$= j0.09 \times \left[\frac{22}{22}\right]^2 \times \left[\frac{100}{80}\right] = j0.1125$$

(5)

Transformer T_1 referred to primary (LV Side)

$$kV_{b\,new} = 22\,kV$$

$$Z_{pu\,new} = j0.1 \times \left[\frac{22}{22}\right]^2 \times \frac{100}{50} = j0.2$$

Transformer T_3 referred to primary (LV Side)

$$kV_{b\,new} = 22\,kV$$

$$Z_{pu\,new} = j0.064 \times \left[\frac{22}{22}\right]^2 \times \left[\frac{100}{40}\right] = j0.16$$

Line 1 Transformer T_1 Secondary Side Change occurs So calculate kV_b new as

$$kV_{b\,new} = 22 \times \frac{220}{22} = 220\,kV$$

$$Z_{pu\,new} = \frac{Z_{actual}}{kV_b^2} \times MVA_{b\,new} \Rightarrow \frac{j121}{(220)^2} \times 100$$

$$\Rightarrow j0.25$$

Transformer T_2 referred to primary Side

$$kV_{b\,new} = 220\,kV$$

$$Z_{pu\,new} = j0.06 \times \left[\frac{220}{220}\right]^2 \times \left[\frac{100}{40}\right] = j0.15$$

Line 2 Transformer T_3 Secondary Side Change occurs So Calculate kV_b new as

$$kV_{b\,new} = 22 \times \frac{110}{22} = 110\,kV$$

$$Z_{pu\,new} = j\frac{42.35}{110^2} \times 100 = j0.35$$

Transformer T_4 refered to primary

$$kV_{b\ new} = 110\ kV$$

$$Z_{pu\ new} = j0.064 \times \left[\frac{110}{110}\right]^2 \times \left[\frac{100}{40}\right] = j0.16$$

Motor M : Transformer T_4 Secondary side change occurs So calculate $kV_{b\ new}$ as

$$kV_{b\ new} = 110 \times \frac{22}{110} = 22kV$$

$$Z_{pu\ new} = j0.225 \times \left[\frac{20}{20}\right]^2 \times \left[\frac{100}{68.85}\right] = j0.327$$

Load at bus 4

$Q_L = 10$ MVA MVA $\sin\phi = 10$

$V = 4kV$ $\sin\phi = \frac{10}{100} = 0.1$

$\phi = \sin^{-1}(0.1) = 5.739°$

$$pf = \cos\phi = 0.9$$

$$P_L = MVA \cdot \cos\phi = 100 \times 0.99 = 99$$

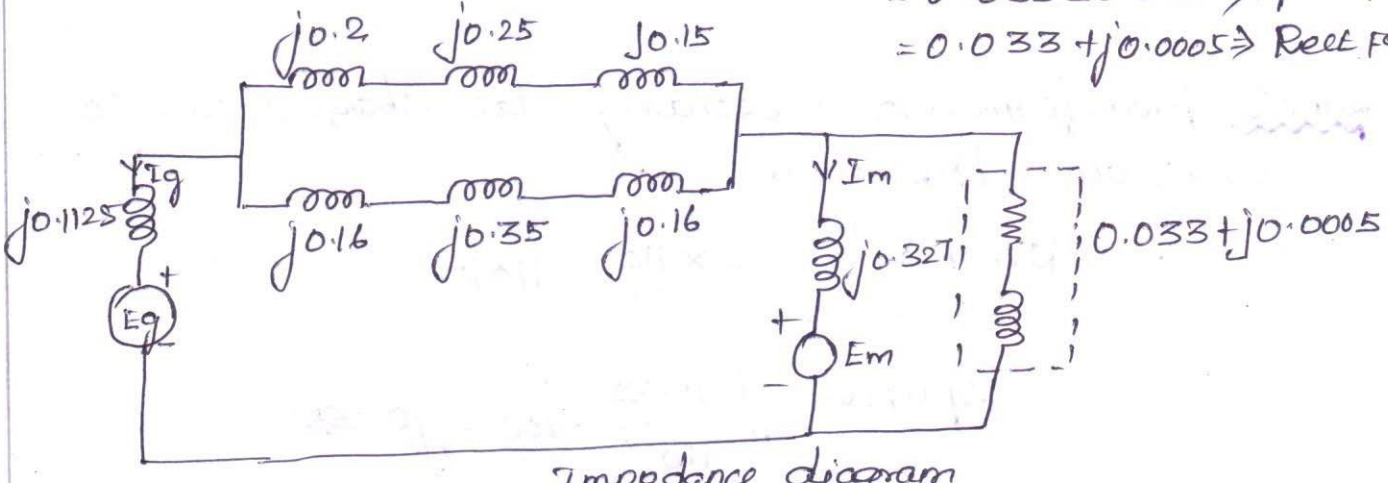
$$S_L = P_L + jQ_L = 99 + j10$$

$$Z_L = \frac{kV^2}{S_L^*} = \frac{4^2}{99 - j10} = \frac{16}{99.5\angle -0.015} = 0.16\angle 0.015 \text{ rad}$$

$$Z_{pu} = \frac{Z_L}{kV_b^2 new} \times MVA = \frac{0.16\angle 0.015}{22^2} \times 100$$

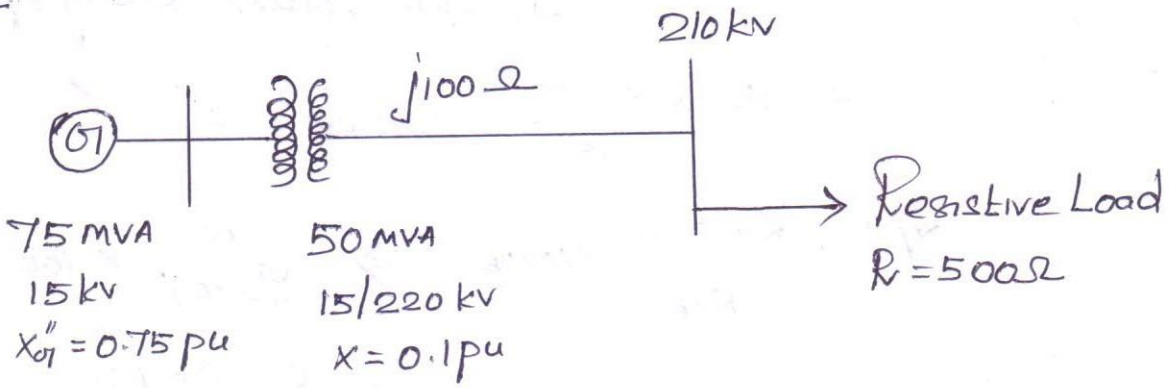
$$= 0.033\angle 0.015 \Rightarrow \text{polar form}$$

$$= 0.033 + j0.0005 \Rightarrow \text{Rect form}$$



Impedance diagram

(4) For the System Shown in Fig determine the generator voltage Take a base of 100MVA and 210 kv in the transmission Line



Solution:

Assume base $MVA_{b\,new}$ = 100 MVA

Base kV_{new} = 15 kV

Generator

kV_b given = 15 kV, MVA given = 75 MVA

$$Z_{pu\,new} = Z_{pu\,given} \times \left[\frac{kV_b\ given}{kV_b\ new}\right]^2 \times \left[\frac{MVA_b\ new}{MVA_b\ given}\right]$$

$$= j0.75 \times \left[\frac{15}{15}\right]^2 \times \left[\frac{100}{75}\right] = j0.1 pu$$

Transformer primary

kV_b given = 15 kV MVA given = 50 MVA

$$Z_{pu\,new} = j0.1 \times \left[\frac{15}{15}\right]^2 \times \frac{100}{50} = j0.2$$

Transmission Line = j100 Ω base kv Changed So Find the new base kv

kV_b new = kV_b of Secondary Side of transformer

$$= kV_b \text{ old} \times \frac{\text{HT Side voltage Rating of transformer}}{\text{LT Side voltage Rating of transformer}}$$

$$= 15 \times \frac{220}{15} = 220 \text{ kv}$$

$$Z_{pu} = \frac{Z_{actual}}{kV_b^2} \times MVA_b \Rightarrow \frac{j100}{(220)^2} \times 100$$

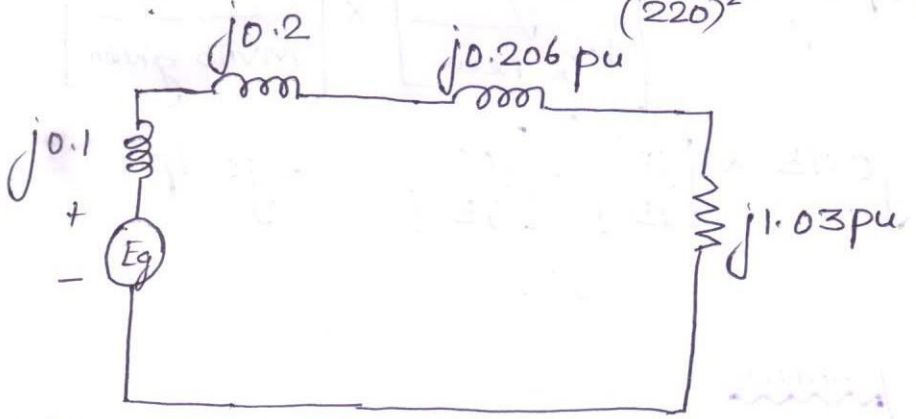
$$\Rightarrow j0.206 \text{ pu}$$

Resistive Load

$$kV_b \text{ new} = 220 \text{ kv}$$

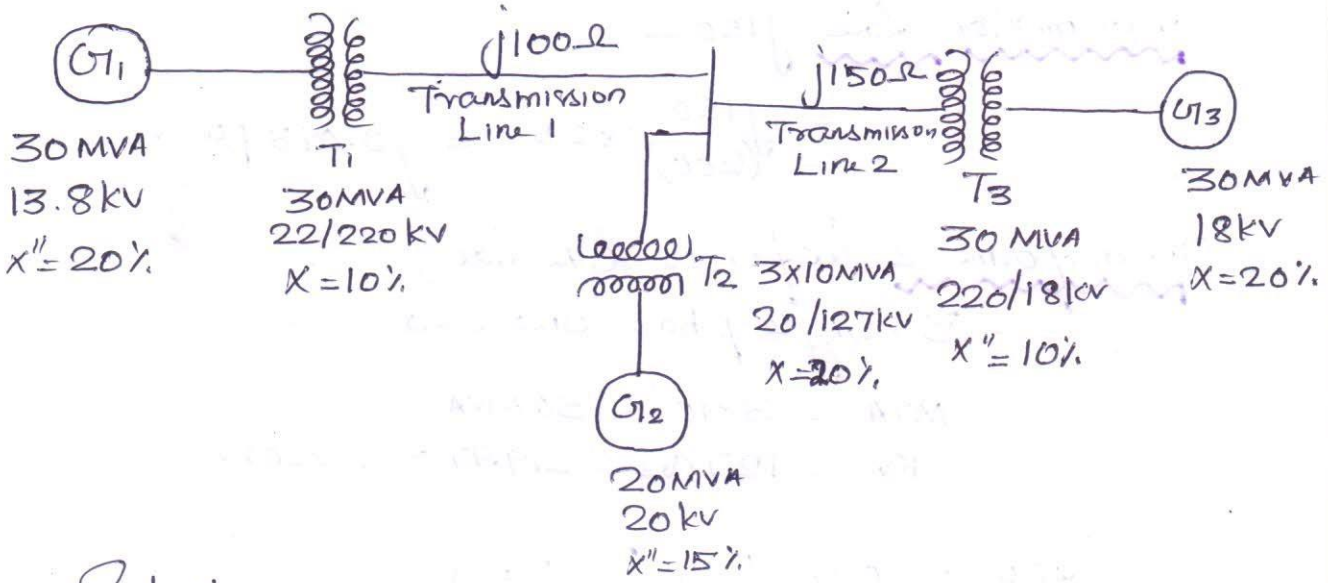
$$R_{pu} = \frac{R_{actual}}{kV_b^2} \times MVA_b$$

$$= \frac{500}{(220)^2} \times 100 \Rightarrow j1.03 \text{ pu}$$



(5) The Single Line diagram of a power System is Shown in Fig along with components data Determine the new per unit value and draw the reactance diagram.

Assume 25 MVA and 20kv as new base on generator G1



Solution

MVA new = 25 MVA

kVb new = 20 kV

Generator 1

$$Z_{pu\ new} = Z_{pu\ given} \times \left[\frac{kV_{b\ given}}{kV_{b\ new}}\right]^2 \times \left[\frac{MVA_{b\ new}}{MVA_{b\ given}}\right]$$

$$= j0.2 \times \left(\frac{13.8}{20}\right)^2 \times \left(\frac{25}{30}\right) = j0.07\ pu$$

Transformer 1 (referred to primary)

$$Z_{pu\ new} = j0.1 \times \left(\frac{22}{20}\right)^2 \times \left(\frac{25}{30}\right) = j0.10\ pu$$

Transmission Line j 100Ω

Transformer T1 Secondary side change occurs So Calculate kVb new as

$$kV_{b\ new} = 20 \times \frac{220}{22} = 200\ kV$$

$$Z_{pu} = \frac{Z_{actual}}{kV_{b\ new}^2} \times MVA \Rightarrow \frac{j100\Omega}{(200)^2} \times 25$$

$$\Rightarrow j0.0625$$

Transmission Line $j150\Omega$

$$= \frac{j150}{(200)^2} \times 25 = j0.093 \text{ pu}$$

Transformer 2 (refer to line side)

3 Single phase unit used

$$\text{MVA} = 3 \times 10 = 30 \text{ MVA}$$

$$\text{kv} = 127 \times \sqrt{3} = 219.97 \sim = 220 \text{ kv}$$

$$Z_{pu} = j0.2 \times \left(\frac{220}{200}\right)^2 \times \left(\frac{25}{30}\right) = j0.201 \text{ pu}$$

Generator 2

$$kV_{b\,new} = kV_{b\,old} \times \frac{\text{LT Side voltage Rating } T_2}{\text{HT Side voltage Rating } T_2}$$

$$= 200 \times \frac{20}{220} = 18 \text{ kv}$$

$$Z_{pu\,new} = j0.15 \times \left(\frac{20}{18}\right)^2 \times \left(\frac{25}{20}\right) = j0.231 \text{ pu}$$

Transformer 3 (Refer to line side)

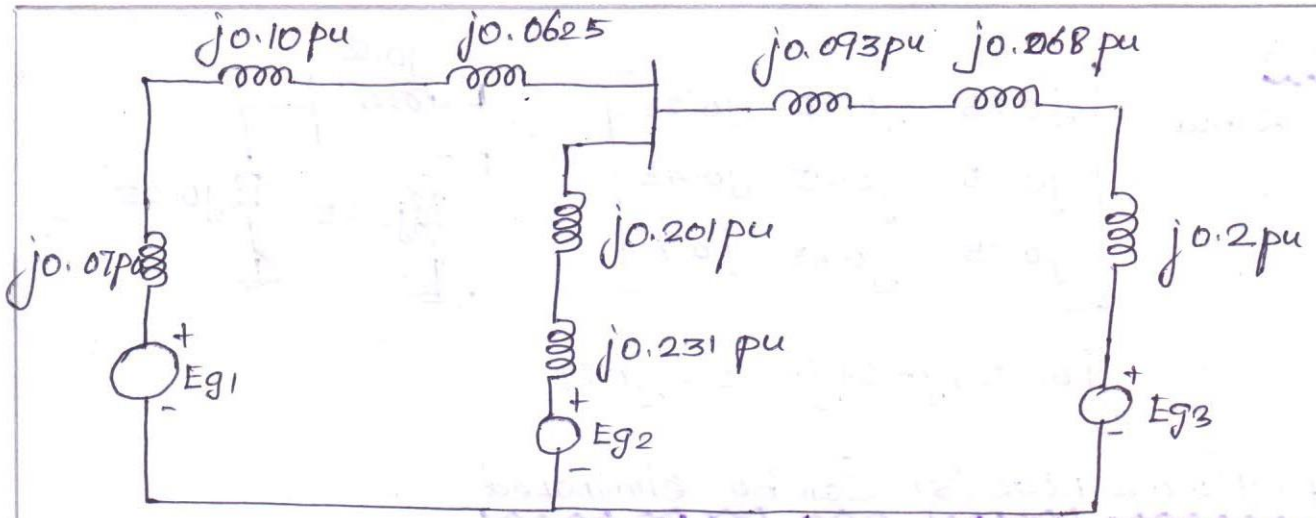
$$kV_{b\,new} = 200 \text{ kv}$$

$$Z_{pu\,new} = j0.1 \times \left(\frac{220}{200}\right)^2 \times \left(\frac{25}{30}\right) = j0.068 \text{ pu}$$

Generator 3 : Transformer T_3 Side base kv changed

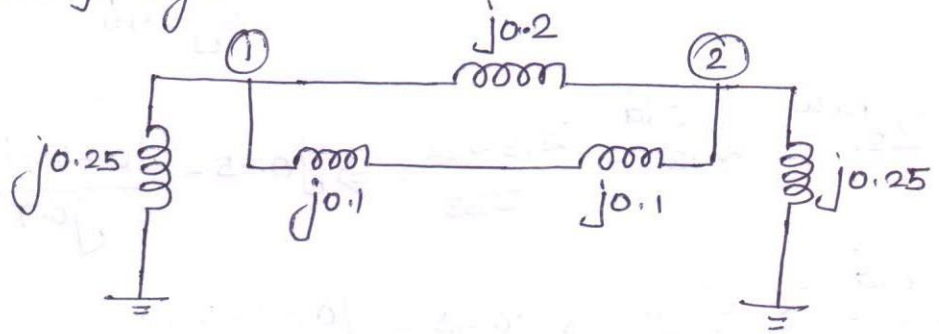
$$kV_{b\,new} = 200 \times \frac{18}{220} \Rightarrow 16.36 \text{ kv}$$

$$Z_{pu} = j0.2 \times \left(\frac{18}{16.36}\right)^2 \times \left(\frac{25}{30}\right) = j0.2 \text{ pu}$$



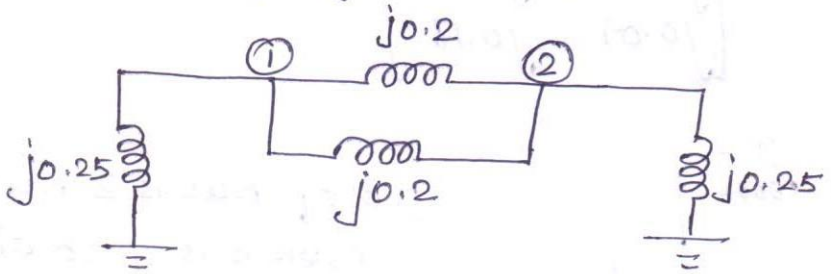
Reactance diagram

⑥ Form the bus impedance matrix for the network shown by building algorithms.



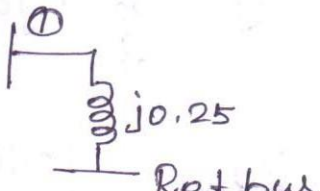
Solution j0.1 and j0.1 Connected in Series

$$Z_{eq} = j0.1 + j0.1 = j0.2$$



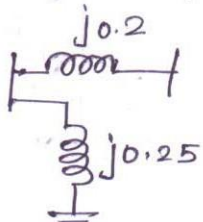
Step 1:

$$Z_{bus} = [j\,0.25]$$



Step 2:

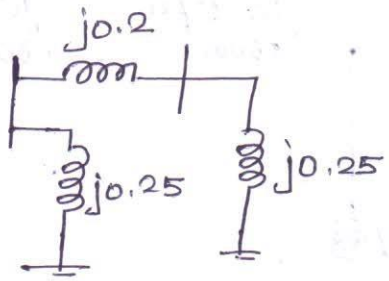
$$Z_{bus} = \begin{bmatrix} j0.25 & j0.25 \\ j0.25 & j0.45 \end{bmatrix}$$



$$= j0.25 + j0.2 = j0.45$$

Step 3

$$Z_{bus} = \begin{bmatrix} j0.25 & j0.25 & j0.25 \\ j0.25 & j0.45 & j0.45 \\ j0.25 & j0.45 & j0.7 \end{bmatrix}$$



$j0.25 + j0.2 + j0.25 = j0.7$

Fictitious node (3) Can be eliminated

$$Z_{11}^{new} = Z_{11}^{old} - \frac{Z_{13}Z_{31}}{Z_{33}} \Rightarrow j0.25 - \frac{j0.25 \times j0.25}{j0.7}$$

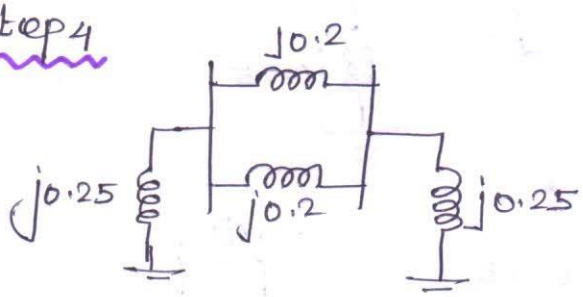
$$= j0.16$$

$$Z_{12}^{new} = Z_{21}^{new} = Z_{12}^{old} - \frac{Z_{13}Z_{32}}{Z_{33}} \Rightarrow j0.25 - \frac{j0.25 \times j0.45}{j0.7} \Rightarrow j0.09$$

$$Z_{22}^{new} = Z_{22}^{old} - \frac{Z_{23}Z_{32}}{Z_{33}} \Rightarrow j0.45 - \frac{j0.45 \times j0.45}{j0.7} = j0.16$$

$$Z_{bus} = \begin{bmatrix} j0.16 & j0.09 \\ j0.09 & j0.16 \end{bmatrix}$$

Step 4



No of bus is 2 but No of element is 4 So eliminate the bus.

$j0.09 - j0.16 = -j0.07$

$j0.16 - j0.09 = +j0.07$

$$Z_{bus} = \begin{bmatrix} j0.16 & j0.09 & j0.07 \\ j0.09 & j0.16 & -j0.07 \\ j0.07 & -j0.07 & j0.34 \end{bmatrix}$$

$$Z_{33} = Z_b + Z_{11} + Z_{22} - 2Z_{12} \Rightarrow j0.2 + j0.16 + j0.16 - 2 \times j0.09$$

$$= j0.34$$

node 3 eliminated

$$Z_{11}^{new} = Z_{11}^{old} - \frac{Z_{13}Z_{31}}{Z_{33}} \Rightarrow j0.16 - \frac{j0.07 \times j0.07}{j0.34} = j0.146$$

$$Z_{12}^{new} = Z_{21}^{new} = Z_{12}^{old} - \frac{Z_{13}Z_{32}}{Z_{33}} \Rightarrow j0.09 - \frac{j0.07 \times (-j0.07)}{j0.34}$$

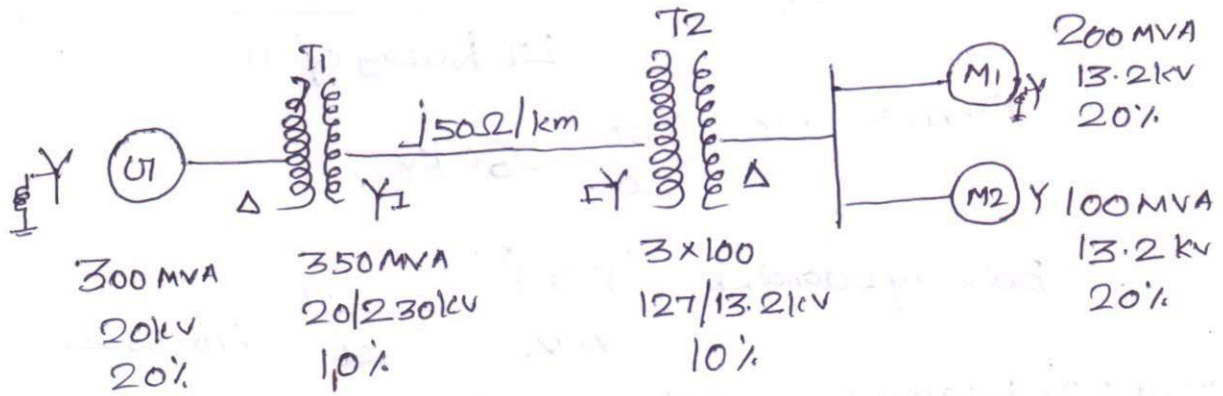
$$= j0.104$$

$$Z_{22}^{new} = Z_{22}^{old} - \frac{Z_{23}Z_{32}}{Z_{33}} \quad j0.16 - \frac{(-j0.07)(-j0.07)}{j0.34} = j0.146$$

$$Z_{bus} = \begin{bmatrix} j0.146 & j0.104 \\ j0.104 & j0.146 \end{bmatrix}$$

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(7) A 300 MVA, 20 kv, 3ϕ generator has a Subtransient reactance of 20% the generator supplies 2 Synchronous motor through a 64 km. transmission line having transformer at both ends. In this T_1 is a 3ϕ transformer and T_2 is made of 3 Single phase transformer rating 100 MVA 127/13.2kv, 10% Reactance. Series reactance of transmission Line 0.5 Ω/km Draw the reactance diagram with all the reactance marked in pu Select the generator ratings as base values.



Solution

Base MVA new = 300 MVA

Base kv new = 20kv

Generator 1

$$X_{pu\,new} = X_{pu\,given} \times \left[\frac{kV_b\ given}{kV_b\ new}\right]^2 \times \left[\frac{MVA_b\ new}{MVA\ given}\right]$$

$$= 0.2 \times \left[\frac{20}{20}\right]^2 \times \left[\frac{300}{300}\right] = j0.2\,pu$$

Transformer 1 (refer to primary side)

$$= 0.1 \times \left(\frac{20}{20}\right)^2 \times \left(\frac{300}{350}\right) = j0.0857\,pu$$

Transmission Line

Reactance of Transmission Line = $j0.5\,\Omega/km$

Km = 64

Total Reactance of Transmission Line = $0.5 \times 64 = 32\,\Omega$

Transformer 1 Secondary Side voltage changed so base kv Changed

Calculate / Find new base kv

$$kV_{b\,new} = kV_b \text{ on old} \times \frac{HT\ Rating\ of\ T_1}{LT\ Rating\ of\ T_1}$$

$$kV_{b\,new} = 20 \times \frac{230}{20} = 230\,kv$$

$$\text{Base impedance } Z_b = \frac{(kV_b)^2}{MVA_b} = \frac{(230)^2}{300} = 176.33\,\Omega$$

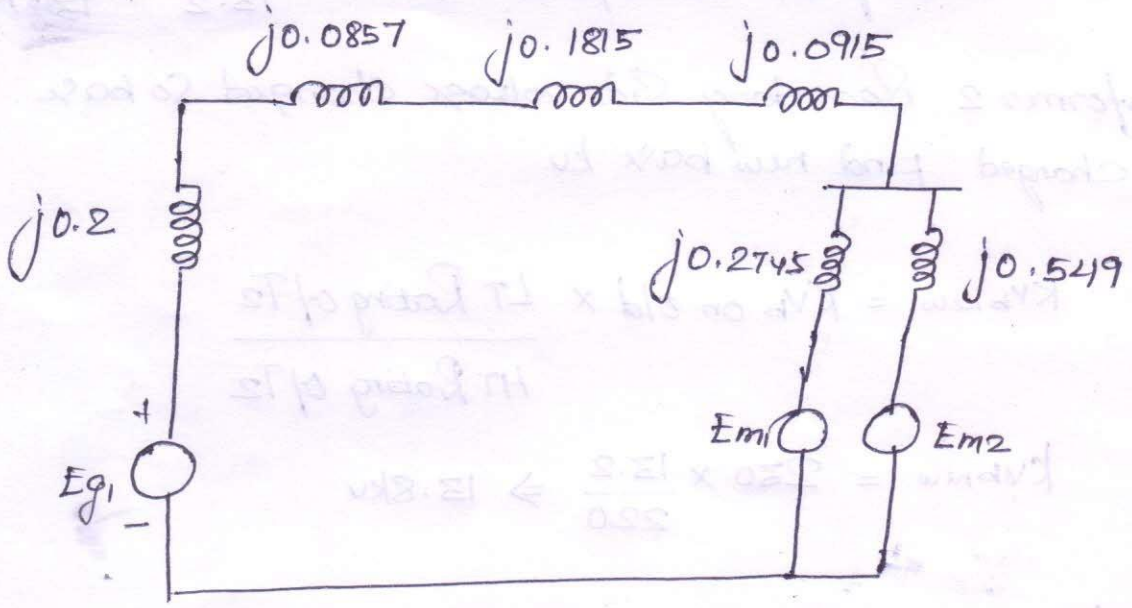
$$\text{per unit of Reactance} = \frac{\text{Actual reactance}}{\text{Base impedance}} = \frac{32}{176.33} = j0.1815\,pu$$

Motor 2

pu Reactance of M2 on new base $= X_{pu\,given} \times \left[\frac{kV_{b\,given}}{kV_{b\,new}}\right] \times \left[\frac{MVA_{new}}{MVA_{gw}}\right]$

$$= 0.2 \times \left(\frac{13.2}{13.8}\right)^2 \times \frac{300}{100} = j0.549\ pu$$

All the Reactance values are in pu



Reactance diagram

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Unit – II

(1) Discuss in detail GAUSS - SEIDAL Procedure & algorithm. [May/June 2013, Nov/Dec 2015,

Algorithm:

Step 1: Form Y_{bus} matrix

Step 2: Assume $V_k = V_{k(spec)} \angle 0^\circ$ at all generator buses

Step 3: Assume $V_k = 1 \angle 0^\circ = 1 + j0$ at all load buses.

Step 4: Set to iteration Count = 1 (iter 1)

Step 5: Let bus number $i = 1$

Step 6: If "i" refers to generator bus go to Step 7, Otherwise go to step 8.

Step 7 a): If "i" refers to the slack bus, go to Step 9. Otherwise go to step 7 (b).

Step 7 b): Compute Q using,

$$Q_i^{cal} = -Im\left[\sum_{j=1}^{N} V_i^* Y_{ij} V_j\right]$$

$$Q_{Gi} = Q_i^{cal} + Q_{Li}$$

check for Q limit Violation.

If $Q_{i(min)} < Q_{Gi} < Q_{i(max)}$, then $Q_{i(spec)} = Q_{i(cal)}$

If $Q_{i(min)} > Q_{Gi}$, then $Q_{i(spec)} = Q_{i(min)} - Q_{Li}$

If $Q_{i(max)} < Q_{Gi}$, then $Q_{i(spec)} = Q_{i(max)} - Q_{Li}$

If Q_{limit} is Violated, then treat this bus as PQ bus till Convergence is Obtained

Step 8: Compute V_i using the equation,

$$V_i^{new} = \frac{1}{Y_{ii}} \left[\frac{P_{i(spec)} - Q_{i(spec)}}{V_i^{old *}} - \sum_{\substack{i=1 \\ i \neq j}}^{} Y_{ij} V_j \right]$$

Step 9: If "i" is less than number of buses, increment i by 1 and go to Step 6.

Step 10: Compute two consequtive iteration values for V_i. If $V_i^{new} - V_i^{old} <$ tolerance, goto Step 12.

Step 11: Update the new voltage as,

$$V_i^{new} = V^{old} + \alpha (V^{new} - V^{old})$$

$V^{old} = V^{new}$, iter = iter + 1,

go to Step 5.

Step 12: Compute relavant qualities.

Slack bus power $S_1 = P_1 - jQ_1 = V^* I = V_i^* \sum_{j=1}^{N} Y_{ij} V_j$

Line flows $S_{ij} = P_{ij} + jQ_{ij}$

$$= V_{ij} \left[V_i^* - V_j^* \right] Y_{ij\,series}^* + |V_i|^2 Y_{ii}^*$$

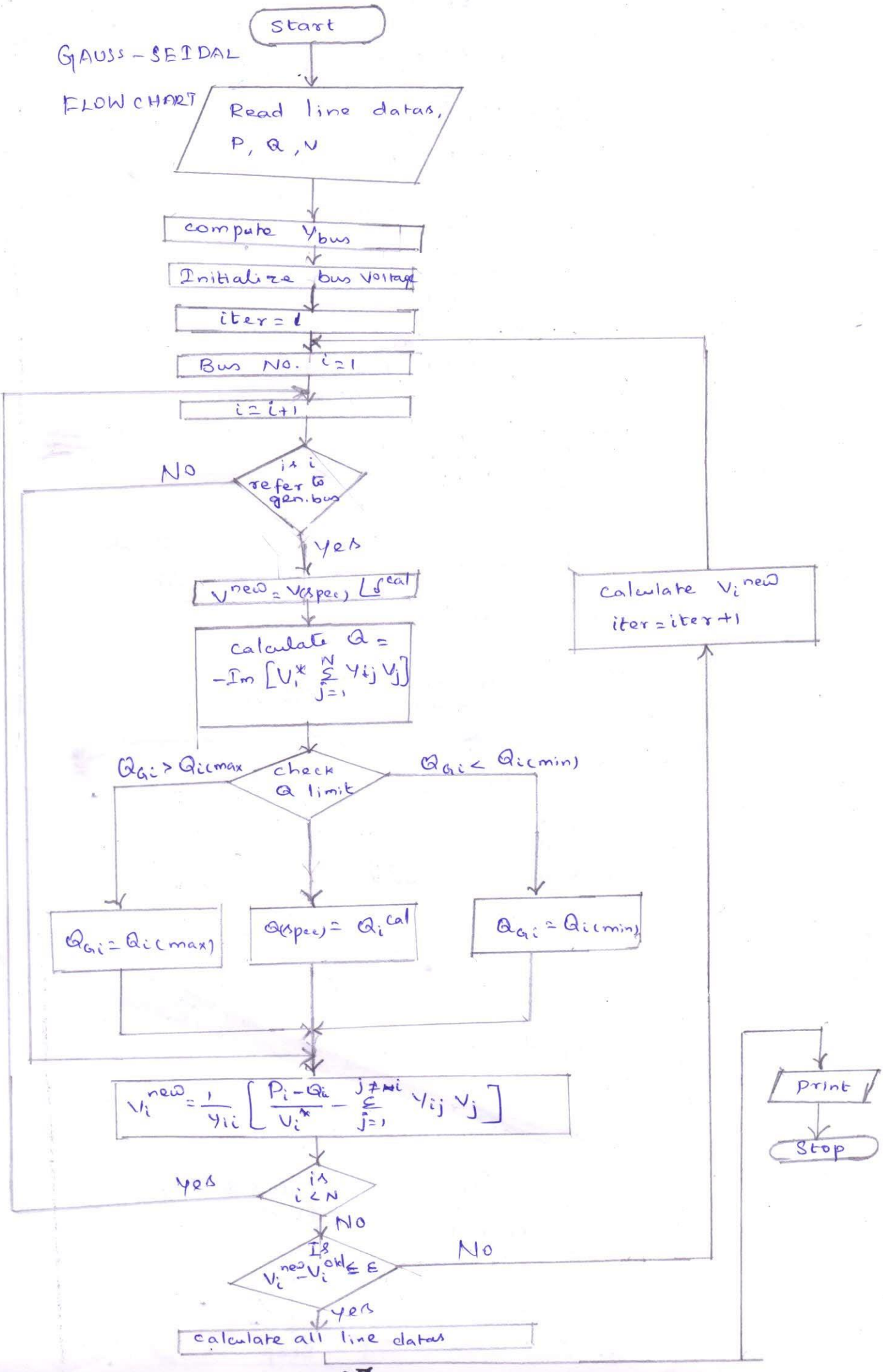
$$P_{loss} = P_{ij} + P_{ji}$$

$$Q_{Loss} = Q_{ij} + Q_{ji}$$

Step 13: Stop the execution.

GAUSS - SEIDAL

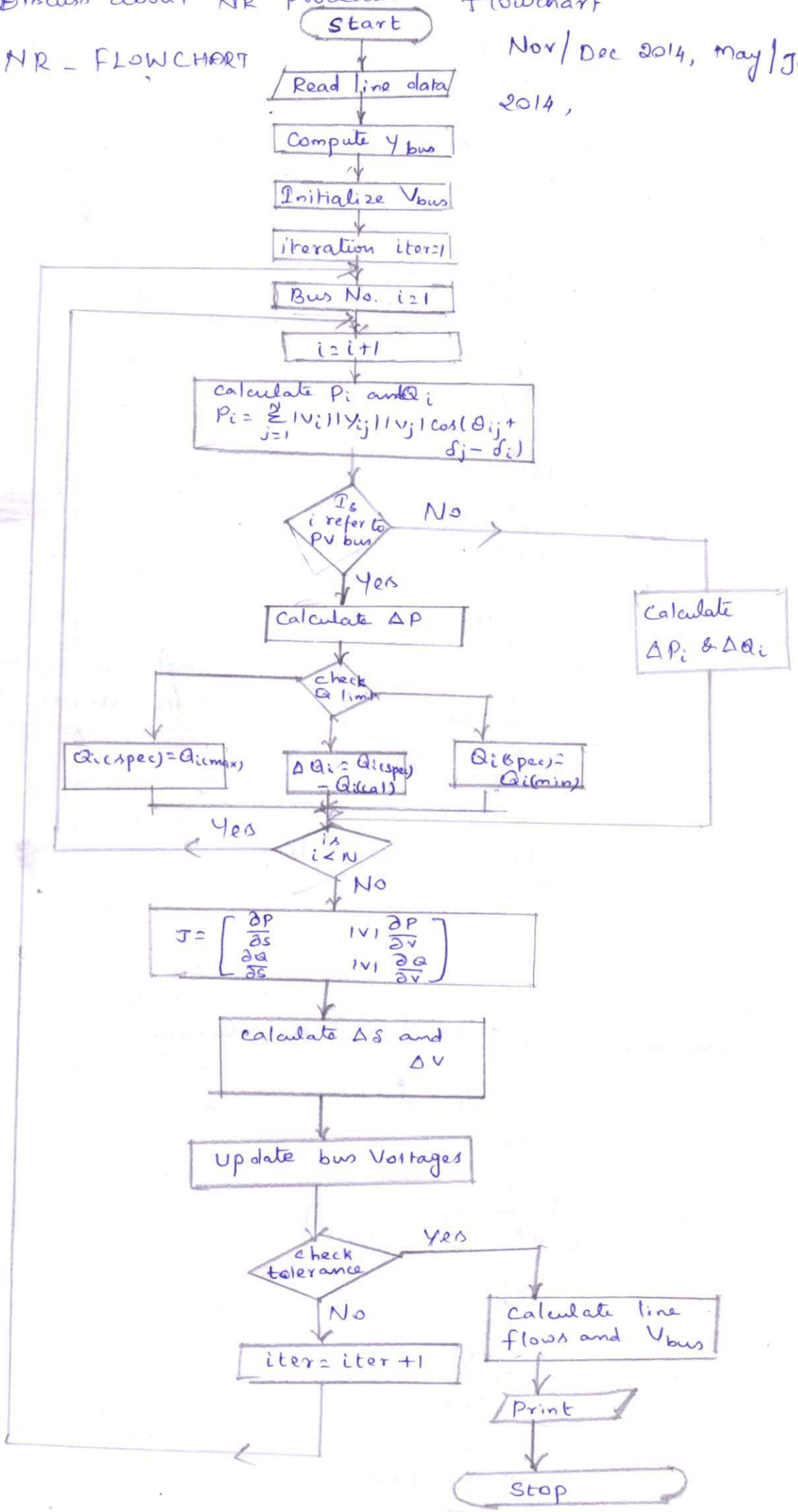
FLOW CHART



(2) Discuss about NR procedure & flowchart

(2) NR - FLOWCHART

Nov/Dec 2014, May/June 2014,



NEWTON - RAPHSON ALGORITHM:

Step 1: Formulate Y_{bus} matrix.

Step 2: Assume flat start for starting Voltage solution.

$\delta_i^0 = 0$, for $i = 1 \ldots N$ for all buses except slack bus.

$|V_i^0| = 1.0$ for $i = M+1, M+2 \ldots N$ (for all PQ buses.

$|V_i| = |V_i|_{(spec)}$ for all PV buses and slack bus.

Step 3: For load buses, Calculate P_i^{cal} and Q_i^{cal}

Step 4: For PV buses, check for Q limit violation.

If $Q_{i(min)} < Q_i^{cal} < Q_{i(max)}$, the bus acts as PV bus.

If $Q_i^{cal} > Q_{i(max)}$, $Q_{i(spec)} = Q_{i(max)}$

If $Q_i^{cal} < Q_{i(min)}$, $Q_{i(spec)} = Q_{i(min)}$, the PV bus will act as PQ bus.

Step 5: Compute mismatch Vector using

$$\Delta P_i = P_{i(spec)} - P_i^{cal}$$

$$\Delta Q_i = Q_{i(spec)} - Q_i^{cal}$$

Step 6: $\Delta P_{i(max)} = \max |\Delta P|$; $i = 1, 2 \ldots N$ except slack bus

$\Delta Q_{i(max)} = \max |\Delta Q|$; $i = M+1 \ldots N$

Step 7: Compute Jacobian matrix

$$J = \begin{bmatrix} \frac{\partial P_i}{\partial \delta} & |V| \frac{\partial P_i}{\partial |V|} \\ \frac{\partial Q_i}{\partial \delta} & |V| \frac{\partial Q_i}{\partial |V|} \end{bmatrix}$$

Step 8: Obtain State Correction Vector

$$\begin{bmatrix} \Delta\delta \\ \frac{\Delta V}{|V|} \end{bmatrix} = [J]^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

Step 9: Update state vector using

$$V^{new} = V^{old} + \Delta V = V^{old} + \frac{\Delta V}{|V^{old}|}$$

$$= V^{old} \left[1 + \frac{\Delta V}{|V^{old}|} \right]$$

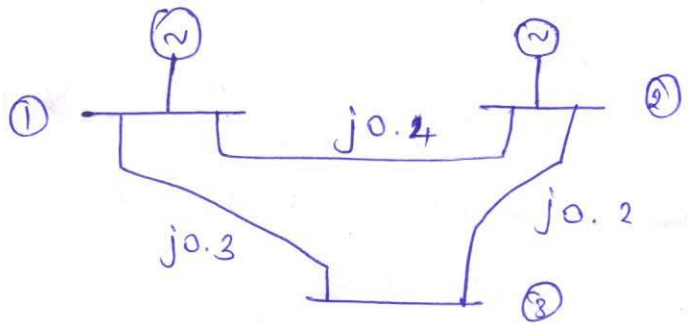
$$\delta^{new} = \delta^{old} + \Delta\delta$$

Step 10: This procedure is continued until $|\Delta P_i| < \varepsilon$ and $|\Delta Q_i| < \varepsilon$, Otherwise go to step 3.

←——→ [Nov/Dec 14]

③ For the system shown in fig. determine the voltages at the end of the first iteration by Gauss-Seidal method and also find the slack bus power, Assume base MVA as 100.

Bus No.	Voltage	Generator P	Generator Q	Load P	Load Q	Q_{min}	Q_{max}
1	$1.05\angle 0^\circ$	—	—	—	—	—	—
2	1.02	0.3	—	—	—	−10	+100
3	—	—	—	0.4	0.2	—	—



Step 1: form Y_{bus}

$$Y_{bus} = \begin{bmatrix} 1/j0.4 + 1/j0.3 & -1/j0.4 & -1/j0.3 \\ -1/j0.4 & 1/j0.4 + 1/j0.2 & -1/j0.2 \\ -1/j0.3 & -1/j0.2 & 1/j0.3 + 1/j0.2 \end{bmatrix}$$

$$= \begin{bmatrix} -j5.8333 & j2.5 & j3.3333 \\ j2.5 & -j7.5 & j5 \\ j3.3333 & j5 & -j8.3333 \end{bmatrix}$$

Step 2: Initialize bus voltages

$V_1^{old} = 1.05 \angle 0^\circ$ pu (slack bus)

$V_2^{old} = 1.02 \angle 0^\circ$ pu (PV bus)

$V_3^{old} = 1.0 \angle 0^\circ$ pu (PQ bus)

Step 3: Calculate Q value for all generator buses.

$$Q_i^{cal} = -Im\left\{ V_i^{old *} \left[\sum_{j=1}^{j=N} Y_{ij} V_j \right] \right\}$$

$i = 2 \qquad j = 1, 2, 3 \qquad N = 3$

$$Q_2^{cal} = -Im\left\{ V_2^{old*} \left[Y_{21} V_1 + Y_{22} V_2 + Y_{23} V_3 \right] \right\}$$

$$= -Im\left\{ 1.02\angle 0^\circ \left[j2.5 \times 1.05\angle 0^\circ + (-j7.5 \times 1.02\angle 0^\circ) + j5 \times 1\angle 0^\circ \right] \right\}$$

$$Q_2 \text{ cal} = -Im\left[1.02\angle 0^\circ (j2.625 - j7.65 + j5) \right]$$

$$Q_2 = 0.025 \text{ pu.}$$

Now $Q_{2(min)} \le Q_2 \text{ cal} \le Q_{2(max)}$

Q_2^{cal} is within the specified limit.

Step 4: Calculate V_i^{new}

$$V_1^{new} = 1.05\angle 0^\circ \text{ pu.}$$

$$V_i^{new} = \frac{1}{Y_{ii}} \left[\frac{P_i - jQ_i}{V_i^{old*}} - \sum_{\substack{j=1 \\ j \neq i}} Y_{ij} V_j \right]$$

$$V_2^{new} = \frac{1}{Y_{22}} \left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21} V_1^{new} - Y_{23} V_3^{old} \right]$$

$P_2 = 0.3$ pu, $Q_2 = 0.025$ pu.

$$V_2^{new} = \frac{1}{-j7.5} \left[\frac{0.3 - j0.025}{1.02\angle 0^\circ} - j2.5 \times 1.05\angle 0^\circ - j5 \times 1\angle 0^\circ \right]$$

$$= 1.0192 + j0.0392$$

$$P_3 = P_{G3} - P_{L3} = 0 - 0.4 = -0.4 \text{ pu.}$$

$$Q_3 = Q_{G3} - Q_{L3} = 0 - 0.2 = -0.2 \text{ pu.}$$

$$V_3^{new} = \frac{1}{Y_{33}} \left[\frac{-0.4 + j0.2}{1.0\angle 0^\circ} - j3.3333 \times 1.05\angle 0^\circ - j5 \times 1.02\angle 2.2^\circ \right]$$

$$= \frac{1}{-j8.3333}\left[-0.4+j0.2-3.4999j-j5.096+0.196\right]$$

$$V_3^{new} = 1.0075 - j0.0244 \text{ (or) } 1.0078 \angle -1.39^\circ$$

Slack bus power:

$$S_1 = P_1 - jQ_1 = V_1^* \sum_{j=1}^{N} Y_{ij} V_j$$

$$= V_1^* \left[Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3\right]$$

$$= 1.05\left[-j5.8333 \times 1.05\angle 0^\circ + j2.5 \times (1.0192 + j0.0392) + j3.3333(1.0075 - j0.024)\right]$$

$$= -0.0175 - j0.2295 \text{ pu.}$$

$P_1 = -0.0175$ pu (or) -1.75 MW

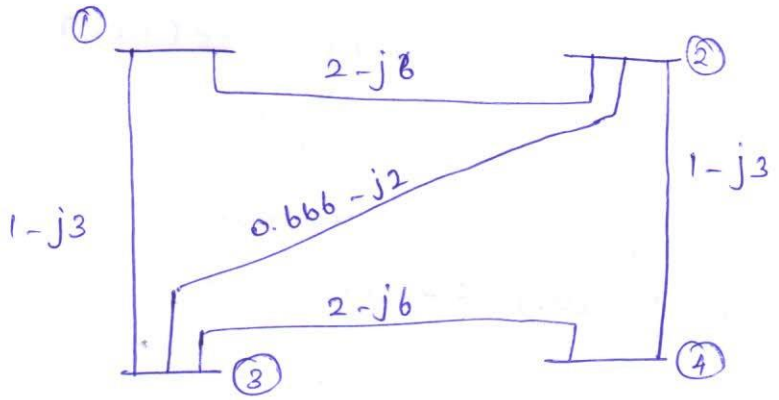
$Q_1 = 0.2295$ pu (or) 22.95 MVAr.



[Nov/Dec 2015,

(4) For the system shown in figure, the generators are connected at all four buses, while the loads are at buses 2 and 3. Values of real and reactive powers are listed in table. Bus 2 be a PV bus with $V_2 = 1.04$ pu and bus 3 and bus 4 are PQ buses. Assuming a flat Voltage start, find bus Voltages and bus angles at the end of first Gauss-Seidal iterations. Assume $0.2 \leq Q_2 \leq 1$.

Bus No.	P_p (pu)	Q_p (pu)	V_p (pu)	Remarks
1	—	—	$1.04 \angle 0^\circ$	Slack
2	0.5	—	1.04 pu	PV
3	-1.0	0.5	—	PQ
4	0.3	-0.1	—	PQ.



Solution:

Step 1: Formulate Y_{bus}

$$Y_{bus} = \begin{bmatrix} 3-j9 & -2+j6 & -1+j3 & 0 \\ -2+j6 & 3.666-j11 & -0.666+j2 & -1+j3 \\ -1+j3 & -0.666+j2 & 3.666-j11 & -2+j6 \\ 0 & -1+j3 & -2+j6 & 3-j9 \end{bmatrix}$$

Step 2: Initialize bus Voltage

$V_1^{old} = 1.04 \angle 0^\circ$

$V_2^{old} = 1.04 \angle 0^\circ$ pu.

$V_3^{old} = 1.0 \angle 0^\circ$ pu

$V_4^{old} = 1.0 \angle 0^\circ$ pu

Step 3: Calculate Q_2 for the PV bus

$$Q_2^{cal} = -Im\{V_2^{old}[Y_{21}V_1^{new} + Y_{22}V_2^{old} + Y_{23}V_3^{old} + Y_{24}V_4^{old}]\}$$

$$= -Im\{1.04[(-2+j6)1.04 + (3.666-j11)1.04 + (-0.666+j2)(1.0) + (-1+j3)(1.0)]\}$$

$$= -Im\{0.069 - j0.208\} = 0.208 \text{ pu}$$

$0.2 < Q_2^{cal} < 1$, within the limit.

Bus 2 act as a PV bus.

$P_2 = 0.5$ pu, $Q_2 = 0.208$ pu.

$$V_2 = 1/Y_{22}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21}V_1^{new} - Y_{23}V_3^{old} - Y_{24}V_3^{old}\right]$$

$$= \frac{1}{3.666-j11}\left[\frac{0.5 - j0.208}{1.04} - (-2+j6)(1.04) - (-0.666+j2)(1.0) - (-1+j3)(1.0)\right]$$

$$= 1.051 + j0.0339 \text{ (or) } 1.0518 \angle 0.032 \text{ rad.}$$

$|V_2| = 1.0518 \qquad \delta_2 = 0.032$ rad.

$$V_3^{new} = 1/Y_{33}\left[\frac{P_3 - jQ_3}{V_3^{old*}} - Y_{31}V_1^{old} - Y_{32}V_2^{old} - Y_{34}V_4^{old}\right]$$

$$= \frac{1}{3.666-j11}\left[\frac{-1.0 - j0.5}{1.0} - (-1+j3)(1.04) - (-0.666+j2)(1.0395 - j0.333) - (-2+j6)\right]$$

$$= 1.0317 - j0.0894 \text{ pu.}$$

$$V_4^{new} = \frac{1}{Y_{44}} \left[\frac{P_4 - jQ_4}{V_4^{old\,*}} - Y_{41} V_1^{new} - Y_{42} V_2^{new} - Y_{43} V_3^{new} \right]$$

$$= \frac{1}{3 - j9} \left[\frac{0.3 + j0.1}{1.0} - 0 \times 1.04 - (-1 + j3)(1.0395) + j0.333 - (-2 + j6)(1.0317 - j0.894) \right]$$

$$V_4^{new} = 1.0343 - j0.015 \text{ pu.}$$

UNIT - III

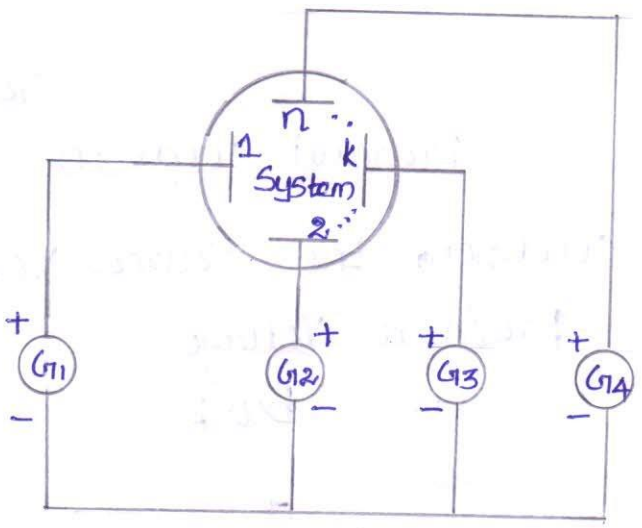
Fault Analysis - Balanced Faults.

1. Fault analysis using Z-bus building algorithm. May/June-13 & 14 Nov/Dec-12

* Bus impedance matrix is used to estimate fault at any point of system.

* This method is Usefull for Large system.

* For Large system, a systematic algorithm is needed, so that a digital computer is used.



Sample n-bus system

Step 1:

Consider the Matrix equation,

$$Z_{bus}\, I = V$$

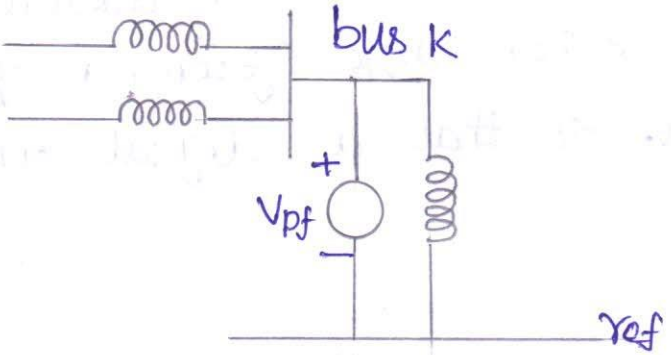
$$\begin{bmatrix} Z_{11} & Z_{12} \cdots & Z_{1k} \cdots & Z_{1n} \\ Z_{21} & Z_{22} \cdots & Z_{2k} \cdots & Z_{2n} \\ \vdots & & & \\ Z_{k1} & Z_{k2} \cdots & Z_{kk} \cdots & Z_{kn} \\ \vdots & & & \\ Z_{n1} & Z_{n2} \cdots & Z_{nk} \cdots & Z_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_k \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_k \\ \vdots \\ V_n \end{bmatrix}$$

Where $I_1, I_2, \ldots I_n \rightarrow$ current injected to bus 1,2,..n respectively.

$V_1, V_2, \ldots V_n \rightarrow$ Voltage at bus 1,2,..n respectively.

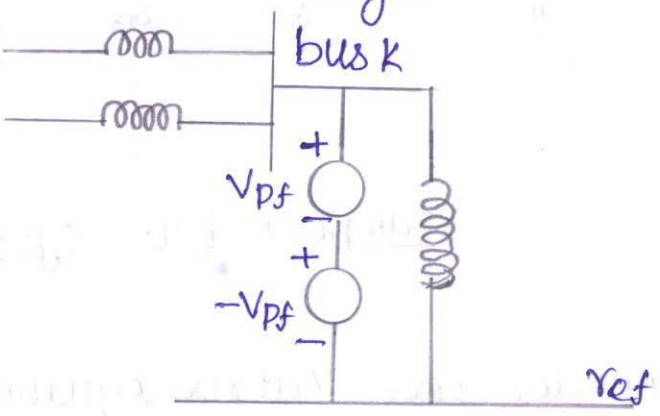
Step 2:

Let a 3φ fault occur in bus 'k', prefault voltage at bus 'k' is given by V_{pf}



Prefault condition

At fault condition, the source voltage "$-V_{pf}$" in series with prefault voltage



∴ Total voltage at bus 'k' is zero. Due to this fault, all other bus voltage will change. Let the change be $\Delta V_1, \Delta V_2 \ldots \Delta V_n$.

Step 3:

* Let us assume prefault current be zero.
* The fault current at bus 'k' is given by '$-I_f$' as the current flow away from bus 'k'
* Replace all sources by zero values, thus current injected to all buses are zero.
* The only source in the network is $-V_{pf}$ and the current injected to bus 'k' is '$-I_f$'
* prefault Voltage in all bus including bus 'k' is 1 p.u.
* Voltages in all other sources are only the change in Voltages.

The above said condition in matrix form,

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ -V_{pf} \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \cdots Z_{1k} \cdots Z_{1n} \\ Z_{21} & Z_{22} \cdots Z_{2k} \cdots Z_{2n} \\ \vdots & \\ Z_{k1} & Z_{k2} \cdots Z_{kk} \cdots Z_{kn} \\ \vdots & \\ Z_{n1} & Z_{n2} \cdots Z_{nk} \cdots Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -I_f \\ \vdots \\ 0 \end{bmatrix}$$

$$\Delta V_1 = -I_f Z_{1k}$$

$$\Delta V_2 = -I_f Z_{2k}$$

$$\vdots$$

$$-V_{pf} = -I_f Z_{kk}$$

$$\vdots$$

$$\Delta V_n = -I_f Z_{nk}$$

Generally, $\boxed{\Delta V_q = -I_f Z_{qk}}$

Step 4:

The fault current in bus k, is given by,

$$I_f = V_{pf} / Z_{kk}$$

If fault impedance Z_f present, then I_f is given by,

$$I_f = \frac{V_{pf}}{Z_{kk} + Z_f}$$

Step 5:

Voltages at all other bus during fault at bus 'k' is given by, sum of prefault voltage and change in voltage.

$$V_1 = V_{pf} + \Delta V_1$$

$$V_1 = V_{pf} - I_f Z_{1k} = 1\angle 0^\circ - I_f Z_{1k}$$

Where $V_{pf} = 1\angle 0^\circ$ during unloaded condition.

$$V_2 = V_{pf} - I_f Z_{2k} = 1\angle 0^\circ - I_f Z_{2k}$$

$$\vdots$$

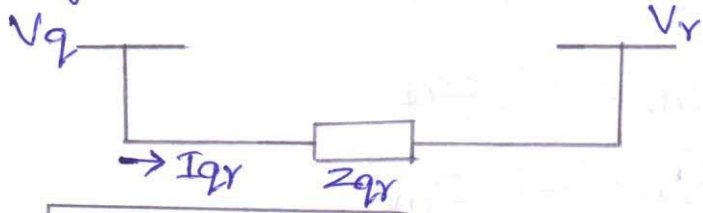
$$V_k = V_{pf} - V_{pf} = 0$$

$$\vdots$$

$$V_n = V_{pf} - I_f Z_{nk} = 1\angle 0^\circ - I_f Z_{nk}$$

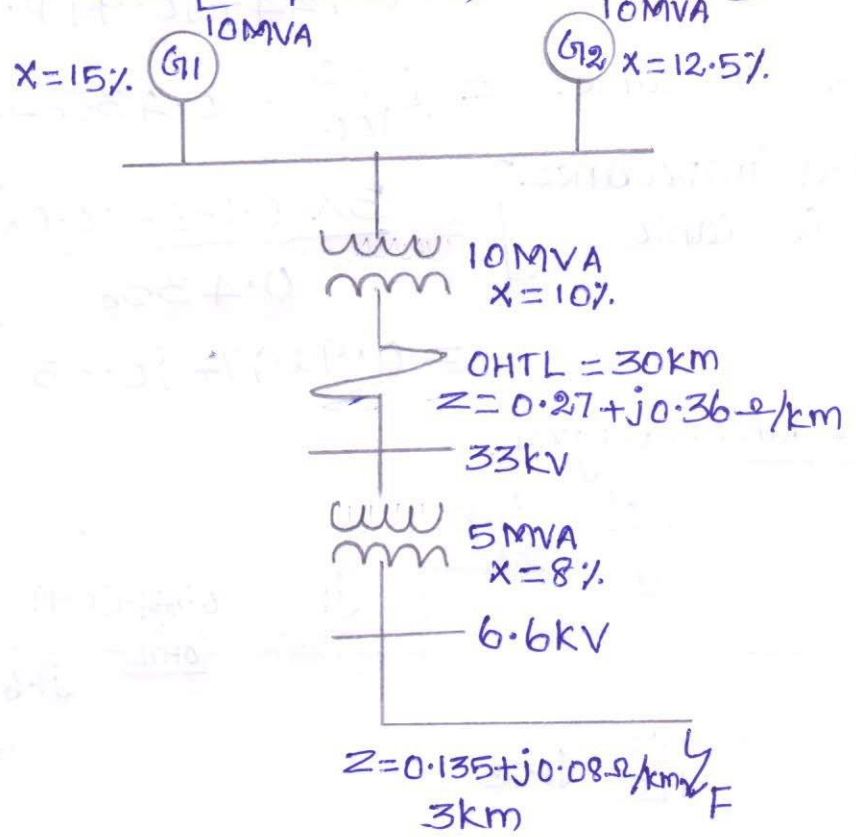
Step 6:

Fault current flowing through lines are given by



$$I_{qr} = \frac{V_q - V_r}{Z_{qr}}$$

2. For the radial network shown, 3φ fault occurs at F. Determine the fault current and the line voltage at 11KV bus under fault conditions. Consider Base MVA = 100. [Nov/Dec-14, Nov/Dec-12]



Solution:

Base MVA = 100

Base kV on Generator side = 11KV

Base kV on Overhead Tr. line = 33KV

Base kV on cable = 6.6 kV

$$X_{g1} = 0.15 \times \left(\frac{100}{10}\right) \times \left(\frac{11}{11}\right)^2 = 1.5 \text{ p.u}$$

$$X_{g2} = 0.125 \left(\frac{100}{10}\right) \times \left(\frac{11}{11}\right)^2 = 1.25 \text{ p.u}$$

$$X_{T1} = 0.1 \times \left(\frac{100}{10}\right) \times \left(\frac{11}{11}\right)^2 = 1 \text{ p.u}$$

$$X_{T2} = 0.08 \times \left(\frac{100}{5}\right) \times \left(\frac{33}{33}\right)^2 = 1.6 \text{ p.u}$$

Z_{base} in OHTL $= \frac{33^2}{100} = 10.89\ \Omega$

P.U impedance of OHTL $= \frac{30 \times [0.27 + j0.36]}{10.89}$

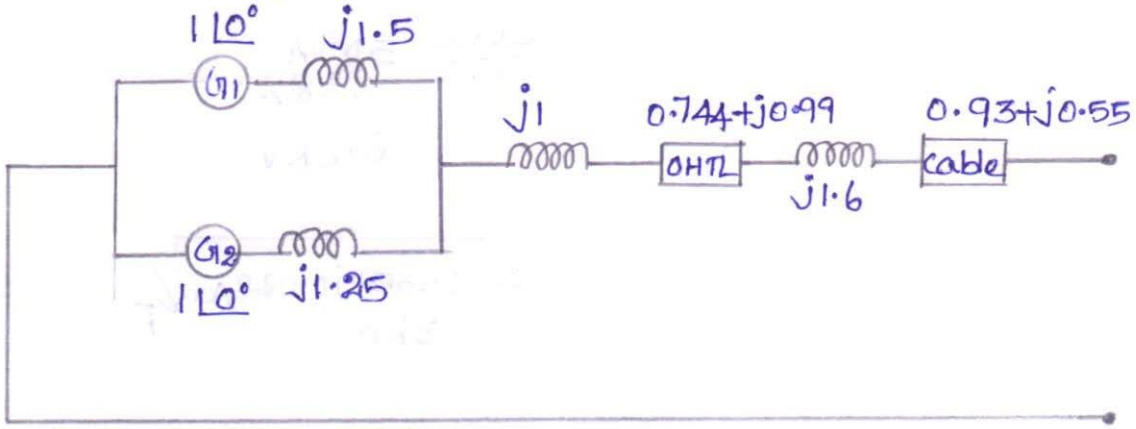
$= 0.744 + j0.99$ P.U

Z_{base} in cable $= \frac{6.6^2}{100} = 0.4356\ \Omega$

P.U impedance of cable $= \frac{3 \times (0.135 + j0.08)}{0.4356}$

$= 0.9297 + j0.55$

Impedance diagram



Fault occurs, when the generator are at no load condition. Therefore $V_t = 1\angle 0°$

$$X_{eq} = \frac{j1.5 \times j1.25}{j2.75} = j0.682$$

$$Z_{th} = j0.682 + j1 + 0.744 + j0.99 + j1.6 + 0.93 + j0.55$$

$$Z_{th} = 1.674 + j4.822$$

$$Z_{th} = 5.1\angle 70.8$$

Short circuit capacity

$$S_{cc} = \frac{100}{5.1} = 19.6\angle -70.8$$

$$I_f = \frac{S_{cc_{3\phi}} \times 10^6}{\sqrt{3}\, V_{lb} \times 10^3} = \frac{19.6\angle -70.8 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3}$$

$$I_f = 1714.55A$$

To find Line Voltage at 11KV bus during fault condition:

Total impedance between F and 11KV bus,

$$= 0.93 + j0.55 + j1.6 + 0.744 + j0.99 + j1$$
$$= 1.674 + j4.14$$

Total impedance between F & 11 KV bus $= 4.43\angle 67.8$ P.U

Voltage at 11KV bus in P.U $= Z_{PU} \times I_{PU}$

$$= 4.43\angle 67.8 \times 0.196\angle -70.8$$

Voltage at 11KV bus during fault $= 0.88\angle -3^\circ$ P.U

Actual Voltage at 11KV bus during fault $= 0.88 \times 11$

$$= 9.68 \text{ KV}$$

Line Voltage at 11KV bus during fault $= 9.68$ KV

3. A synchronous generator and motor are rated for 30,000 kVA, 13.2 kV and both have subtransient reactance of 20%. The line connecting them has a reactance of 10% on the base of machine ratings. The motor is drawing 20,000 kW at 0.8 pf leading. The terminal voltage of the motor is 12.8 kV. When a symmetrical three-phase fault occurs at motor terminals, find the subtransient current in generator, motor and at the fault point. (Nov/Dec-15)

Solution:

The single line diagram and the circuit model to compute subtransient fault current are shown in fig.

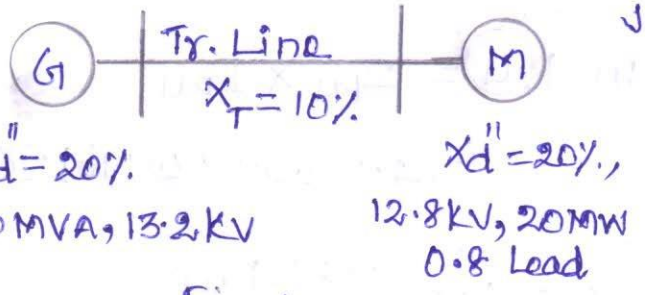


Fig. 1

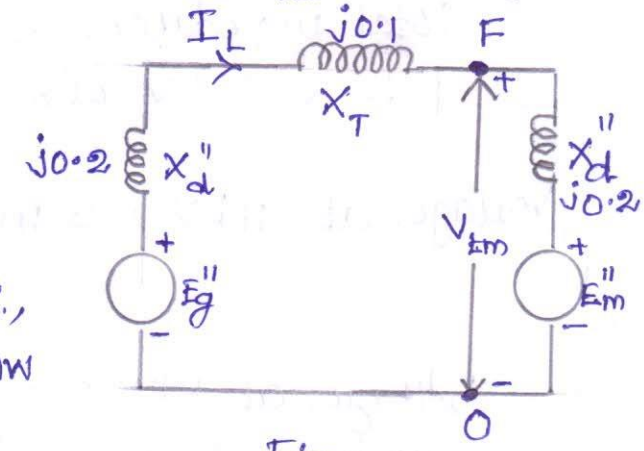


Fig. 2

In the figure-2, the generator and motor are represented by a source in series with subtransient reactance.

The base values are, $MVA_b = 30$ MVA;

$kV_b = 13.2$ kV

Base current $I_b = \frac{MVA_b \times 1000}{\sqrt{3} \times kV_b} = \frac{30 \times 1000}{\sqrt{3} \times 13.2}$

$= 1312.16\ A$

Actual value of prefault voltage at fault point, $V_{tm} = 12.8\ kV$

P.u. value of prefault voltage at fault point,

$$V_{tm} = \frac{\text{Actual value}}{\text{Base value}} = \frac{12.8}{13.2} = 0.9697\ p.u$$

Actual value of real power of the load,

$$P_m = 20\ MW,\ 0.8\ lead$$

P.U. value of real power of the load,

$$P_m = \frac{\text{Actual value}}{\text{Base value}} = \frac{20}{30} = 0.6667\ p.u$$

∴ P.U. value of magnitude of load current

$$|I| = \frac{P_m}{V_{tm} \cos\phi} = \frac{0.6667}{0.9697 \times 0.8} = 0.8594\ p.u$$

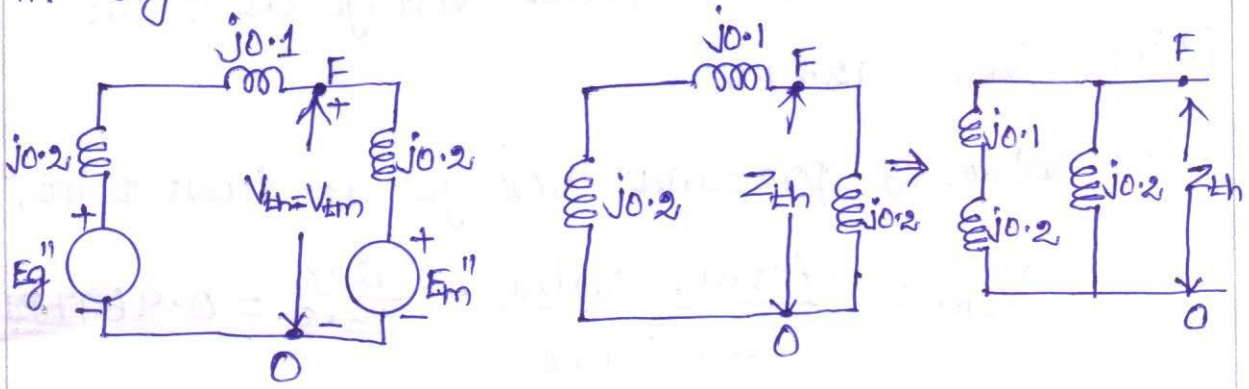
Let us take the terminal voltage of motor V_{tm} as reference vector and so the load current will lead the terminal voltage of motor with an angle $\cos^{-1} 0.8$

$\therefore V_{tm} = 0.9697 \angle 0^\circ\ p.u$

and $I_L = 0.8594 \angle \cos^{-1} 0.8 = 0.8594 \angle 36.9^\circ\ p.u$

To find fault current using Thevenin's theorem.

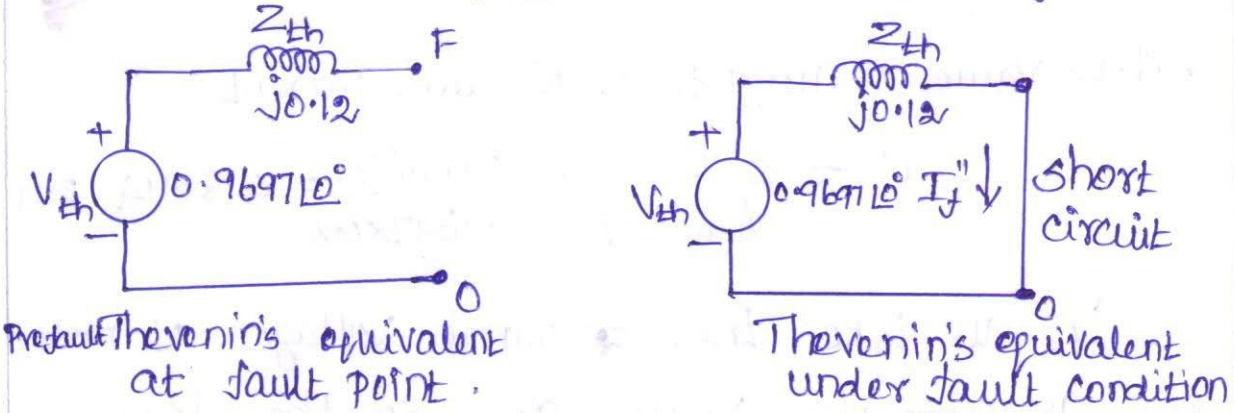
Consider the prefault circuit model shown in fig.



Thevenin's equivalent impedance,

$$Z_{th} = \frac{(j0.1 + j0.2)\,j0.2}{(j0.1 + j0.2) + j0.2} = j0.12$$

The thevenin's equivalent of the circuit respect to fault point is shown in fig.



Prefault Thevenin's equivalent at fault point.

Thevenin's equivalent under fault condition.

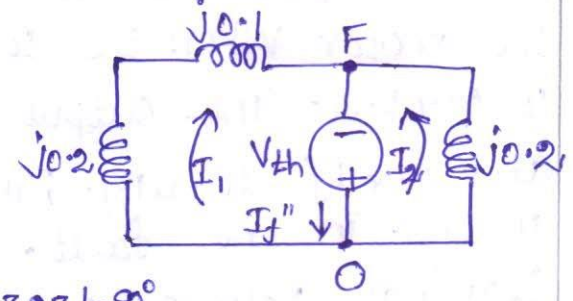
Current in the fault,

$$I_f'' = \frac{V_{th}}{Z_{th}} = \frac{0.9697\angle 0^\circ}{j0.12} = \frac{0.9697\angle 0^\circ}{0.12\angle 90^\circ}$$

$$= 8.081\angle -90^\circ \text{ P.U.}$$

To find the change in current due to fault:

The change in current due to fault can be calculated by connecting the thevenin's generator with reversed polarity at the fault point as shown in fig.



Now, $I_1 = \frac{V_{th}}{j0.2 + j0.1}$

$$I_1 = \frac{0.9697\angle 0^\circ}{0.3\angle 90^\circ} = 3.2323\angle -90^\circ$$

$$I_2 = \frac{V_{th}}{j0.2} = \frac{0.9697\angle 0^\circ}{0.2\angle 90^\circ} = 4.8485\angle -90^\circ$$

To find the subtransient fault current in motor and generator:

$$I_g'' = I_1 + I_L = 3.2323\angle -90^\circ + 0.8594\angle 36.9^\circ$$
$$= j3.2323 + 0.6872 + j0.516$$
$$= 0.6872 - j2.7163 = 2.802\angle -75.8^\circ \text{ P.u}$$

$$I_m'' = I_2 - I_L = 4.8485\angle -90^\circ - (0.8594\angle 36.9^\circ)$$
$$= -j4.8485 - (0.6872 + j0.516)$$
$$= -0.6872 - j5.3645 = 5.4083\angle -97.3^\circ \text{ PU}$$

Result:

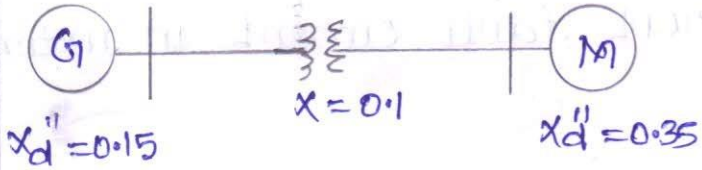
$I_g'' = 2.802\angle -75.8^\circ$ P.U

$I_m'' = 5.4085\angle -97.3^\circ$ PU

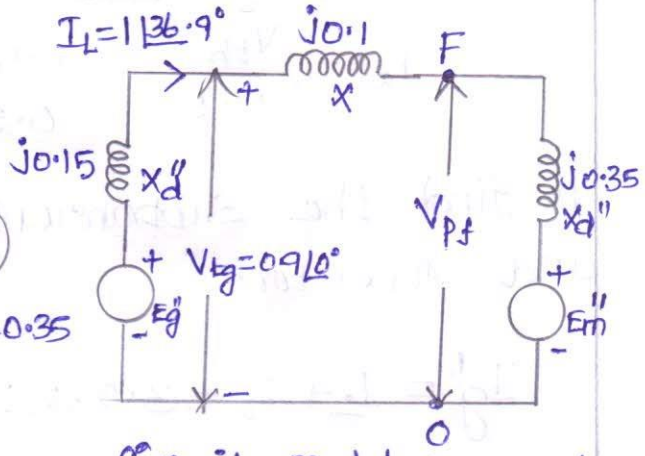
$I_f'' = 8.081\angle -90^\circ$ P.U.

4 A generator is connected through a transformer to a synchronous motor. The sub transient reactance of generator and motor are 0.15 and 0.35 respectively. The leakage reactance of the transformer is 0.1 pu. All the reactances are calculated on a common base, A three phase fault occurs at the terminals of the motor When the terminal voltage of the generator is 0.9 p.u. The output current of generator is 1 p.u. and 0.8 pf leading. Find the subtransient current in p.u. in the fault, generator and motor. Use the terminal voltage of generator as reference vector

Solution:



Single Line diagram

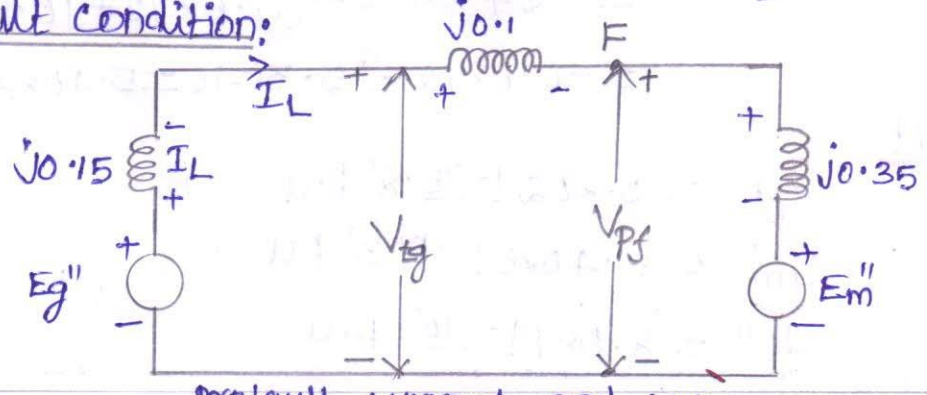


Circuit model to compute subtransient fault current

Load current in p.u, $I_L = 1\angle \cos^{-1} 0.8$

$= 1\angle 36.9°$ p.u

Prefault condition:



prefault current and voltages.

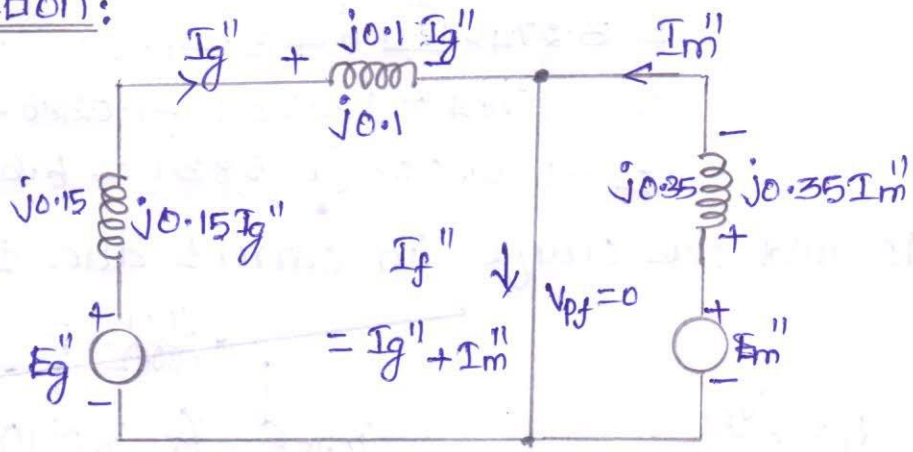
By applying KVL in the circuit,

$$E_g'' = j0.15 I_L + V_{tg}$$
$$= 0.15 \angle 90^\circ \times 1 \angle 36.9^\circ + 0.9 \angle 0^\circ$$
$$= 0.15 \angle 126.9^\circ + 0.9 \angle 0^\circ$$
$$= -0.0901 + j0.12 + 0.9$$
$$= 0.8099 + j0.12 = 0.8187 \angle 8.4^\circ \text{ p.u}$$

Using KVL in the circuit,

$$E_m'' + j0.35 I_L + j0.1 I_L = V_{tg}$$
$$\therefore E_m'' = V_{tg} - j0.45 I_L$$
$$= 0.9 \angle 0^\circ - (0.45 \angle 90^\circ \times 1 \angle 36.9^\circ)$$
$$= 0.9 \angle 0^\circ - (0.45 \angle 126.9^\circ)$$
$$= 0.9 - (-0.2702 + j0.3599) = 1.1702 - j0.3599$$
$$= 1.2243 \angle -17.1^\circ \text{ p.u.}$$

Fault condition:



Subtransient currents and voltages.

Using KVL in the circuit,

$$j0.15 I_g'' + 0.1 I_g'' = E_g'' \text{ (or)}$$

$$j0.25 I_g'' = E_g''$$

∴ Subtransient fault current in generator

$$I_g'' = \frac{E_g''}{j0.25} = \frac{0.8187 \angle 8.4^\circ}{0.25 \angle 90^\circ} = 3.2748 \angle -81.6^\circ \text{ p.u}$$

Using KVL in the circuit,

$$j0.35 I_m'' = E_m''$$

∴ Subtransient fault current in motor,

$$I_m'' = \frac{E_m''}{j0.35} = \frac{1.2243 \angle -17.1^\circ}{0.35 \angle 90^\circ}$$

$$= 3.498 \angle -107.1^\circ \text{ p.u.}$$

The current in the fault during subtransient state $I_f'' = I_g'' + I_m''$

$$= 3.2748 \angle -81.6^\circ + 3.498 \angle -107.1^\circ$$

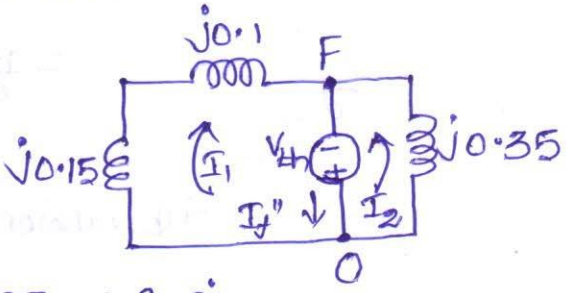
$$= 0.4784 - j3.2397 - 1.0286 - j3.3434$$

$$= -0.5502 - j6.5831 = 6.606 \angle -94.8^\circ \text{ p.u}$$

To find the change in current due to fault:

$$I_1 = \frac{V_{th}}{j0.15 + j0.1}$$

$$= \frac{0.9633 \angle -4.8^\circ}{0.25 \angle 90^\circ} = 3.8532 \angle -94.8^\circ$$



$$I_2 = \frac{V_{th}}{j0.35} = \frac{0.9633\angle -4.8^\circ}{0.35\angle 90^\circ} = 2.7523\angle -94.8^\circ \text{ p.u}$$

To find the subtransient fault current in motor and generator:

$$I_g'' = I_1 + I_L = 3.8532\angle -94.8^\circ + 1\angle 36.9^\circ$$
$$= -0.3224 - j3.8397 + 0.7997 + j0.6004$$
$$= 0.4773 - j3.2393$$
$$= 3.274\angle -81.6^\circ \text{ p.u}$$

$$I_m'' = I_2 - I_L = 2.7523\angle -94.8^\circ - 1\angle 36.9^\circ$$
$$= -0.2303 - j2.7426 - (0.7997 + j0.6004)$$
$$= -1.03 - j3.343 = 3.498\angle -107.1^\circ \text{ p.u}$$

Result:

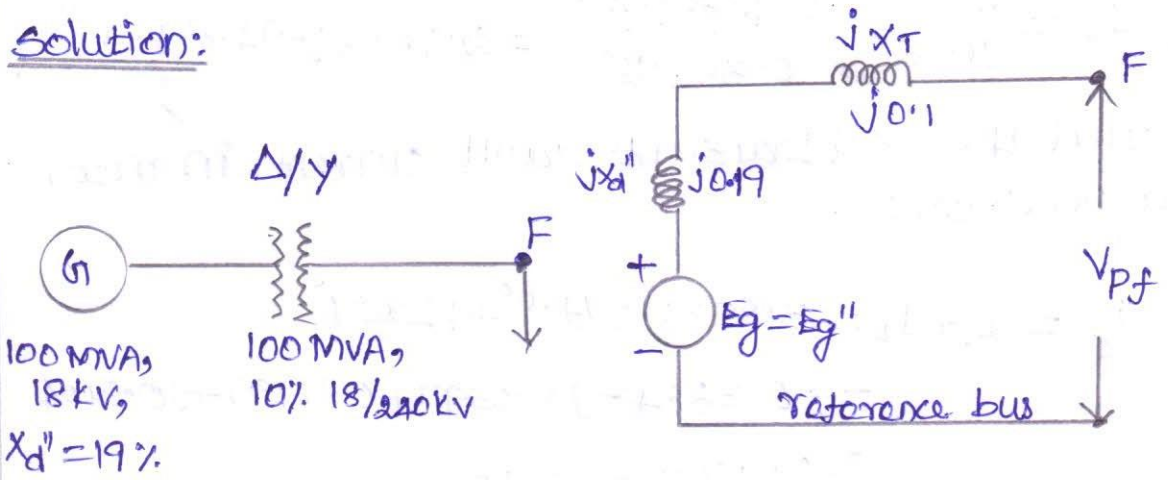
$I_g'' = 3.274\angle -81.6^\circ$ p.u

$I_m'' = 3.498\angle -107.1$ p.u

$I_f'' = 6.606\angle -94.8^\circ$ p.u

5. A generator is connected through a circuit breaker to a transformer. The ratings of the generator are 100 MVA, 18kV, $X_d'' = 19\%$, $X_d' = 26\%$ and $X_d = 130\%$. The transformer ratings are 100 MVA, 240/18kV, Y–Δ, $X = 10\%$. With 18kV on Δ side. If a 3-phase short circuit occurs on the high tension side of a transformer at rated voltage and no load, find a) initial symmetrical rms current in the transformer winding on the high tension side. b) The initial symmetrical rms current in the line on low tension side.

Solution:



Let us choose the generator rating as base values,

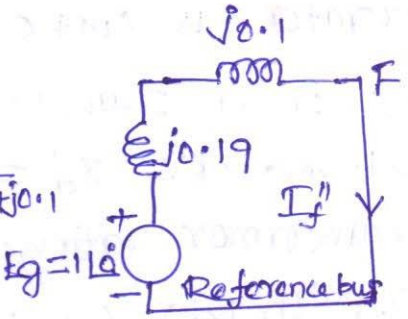
$\therefore MVA_b = 100 MVA$, $kV_b = 18 kV$

Subtransient reactance of generator, $X_d'' = 19\% = 0.19$ P.U.

Leakage reactance of transformer, $X_T = 10\% = 0.1$ P.U.

Prefault voltage, $V_{pf} = E_g = 1\angle 0^\circ$ P.U.

The fault condition reactance diagram is shown in fig.



The P.U. value of initial symmetrical fault current $I_f'' = \frac{E_g}{j0.19 + j0.1}$

$$I_f'' = \frac{1\angle 0^\circ}{0.29\angle 90^\circ} = 3.4483\angle -90^\circ$$

$$|I_f''| = 3.4483 \text{ P.U.}$$

Base kV on HT Side of transformer $= 18 \times \frac{240}{18}$

$= 240\,kV$

Base current on HT Side of transformer

$= \frac{kVA_b}{\sqrt{3}\,kV_b} = \frac{100 \times 1000}{\sqrt{3} \times 240} = 240.56A$

The HT Winding of the transformer is star connected and so the fault current in the transformer winding is same as the fault current in the line.

∴ P.U Value of initial symmetrical fault current on the HT Winding of transformer $= |I_f''| = 3.4483\,P.U$

Actual Value of initial symmetrical fault current on the HT Winding of transformer = P.U. Value × Base current

$= 3.4483 \times 240.56 = 829.5A$

(or) $0.8295\,kA$

The LT Winding of transformer is delta connected but the transmission line is considered as star circuit.

∴ Base current on LT side of transformer $= \frac{kVA_b}{\sqrt{3}\,kV_b} = \frac{100 \times 1000}{\sqrt{3} \times 18}$

$= 3207.5A$

∴ P.U. Value of initial symmetrical fault current on the LT Line $= |I_f''| = 3.4483\,P.U$

Actual Value of initial symmetrical fault current on the LT Line = P.U. Value × Base current

$= 3.4483 \times 3207.5 = 11060.4\,A$

$= 11.0604\,KA$

Actual value of initial symmetrical fault current on the LT winding of transformer $= \frac{11.0604}{\sqrt{3}}$

$= 6.3857\,KA$

6. The bus impedance matrix of 4 bus system with values in p.u. is given by,

$$Z_{bus} = j\begin{bmatrix} 0.1488 & 0.0651 & 0.0864 & 0.0978 \\ 0.0651 & 0.01554 & 0.0799 & 0.0967 \\ 0.0864 & 0.0798 & 0.1314 & 0.1058 \\ 0.0978 & 0.0967 & 0.1058 & 0.1566 \end{bmatrix}$$

If a 3φ fault occurs at bus 1 when there is no load, find the subtransient current in the fault and voltages at all buses. Also find the subtransient current supplied by generator connected to bus 2 by taking the subtransient reactance of generator as $j0.2$ p.u. The prefault voltage is 1 pu.

Solution:

To find sub. transient current in fault.

$$I_f'' = \frac{V_{pf}}{Z_{kk}} = \frac{1\angle 0^\circ}{Z_{11}} = \frac{1\angle 0^\circ}{0.1488\angle 90^\circ}$$

$$I_f'' = 6.72 \angle -90^\circ \text{ P.U}$$

Voltage at all bus:

$$V_1 = V_{pf} - V_{pf} = 0$$

$$V_2 = V_{pf} - I_f'' Z_{2K} = 1 + j0 - [j\,6.72 \times j0.0651]$$

$$V_2 = 0.5625 \text{ p.u}$$

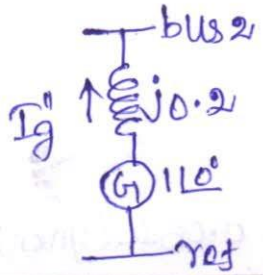
$$V_3 = 1 + j0 - [j6.72 \times j0.0864]$$

$$V_3 = 0.4193 \text{ p.u.}$$

$$V_4 = 1 + j0 - [j6.72 \times j0.0978]$$

$$V_4 = 0.3427 \text{ p.u}$$

Sub transient current supplied by generator:



$$I_g'' = \frac{1\angle 0^\circ - 0.5625\angle 0^\circ}{0.2\angle 90^\circ}$$

$$= 2.1875 \angle -90^\circ$$

$$I_g'' = 2.1875 \text{ P.U}$$

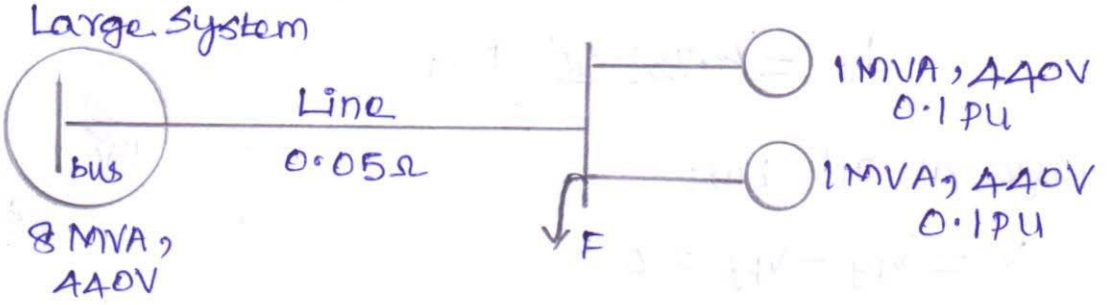
7. TWO synchronous motors are connected to the bus of a large system through a short transmission line as shown. The rating of various components are,

Motors [each] : 1MVA, 440V, 0.1 p.u

Transient reactance Line : 0.05 Ω reactance.

Large system : short circuit MVA and its bus at 440V is ∞

When the motors are operating at 440V, calculate the short circuit current fed into a 3φ fault at motor bus.



Solution:

Taking 8MVA as base MVA

440V → 0.44kV as base kV,

P.U, impedance of large system,

Base MVA = 8

$Scc = S_b / Z_{th} = \frac{8}{Z_{th}} = 8$

$Z_{th} = 1$ P.U

Motor P.U. impedance

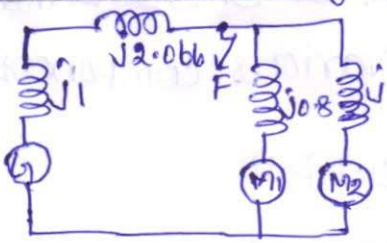
X_m p.u $= 0.1 \times 8/1 = 0.8$ p.u

Line impedance;

$Z_{base} = \frac{(0.440)^2}{8} = 0.0242\ \Omega$; $Z_{actual} = 0.05\ \Omega$ (given)

P.U Impedance of line $= \frac{0.05}{0.0242} = 2.066$ P.U

The reactance diagram



$Z_{th} = \frac{1}{(j1 + j2.066)} + \left[\frac{1}{j0.8 \| j0.8}\right]$

$= \frac{1}{j3.066} + \frac{1}{j0.4}$

$Z_{th} = j0.3538$

Scc MVA at fault $= \frac{8}{|0.3538|} = 22.6$ MVA

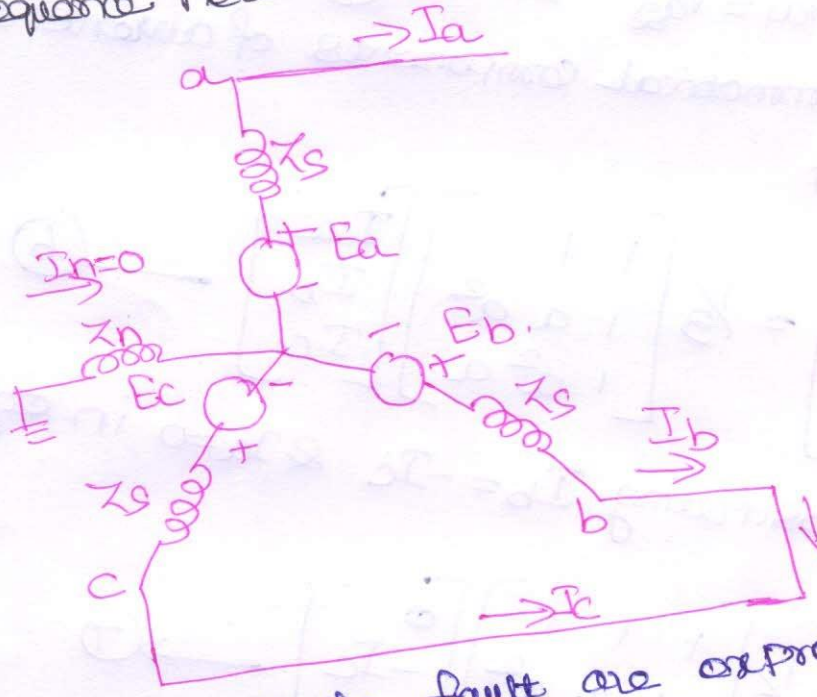
SC current $= \frac{Scc \times 10^6}{\sqrt{3} \times V_{LL} \times 10^3} = \frac{22.6 \times 10^6}{\sqrt{3} \times 440} = 30$ kA

SC current = 30 kA

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Unit – IV – Unsymmetrical Fault Analysis
PART-B Questions:

1. Derive the necessary equation to determine the fault current for a line-to-line fault. Draw a diagram showing the interconnection of sequence networks. NOV/DEC 2013.



The connection at the fault are expressed by the following equations.

$V_b = V_c$; $I_a = 0$

$I_b + I_c = 0 \Rightarrow I_b = -I_c$ —(1)

with $V_c = V_b$. The symmetrical components of voltage are given by

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{—(2)}$$

on multiplying row 2 & 3 of eq (2) we get.

$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c)$ —(3)

$$V_{a2} = \frac{1}{3}\left[V_a + a^2 V_b + a V_b\right] \quad \text{——④}$$

from eq ③ & ④, we can write

$$V_{a1} = V_{a2} \quad \text{——⑤}$$

The symmetrical components of current are given by

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad \text{——⑥}$$

on substituting $I_b = -I_c$ & $I_a = 0$ in eq ⑥

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ a1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ -I_c \\ I_c \end{bmatrix} \quad \text{——⑦}$$

$$I_{a0} = \frac{1}{3}\left[-I_c + I_c\right] = 0$$

$$I_{a1} = \frac{1}{3}\left[-aI_c + a^2 I_c\right] \quad \text{——⑧}$$

$$I_{a2} = \frac{1}{3}\left[-a^2 I_c + aI_c\right] = -\frac{1}{3}\left[-aI_c + a^2 I_c\right] \quad \text{——⑨}$$

$$I_{a2} = -I_{a1} \quad \text{——⑩}$$

from eq ⑧ & ⑨

From the sequence network of the generator we get the following matrix equation

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{— (11)}$$

Sub $I_{a0} = 0$, $I_{a2} = -I_{a1}$ in eq (11)

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} 0 \\ I_{a1} \\ -I_{a1} \end{bmatrix} \quad \text{— (12)}$$

on multiplying eq (12)

$$V_{a0} = 0$$

$$V_{a1} = E_a - Z_1 I_{a1} \quad \text{— (13)}$$

$$V_{a2} = Z_2 I_{a1} \quad \text{— (14)}$$

From eq (5) we know that $V_{a1} = V_{a2}$

∴ equating eq (13) & (14)

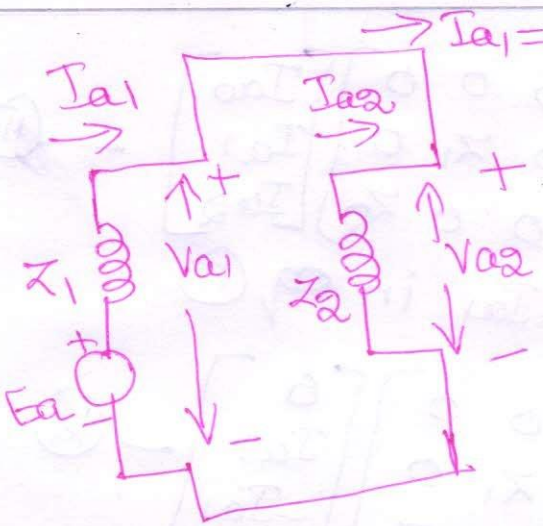
$$E_a - Z_1 I_{a1} = Z_2 I_{a1}$$

$$E_a = Z_1 I_{a1} + Z_2 I_{a1} = I_{a1}[Z_1 + Z_2]$$

$$I_{a1} = \frac{E_a}{Z_1 + Z_2} \quad \text{— (15)}$$

Hence the fault current

$$I_f = I_b = -I_c$$



$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{— (16)}$$

$$I_b = I_{a0} + a^2 I_{a1} + a I_{a2} \quad \text{— (17)}$$

Sub $I_{a0} = 0$, $I_{a2} = -I_{a1}$

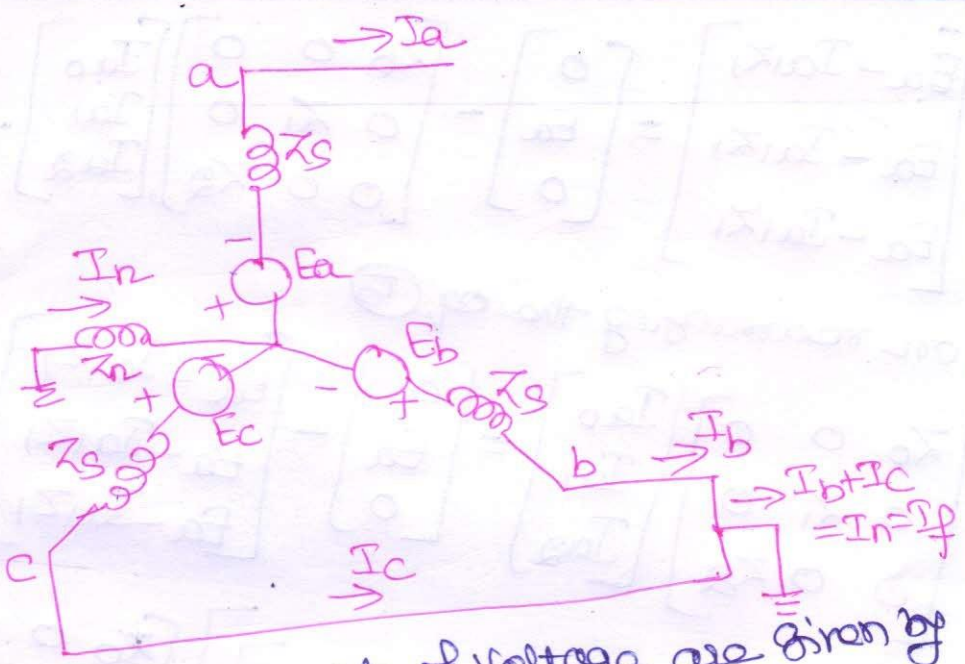
$$\therefore I_b = a^2 I_{a1} - a I_{a1} = I_{a1}(a^2 - a). \quad \text{— (18)}$$

$\therefore$ fault current $I_f = I_b = I_{a1}(a^2 - a)$

2. Draw the sequence network connection for a double line to ground fault at any point in a power system & from that obtain an expression for the fault current. NOV/DEC 18.

The conditions at the fault are expressed by the following equation.

$V_b = 0$, $V_c = 0$, $I_a = 0$. with $V_b = V_c = 0$.



The Symmetrical Component of voltage are given by

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ 0 \\ 0 \end{bmatrix} \quad \text{—①}$$

$$V_{a0} = V_{a1} = V_{a2} = \frac{V_a}{3} \quad \text{—②}$$

From the sequence network of the generator

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{—③}$$

$$V_{a1} = E_a - I_{a1}Z_1 \quad \text{—④}$$

from eq ② we get $V_{a0} = V_{a1} = V_{a2} = E_a - I_{a1}Z_1$.

Sub $V_{a0} = V_{a1} = V_{a2} = E_a - I_{a1}Z_1$ in eq ③

$$\begin{bmatrix} E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{---(5)}$$

on rearranging the eq (5)

$$\begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \end{bmatrix} \quad \text{---(6)}$$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \left[\begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \end{bmatrix} \right] \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}^{-1}$$

$$= \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} \begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix} - \begin{bmatrix} \frac{1}{Z_0} & 0 & 0 \\ 0 & \frac{1}{Z_1} & 0 \\ 0 & 0 & \frac{1}{Z_2} \end{bmatrix} \begin{bmatrix} E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \\ E_a - I_{a1}Z_1 \end{bmatrix}$$

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{E_a}{Z_1} \\ 0 \end{bmatrix} - \begin{bmatrix} \frac{E_a - I_{a1}Z_1}{Z_0} \\ \frac{E_a - I_{a1}Z_1}{Z_1} \\ \frac{E_a - I_{a1}Z_1}{Z_2} \end{bmatrix} \quad \text{---(7)}$$

$$I_{ao} = -\left(\frac{E_a - I_{a1}Z_1}{Z_0}\right) = -\frac{E_a}{Z_0} + \frac{I_{a1}Z_1}{Z_0} \quad \text{—(8)}$$

$$I_{a1} = \frac{E_a}{Z_1} - \left(\frac{E_a - I_{a1}Z_1}{Z_1}\right) = \frac{E_a}{Z_1} - \frac{E_a}{Z_1} + \frac{I_{a1}Z_1}{Z_1}$$

$$I_{a1} = I_{a1} \quad \text{—(9)}$$

$$I_{a2} = \left(\frac{E_a - I_{a1}Z_1}{Z_2}\right) = -\frac{E_a}{Z_2} + \frac{I_{a1}Z_1}{Z_2} \quad \text{—(10)}$$

Here $I_a = 0$

$$I_a = I_{ao} + I_{a1} + I_{a2} = 0 \quad \text{—(11)}$$

Sub I_{ao}, I_{a1}, I_{a2} in eq (11).

$$-\frac{E_a}{Z_0} + \frac{I_{a1}Z_1}{Z_0} + I_{a1} - \frac{E_a}{Z_2} + \frac{I_{a1}Z_1}{Z_2} = 0.$$

$$I_{a1}\left(\frac{Z_1}{Z_0} + 1 + \frac{Z_1}{Z_2}\right) = \frac{E_a}{Z_0} + \frac{E_a}{Z_2}$$

$$I_{a1}\left[1 + Z_1\left(\frac{1}{Z_0} + \frac{1}{Z_2}\right)\right] = E_a\left[\frac{1}{Z_0} + \frac{1}{Z_2}\right]$$

$$I_{a1}\left[1 + Z_1\left[\frac{Z_2 + Z_0}{Z_0 Z_2}\right]\right] = E_a\left[\frac{Z_2 + Z_0}{Z_0 Z_2}\right] \quad \text{—(12)}$$

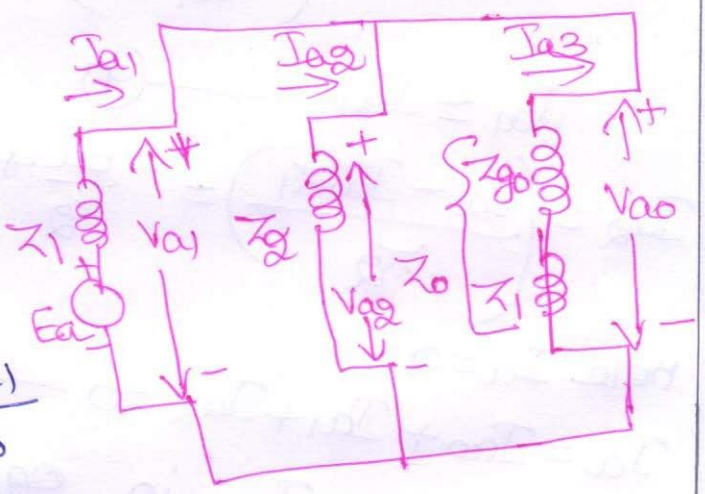
on multiplying the eq (12) throughout by $\frac{Z_0 Z_2}{Z_0 + Z_2}$

$$I_{a1}\left[\frac{Z_0 Z_2}{Z_0 + Z_2} + Z_1\right] = E_a.$$

$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_0 Z_2}{Z_0 + Z_2}} \quad \text{— (13)}$$

Here the fault current

$$I_f = I_b + I_c \quad \text{— (14)}$$



$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_0 Z_2}{Z_0 + Z_2}}$$

$$I_{ao} = \frac{-E_a}{Z_0} + \frac{I_{a1} Z_1}{Z_0}$$

$$I_{a2} = \frac{-E_a}{Z_2} + \frac{I_{a1} Z_1}{Z_2}$$

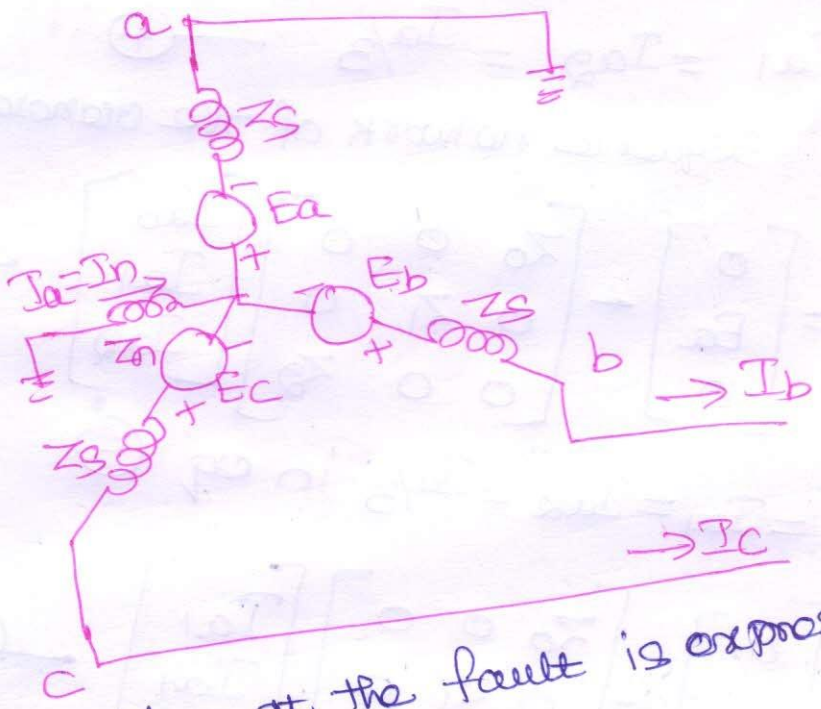
$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{— (15)}$$

$$I_b = I_{ao} + a^2 I_{a1} + a I_{a2}; \quad I_c = I_{ao} + a I_{a1} + a^2 I_{a2}$$

$$\begin{aligned} I_f &= I_b + I_c \\ &= I_{ao} + a^2 I_{a1} + a I_{a2} + I_{ao} + a I_{a1} + a^2 I_{a2} \\ &= 2 I_{ao} + (a + a^2) I_{a1} + (a + a^2) I_{a2} \\ &= 2 I_{ao} + (a + a^2)(I_{a1} + I_{a2}) \quad \text{— (16)} \end{aligned}$$

$$I_f = 2 I_{ao} + (a + a^2)(I_{a1} + I_{a2})$$

3 Derive the necessary equation to determine the fault current for a single line to ground fault. Draw a diagram showing the interconnection of sequence networks.



The condition at the fault is expressed by the following equation

$I_b = 0$; $I_c = 0$; $V_a = 0$ — (1).

The symmetrical components of the currents are given by

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad \text{— (2)}$$

Sub $I_b = I_c = 0$ in eq (2)

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} \quad \text{—(3)}$$

$$I_{ao} = I_{a1} = I_{a2} = I_a/3 \quad \text{—(4)}$$

from the sequence network of the generator

$$\begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{—(5)}$$

sub $I_{ao} = I_{a1} = I_{a2} = I_a/3$ in eq (5)

$$\begin{bmatrix} V_{ao} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix}\begin{bmatrix} I_{a1} \\ I_{a1} \\ I_{a1} \end{bmatrix} \quad \text{—(6)}$$

$$V_{ao} = -Z_0 I_{a1} \quad \text{—(7)}$$

$$V_{a1} = E_a - Z_1 I_{a1} \quad \text{—(8)}$$

$$V_{a2} = -Z_2 I_{a1} \quad \text{—(9)}$$

$$V_a = V_{ao} + V_{a1} + V_{a2}$$

$$0 = -Z_0 I_{a1} + E_a - Z_1 I_{a1} - Z_2 I_{a1} \quad \text{—(10)}$$

$$E_a = I_{a1}(Z_0 + Z_1 + Z_2)$$

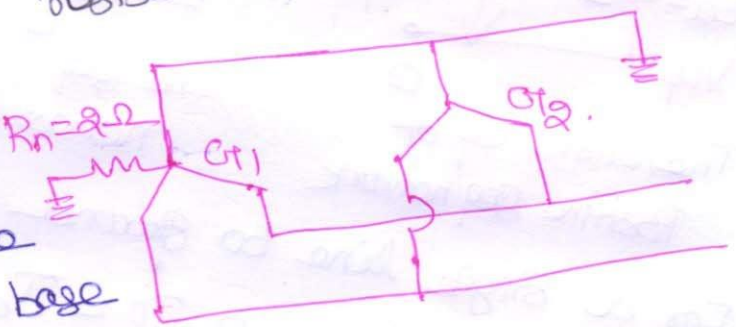
$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + Z_0} \quad \text{—— (11)}$$

Here the fault current is given by

$$I_f = I_a = 3I_{a1} \quad \text{—— (12)}$$

4. Two 11KV, 20MVA, 3ϕ, star connected generators operate in parallel as shown in figure. The positive, negative and zero sequence reactances of each being respectively j0.18, j0.15, j0.10Ω. The star point of one of the generator is isolated and that of the other is earthed through a 2.0Ω resistor. A single line to ground fault occurs at the terminals of one of the generators. To estimate i) fault current. ii) Current in grounded resistor iii) voltage across grounding resistor.

Sol :-

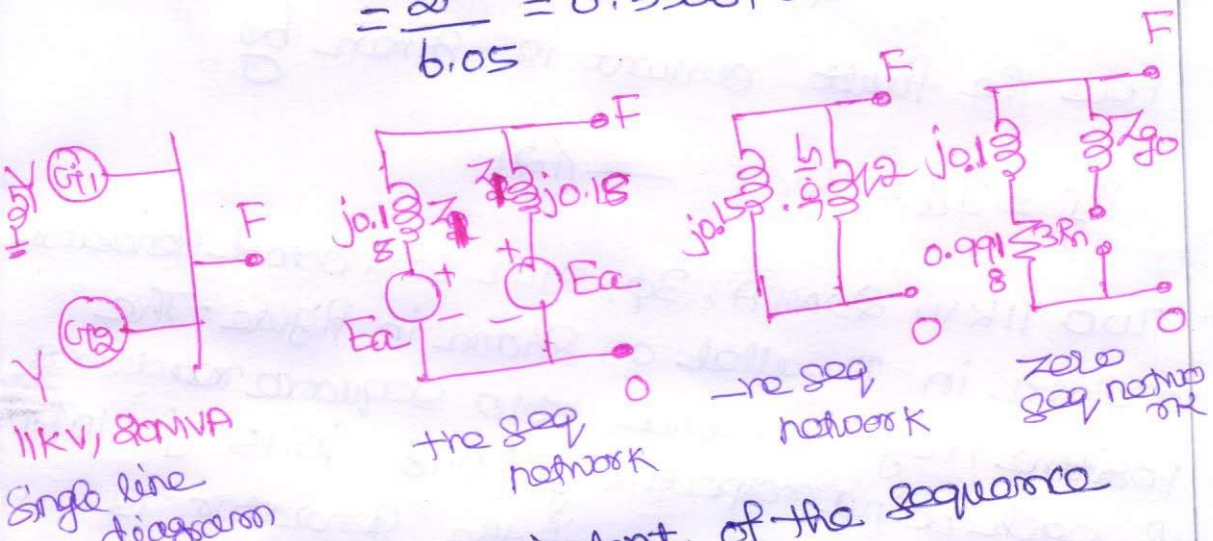


Let us choose the generator rating as base values $MVA_b = 20MVA$; $KV_b = 11KV$.

Base impedance $Z_b = \frac{KV_b^2}{MVA_b} = \frac{11^2}{20} = 6.05\Omega$.

P.U. Value of neutral resistance = $\frac{\text{Actual}}{\text{Base}}$

$= \frac{2}{6.05} = 0.3306$ P.U.



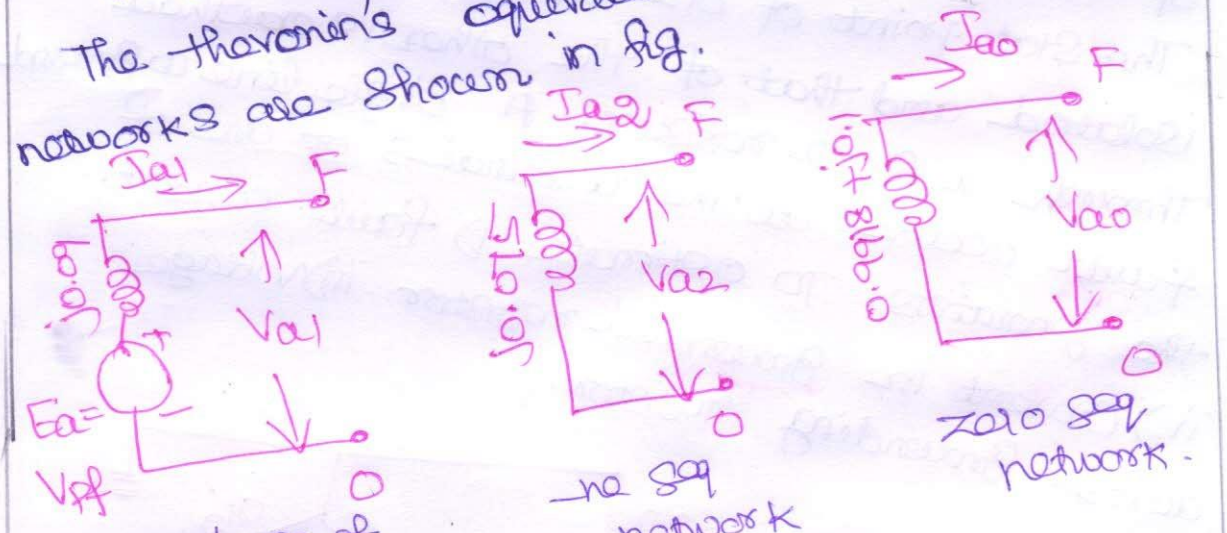
11KV, 50MVA Single line diagram

+ve seq network

-ve seq network

zero seq network

The thavonin's equivalent of the sequence networks are shown in fig.



Thavonin's eq of Positive seq network

-ve seq network

zero seq network.

For a single line to ground fault.

$I_{a1} = I_{a2} = I_{ao}$ & $I_f = I_a = 3I_{a1}$

$V_{af} = 1$ P.U.

$$I_{a1} = \frac{1\angle 0^\circ}{j0.09 + j0.0915 + 0.9918 + j0.1}$$

$$= \frac{1}{0.9918 + j0.265} = \frac{1}{1.0266 \angle 15^\circ}$$

$$I_{a1} = 0.9741 \angle -15^\circ \text{ P.U.}$$

i) To find fault current

Fault current $I_f = I_a = 3I_{a1}$

$$= 3 \times 0.9741 \angle -15^\circ$$

$$= 2.9223 \angle -15^\circ \text{ P.U.}$$

Base current $I_b = \frac{KVA_b}{\sqrt{3} KV_b} = \frac{20 \times 1000}{\sqrt{3} \times 11}$

$$I_b = 1049.7 A$$

Actual Value of I_f = P.U. value × Base current.

$$= 2.9223 \angle -15^\circ \times 1049.7$$

$$= 3067.5 \angle -15^\circ A.$$

$$= 3.0675 \angle -15^\circ A.$$

ii) To find the current through neutral resistor

The current through the neutral resistor is same as that of fault current.

$$= 2.9223 \angle -15^\circ \text{ P.U. or } 3.0675 \angle -15^\circ KA$$

iii) To find the voltage across grounding resistor:-

Grounding resistor $= 3R_n I_{a0} = 3R_n I_{a1}$

$$= 3 \times 0.3306 \times 0.9741 \angle -15^\circ = 0.9661 \angle -15^\circ \text{ P.U.}$$

Actual value of voltage across grounding resistor = P.U. value $\times \frac{KV_b}{\sqrt{3}}$

$= 0.9661 \angle -15^\circ \times \frac{11}{\sqrt{3}}$

$= 6.1356 \angle -15^\circ$ KV.

5. A Generator of negligible resistance having 1 P.U. voltage behind transient reactance is subjected to different types of fault.

Type of fault	Resulting fault current in P.U.
3φ	3.33
L-L	2.23
L-G	3.01

Calculate the per unit value of 3 sequence reactances.

Sol :-

i) 3φ fault :-

Given that $E_g' = 1$ P.U.

$I' = 3.33$ P.U.

When load current is neglected

$E_g'' = E_g' = E_g = E_a$.

$\therefore X_d' = \frac{|E_a|}{(I')} = \frac{1}{3.33} = 0.3$ P.U.

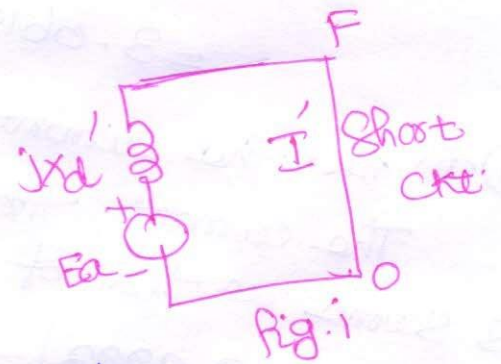


Fig. 1

∴ positive sequence reactance of generator $X_1 = X_d' = 0.3$ P.U.

ii) L-L Fault:- $I_{a1} = -I_{a2}$

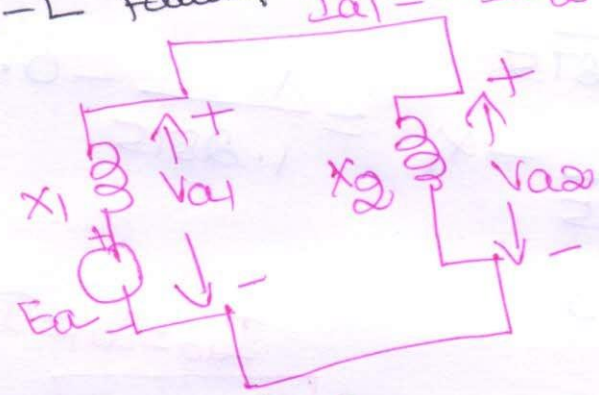


Fig 2.

From fig. 2

$$I_{a1} = \frac{E_a}{jX_1 + jX_2} = \frac{E_a}{X_1 + X_2} \quad \text{—(1)}$$

$I_b = I_{a0} + a^2 I_{a1} + a I_{a2}$

For L-L fault $I_{a0} = 0$, $I_{a2} = -I_{a1}$

$I_b = 0 + a^2 I_{a1} - a I_{a1} = I_{a1}(a^2 - a)$

$I_b = I_{a1}[(-0.5 - j0.866) - (-0.5 + j0.866)]$

$I_b = I_{a1}(-j1.732) = -j1.732 I_{a1}$

fault current, $I_f = |I_b| = 1.732\ |I_{a1}|$

$|I_{a1}| = \frac{I_f}{1.732}$ Given that $I_f = 2.23$ P.U.

$|I_{a1}| = \frac{2.23}{1.732} = 1.2875$ P.U —(2)

from eq ① & ②

$$1.2875 = \frac{Ea}{X_1 + X_2}$$

$$X_1 + X_2 = \frac{Ea}{1.2875}$$

$$X_2 = \frac{Ea}{1.2875} - X_1 = \frac{1}{1.2875} - 0.3$$

$$X_2 = 0.48 \text{ P.U.}$$

iii) L-G fault.

$I_f = 3.01$ P.U.

$3|I_{a1}| = I_f = 3.01$

$$|I_{a1}| = \frac{3.01}{3} = 1.0033 \text{ P.U.}$$

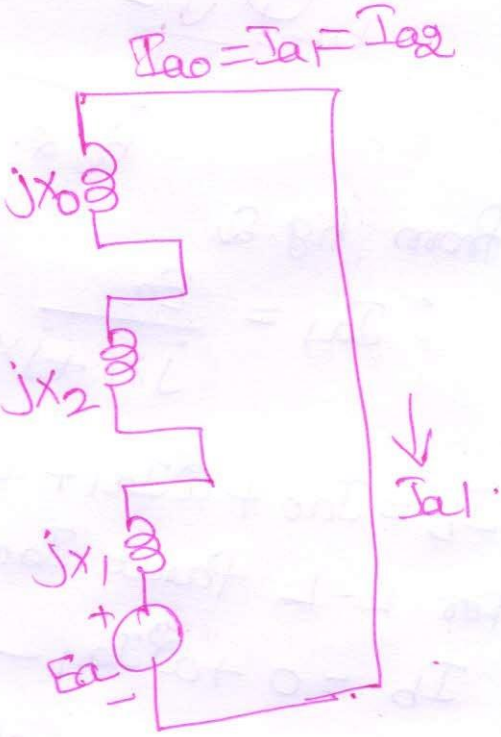
$$I_{a1} = \frac{Ea}{jX_1 + jX_2 + jX_0}$$

$$|I_{a1}| = \frac{Ea}{X_1 + X_2 + X_0}$$

$$X_0 + X_1 + X_2 = \frac{Ea}{|I_{a1}|}$$

$$X_0 = \frac{Ea}{|I_{a1}|} - X_1 - X_2 = \frac{1}{1.0033} - 0.3 - 0.48$$

$$X_0 = 0.22 \text{ P.U.}$$



6) i) A 30MVA, 11KV 3φ Synchronous generator has a direct subtransient reactance of 0.25 P.U. The negative & zero sequence reactance are 0.35 & 0.1 P.U. respectively. The neutral of the generator is solidly grounded. Determine the subtransient current in the generator & the line to line voltage for subtransient condition when a single line to ground fault occurs at the generator terminals with the generator operating unloaded at rated voltage N/D15.

Sol:-

$MVA_b = 30MVA$; $KV_b = 11KV$.

Base current $I_b = \frac{KVA_b}{\sqrt{3}KV_b} = \frac{30\times1000}{\sqrt{3}\times11} = 1574.59\ A$

$Z_1 = j0.25PU$, $Z_2 = j0.35PU$, $Z_0 = j0.1PU$.

Single line to ground fault

$I_{a0} = I_{a1} = I_{a2}$; $I_f = I_a = 3I_{a1}$

$I_{a1} = \frac{E_a}{Z_1+Z_2+Z_0}$; $E_a = 1\ P.U.$

$I_{a1} = \frac{1}{j0.25+j0.35+j0.1} = -j1.43 = 1.43\angle -90^\circ\ P.U.$

Subtransient fault current in P.U $I_f'' = |I_a|$

$= 3|I_{a1}| = 3\times1.43 = 4.29\ P.U.$

Actual value = P.U × Base $= 4.29\times1574.59$

$= 6754.99A = 6.7599\ KA.$

Phase - a voltages are

$V_{a1} = E_a - I_{a1}Z_1 = 1-(-j1.43)(j0.25) = 0.693\ P.U.$

$V_{a2} = -I_{a2}Z_2 = -(-j1.43)(j0.35) = -0.50\ P.U.$

$V_{ao} = -I_{ao}Z_0 = -(-j1.43)(j0.1) = -0.143$ P.U.

$V_a = V_{ao} + V_{a1} + V_{a2} = 0.643 - 0.5 - 0.143 = 0$

$V_b = V_{ao} + a^2V_{a1} + aV_{a2} = -0.215 - j0.99$ P.U.

$V_c = V_{ao} + aV_{a1} + a^2V_{a2} = -0.215 + j0.99$ P.U.

Line to line voltages.

$V_{ab} = V_a - V_b = 1.01\angle 77.7^\circ$ P.U ; $V_{bc} = V_b - V_c = 1.98\angle 270^\circ$ P.U.

Phase value of base voltage $= \frac{11}{\sqrt{3}}$ KV $= 6.35$ KV.

$V_{ab} = 1.01 \times 7.97\angle 77.7^\circ = 8.05\angle 77.7^\circ$ KV

$V_{bc} = 1.98 \times 7.97\angle 270^\circ = 15.78\angle 270^\circ$ KV

$V_{ca} = 1.01 \times 7.97\angle 102.3 = 8.05\angle 102.3^\circ$ KV.

6ii) A 25 MVA, 13.2 KV alternator with solidly grounded neutral has a sub transient reactance of 0.25 P.U. The negative & zero sequence reactances are 0.35 & 0.1 PU. respectively. If a double line to ground fault occurs at the terminals of the alternator determine the fault current & line to line voltages at the fault.

May/June 14.

Solution:

Let us choose the generator ratings as base values

$\therefore MVA_b = 25MVA$; $KV_b = 13.2KV$

Base current, $I_b = \frac{KVA_b}{\sqrt{3}KV_b} = \frac{25\times10^3}{13.2\times\sqrt{3}} = 1093.47A.$

Given that $Z_1 = j0.25PU.$ $Z_2 = j0.35PU$, $Z_0 = j0.1PU.$

The following relations exists for a double line to ground fault.

$I_{a1} = -(I_{a2} + I_{a0})$; $V_{a0} = V_{a1} = V_{a2}$; $V_b = V_c = 0.$

$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_2 Z_0}{Z_0 + Z_2}} = \frac{1}{j0.25 + \frac{j0.35 \times j0.1}{j0.35 + j0.1}}$$

$$= j3.05PU.$$

$I_{a1} = -j3.05PU.$

$V_{a1} = V_{a0} = V_{a2} = E_a - I_{a1}Z_1 = 1 - (-j0.35)(j0.25)$

$= 0.237P.U.$

$$I_{a2} = \frac{-V_{a2}}{Z_2} = \frac{-0.237}{j0.35} = j0.68\ PU.$$

$$I_{a0} = \frac{-V_{a0}}{Z_0} = \frac{-0.237}{j0.1} = j2.37PU.$$

The line currents are related to symmetrical components by the following equation

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

$I_a = I_{ao} + I_{a1} + I_{a2} = j2.37 - j3.05 + j0.68 = 0$

$I_b = I_{ao} + a^2 I_{a1} + a I_{a2}$

$= j2.37 + (-0.5 - j0.866)(-j3.05) + (-0.5 + j0.866)(j0.68)$

$I_b = -3.230 + j3.555 = 4.80 \angle 132.3^\circ$ P.U.

$I_c = I_{ao} + a I_{a1} + a^2 I_{a2}$.

$= j2.37 + (-0.5 + j0.866)(-j3.05) + (-0.5 - j0.866)(j0.68)$

$I_c = 3.23 + j3.555 = 4.8 \angle 47.7^\circ$ P.U.

Fault current, $I_f = I_b + I_c = -3.23 + j3.555 + 3.23 + j3.555$

$I_f = j7.11$ P.U

The phase and line voltages are calculated as

$V_a = V_{a1} + V_{a2} + V_{ao} = 3V_{a1} = 3 \times 0.237$

$V_a = 0.711$ PU.

$V_b = V_c = 0$

$V_{ab} = V_a - V_b = 0.711 PU.$

$V_{bc} = 0$

$V_{ca} = V_c - V_a = -0.711 PU.$

The actual values of line currents & voltages are calculated as shown below.

$I_a = 0$

$I_b = 1093.47 \times 4.8 \angle 139.3^\circ = 5248.66 \angle 139.3 A$

$I_c = 1093.47 \times 4.8 \angle 47.7^\circ = 5248.66 \angle 47.7 A.$

$I_f = 1093.47 \times 7.11 \angle 90^\circ = 7774.57 \angle 90^\circ A.$

$V_{bc} = 0$

$V_{ab} = 0.711 \times 7.97 = 5.66 \angle 0^\circ KV$

$V_{ca} = -0.711 \times 7.97 = 5.66 \angle 180^\circ KV.$

6iii) Drive the expression for the three phase power in terms of symmetrical components. NOV/DEC 15.

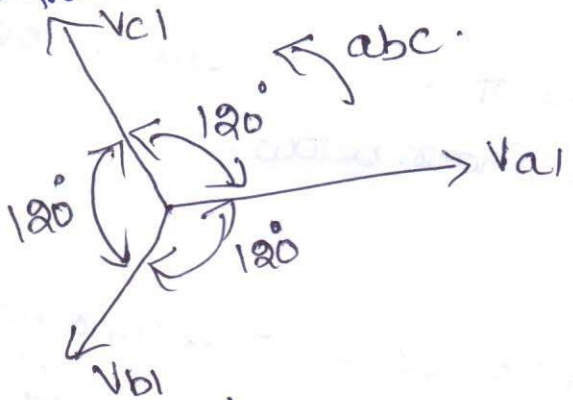
The symmetrical components of three phase system are

1. Positive Sequence Components.

2. Negative Sequence components
3. Zero Sequence components.

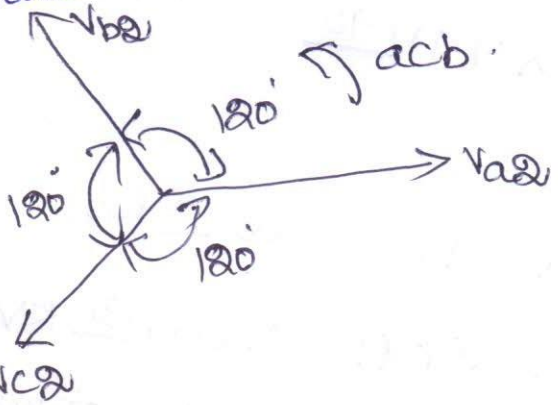
Positive Sequence :-

* It consists of three vectors equal in magnitude displaced from each other by 120° in phase.



Negative Sequence :-

* It consists of three vectors equal in magnitude displaced from each other by 120° in phase.



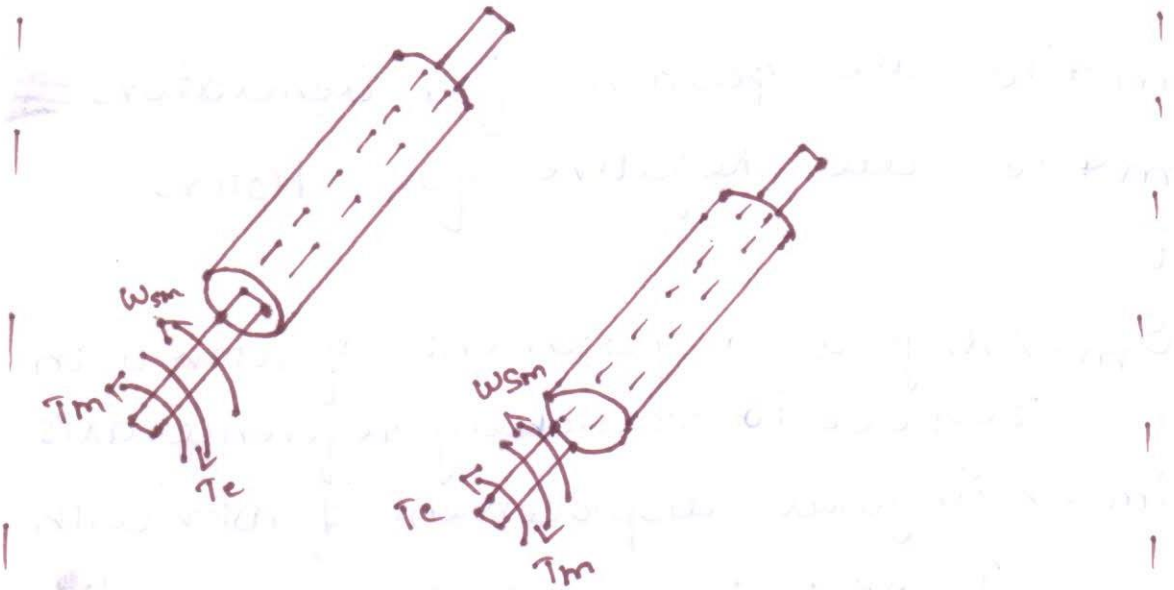
Zero Sequence :-

* It consist of three vectors equal in magnitude & with zero phase displacement from each other.



1. Derive swing Equation of a Synchronous Machine

The roton of a Synchronous Machine is subjected to two torques T_e and T_m which are acting in oppasite directions



Torque acting on roton of Synchronous Machine

where T_e => Net electrical (or) electromechanical torque in N-m

T_m => Mechanical (or) Shaft torque supplied by the prime mover in N-m

Under steady state operating condition the Te and Tm are equal and the machine runs at constant speed known as Synchronous

speed. If there is a difference between the two torques, then the rotor will have an accelerating (or) decelerating torque denoted as T_a.

$$\therefore T_a = T_m - T_e \quad \text{---------- (1)}$$

T_m & T_e are positive for Generators

T_m & T_e are negative for Motors.

Let.

θ_m => Angular displacement of rotor with respect to stationary reference axis

δ_m => Angular displacement of rotor with respect to synchronously rotating reference axis.

By Newton's II nd law of Motion,

$$T_a \propto \frac{d^2\theta_m}{dt^2}$$

(or)

$$T_a = J \frac{d^2\theta_m}{dt^2} \quad \text{---------- (2)}$$

Sub (1) in (2).

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e \quad \text{----------} \rightarrow (3)$$

The angular displacement θ_m & δ_m are related to synchronous speed by

$$\theta_m = \omega_{sm} t + \delta_m \quad \text{----------} \rightarrow (4)$$

differentiate equ (4)

$$\frac{d\theta_m}{dt} = \omega_{sm} + \frac{d\delta_m}{dt} \quad \text{----------} \rightarrow (5)$$

differentiate equ (5)

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \quad \text{----------} \rightarrow (6)$$

From equ (5)

The rotor angular velocity $d\theta_m/dt$ is constant & equal to ω_{sm} only if $d\delta_m/dt$ is zero. Hence $d\delta_m/dt$ represents the deviation of the rotor speed from synchronism. $\therefore J d^2\delta_m/dt^2 = T_m - T_e \rightarrow (7)$

Let $P_{m,act}$ → Shaft power input

$P_{e,act}$ → Electrical power developed in rotor.

$$\text{Power } P = \frac{2\pi NT}{60} = \omega T$$

$P_{m,act} = \omega_{sm} T_m$ (or) $T_m = \frac{P_{mact}}{\omega_{sm}}$ ⟶ (8)

$P_{eact} = \omega_{sm} T_e$ (or) $T_e = \frac{P_{eact}}{\omega_{sm}}$ ⟶ (9)

Sub (9) & (8) in (7)

$J \, d^2\delta_m / dt^2 = \frac{P_{m,act}}{\omega_{sm}} - \frac{P_{eact}}{\omega_{sm}}$

$J \omega_{sm} \frac{d^2\delta_m}{dt^2} = P_{m,act} - P_{eact}$ ⟶ (10)

Let H ⇒ Inertia Constant ; $H = \frac{\frac{1}{2} J \omega_{sm}^2}{S}$ ⟶ (11)

$J\omega_{sm} = \frac{2HS}{\omega_{sm}}$ ⟶ (12)

sub (12) in (10) ⇒ $\frac{2HS}{\omega_{sm}} \frac{d^2\delta_m}{dt^2} = P_{m,act} - P_{eact}$ ⟶ (13)

$\omega_{sm} = \frac{2}{P} \omega_s$; $\delta_{sm} = \frac{2}{P} \delta$ ⟶ (14)

Sub (14) in (13), $\frac{2HS}{(2\omega_s/P)} \frac{d^2(2\delta/P)}{dt^2} = P_{mact} - P_{eact}$

$\frac{2HS}{\omega_s} \frac{d^2\delta}{dt^2} = P_{mact} - P_{eact}$ ⟶ (15)

Sub $\boxed{\omega_s = 2\pi f}$ in equ (15).

$$\frac{2HS}{2\pi f}\frac{d^2\delta}{dt^2} = P_{mact} - P_{eact}$$

$$\frac{HS}{\pi f}\frac{d^2\delta}{dt^2} = P_{mact} - P_{eact} \longrightarrow (16)$$

P.u value of mechanical power $P_m = \frac{P_{m,act}}{S}$.

P.u value of electrical power $P_e = \frac{P_{e,act}}{S}$.

$$\therefore \frac{H}{\pi f}\frac{d^2\delta}{dt^2} = \frac{P_{mact}}{S} - \frac{P_{eact}}{S}$$

$$\boxed{\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e} \longrightarrow (17)$$

The equ (17) is known as Swing Equation

2. Explain about the equal Area Criterion

The transient stability analysis of simple system can be performed by using a simple criterion called equal Area Criterion.

(i) The system is stable, if $\frac{d\delta}{dt} = 0$ at some time instant

(ii) The system is unstable, if $\frac{d\delta}{dt} > 0$ for a sufficiently long time.

Consider the swing equation of a generator connected to infinite bus

$$\frac{H}{\pi f} \frac{d^2\delta}{dt^2} = P_m - P_e. \longrightarrow (1)$$

Let there be a change in P_e due to large disturbance with P_m remaining constant.

$$P_m - P_e = P_a \longrightarrow (2)$$

$P_a \Rightarrow$ Accelerating Power.

The p.u value of $M = \frac{H}{\pi f}$

$$\therefore M \frac{d^2\delta}{dt^2} = P_a.$$

$$\frac{d^2\delta}{dt^2} = \frac{P_a}{M} \longrightarrow (3).$$

On multiplying equ (3) by $2\frac{d\delta}{dt}$

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = 2\frac{d\delta}{dt}\frac{Pa}{M}.$$

$$2\frac{d\delta}{dt}\frac{d}{dt}\frac{d\delta}{dt} = \frac{2}{M}Pa\frac{d\delta}{dt}.$$

$$2\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = \frac{2}{M}Pa\frac{d\delta}{dt} \longrightarrow (4)$$

On integrating equ (4)

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{1}{M}\int_{\delta_0}^{\delta} Pa\, d\delta \longrightarrow (5)$$

Where δ_0 ⇒ Initial value of torque angle.

Taking Square root of equ (5).

$$\frac{d\delta}{dt} = \sqrt{\frac{1}{M}\int_{\delta_0}^{\delta} Pa\, d\delta}$$

For a stable system $\frac{d\delta}{dt} = 0$ at a particular time instance.

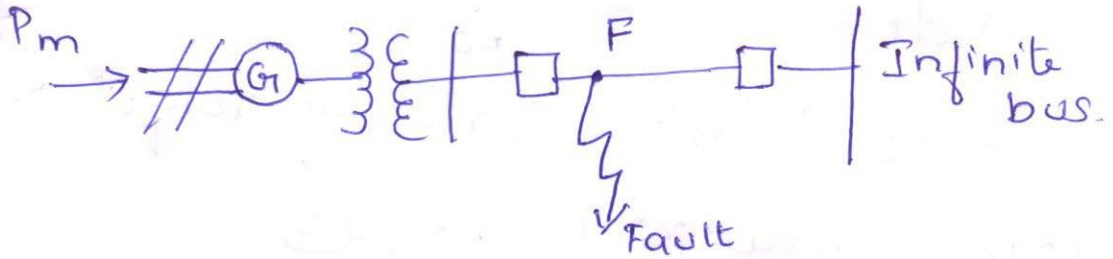
$$\therefore \sqrt{\frac{1}{M}\int_{\delta_0}^{\delta} P_a \, d\delta} = 0 \quad \longrightarrow (6)$$

$$\therefore \frac{d\delta}{dt} = 0; \text{ the term } \int_{\delta_0}^{\delta} P_a \, d\delta = 0 \quad \longrightarrow (7).$$

Hence the integral of P_a equal to zero refers to zero area.

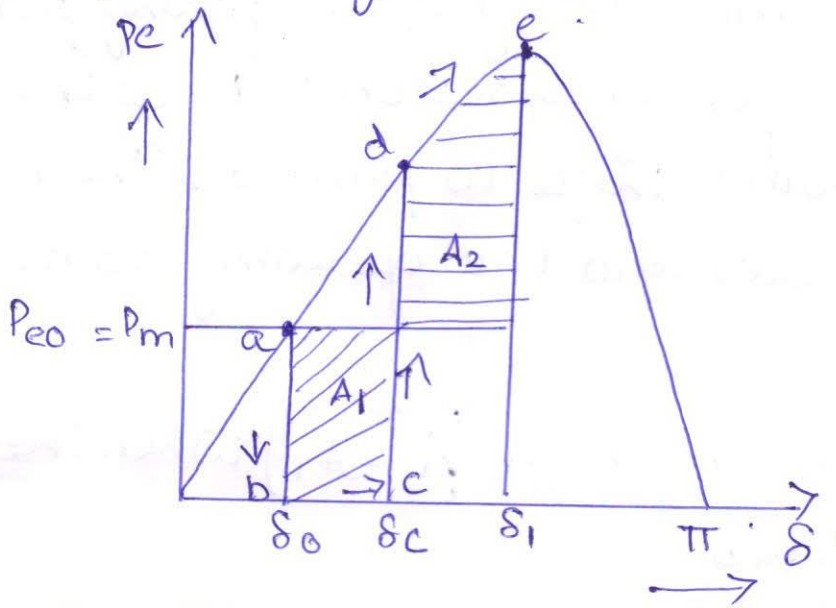
3. Derive about the critical clearing angle and time of a single machine system

Consider a single machine which is shown below



Let the mechanical input be P_m and the machine is operating in steady state with torque angle δ_0

The power angle curve is shown below.



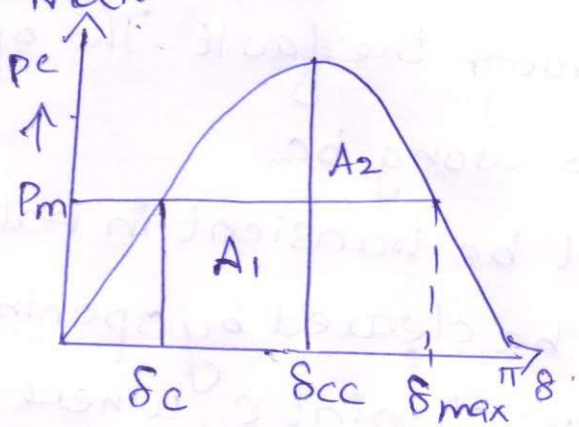
Let the 3φ fault occurs at point F in the system. Now $P_e = 0$ and the operating point drops to b. This means that the power transferred to infinite bus is zero and the entire power is flowing through the fault. The operating point 'a' moves along bc.

Let the fault be transient in nature and so the fault be cleared by opening of circuit breaker at point c, where $\delta = \delta_c$ and the time be 't_c'. Hence t_c is known as clearing time and 'δ_c' is known as clearing angle.

It is assumed that the circuit breaker closes its contact immediately after opening. Hence the normal opening is restored. Now the operating point shifts to point 'd'. The rotor now decelerates and the operating point moves along de.

For this transient state, $A_2 - A_1$ when the system is stable.

It is assumed that the fault is cleared at δc, but if the fault clearing is delayed angle δ, continue to increase to an upper limit δ_{max} which is shown in below fig



$\delta_{max} = \pi - \delta_c \rightarrow (1)$

Under steady state,

$P_m = P_e = P_m \sin \delta_0 \rightarrow (2)$

The accleration power $P_e = P_m - P_e$ → (3).

When a 3ϕ fault occurs $P_e = 0$.

$\therefore P_e = P_m = \text{constant}$ → (4)

$$\therefore A_1 = \int_{\delta_0}^{\delta_{cc}} P_m \, d\delta = P_m [\delta]_{\delta_0}^{\delta_{cc}} = P_m (\delta_{cc} - \delta_0)$$

↳ (5)

When the power Feeding is resumed after fault, $P_e = P_{max} \sin\delta$.

$$P_a = P_e - P_m = P_{max} \sin\delta - P_m \longrightarrow (6)$$

$$\therefore A_2 = \int_{\delta_{cc}}^{\delta_{max}} [P_{max} \sin\delta - P_m] \, d\delta$$

$$= [-P_{max} \cos\delta - P_m \delta]_{\delta_{cc}}^{\delta_{max}}$$

$$= P_{max} [\cos\delta_{cc} - \cos\delta_{max}] - P_m [\delta_{max} - \delta_{cc}]$$

↳ (7)

For a stable system $A_1 = A_2$, thus (5) & (7) can be equated as

$$P_{max} [\cos\delta_{cc} - \cos\delta_{max}] - P_m [\delta_{max} - \delta_{cc}] = P_m [\delta_{cc} - \delta_0].$$

$$\therefore P_{max} \cos\delta_{cc} = P_m \delta_{cc} - P_m \delta_0 + P_{max} \cos\delta_{max} + P_m \delta_{max} - P_m \delta_{cc}$$

$$P_{max} \cos\delta_{cc} = P_m (\delta_{max} - \delta_0) + P_{max} \cos\delta_{max}$$

$$\therefore \cos\delta_{cc} = \frac{P_m}{P_{max}} [\delta_{max} - \delta_0] + \cos\delta_{max}.$$

$$(or)\ \delta_{cc} = \cos^{-1}\left[\frac{P_m}{P_{max}} [\delta_{max} - \delta_0] + \cos\delta_{max}\right] \longrightarrow (8)$$

The equ (8) is used to estimate the value of critical clearing angle.

Consider the swing equation of single s/m,

$$\frac{H}{\pi f} \frac{d^2\delta}{dt^2} = P_m - P_e \longrightarrow (9)$$

during 3ϕ fault $P_e = 0$.

$$\therefore \frac{H}{\pi f} \frac{d^2\delta}{dt^2} = P_m.$$

$$\frac{d^2\delta}{dt^2} = \frac{\pi f P_m}{H} \longrightarrow (10).$$

Integrating equ (10)

$$\delta = \frac{\pi f}{2H} P_m t^2 + \delta_0 \longrightarrow (11).$$

where δ_0 is the integral constant.

When $\delta = \delta_{cc}$; $t = t_{cc}$.

$$\text{At } t = t_{cc} \quad \delta_{cc} = \frac{\pi f}{2H} P_m t_{cc}^2 + \delta_0$$

$$\frac{\pi f}{2H} P_m t_{cc}^2 = \delta_{cc} - \delta_0$$

$$\therefore t_{cc} = \sqrt{\frac{2H(\delta_{cc} - \delta_0)}{\pi f P_m}} \rightarrow (12)$$

The equ (12) can be used to estimate the value of critical clearing time.

4. Explain about the computational procedure using R-K Method

(i) Read inertia constant, transient reactance, line reactance, voltages at generator buses, bus powers; system frequency, type of fault etc.

(ii) Conduct load flow Analysis.

(iii) Calculate the machine currents.

(iv) Calculate voltage $E' = V_t + jX_d' I_t$.

(v) Assume P_m = Constant

(vi) Take initial value of δ

(vii) Compute reduced Y_{bus} for faulted & post faulted systems

(viii) calculate K_1 & K_2.

$$K_1 = d\delta/dt \; ; \; I_1 = d\omega/dt$$

(ix) $K_2 = \left((\omega(0) + I_1/2) - 2\pi f_0\right) \Delta t$.

$$I_2 = \pi f_0 / H \; (P_m - P_e) \; \Delta t.$$

(x). Calculate phase angle & speed.

(xi) Plot the swing curve & state whether the system will be stable (or) Not.

5. **Derive the computational procedure of modified Euler's Method**

Step 1: Assume initial condition δ^0 & $\omega^0 = \omega_s$.

Step 2: Compute $d\delta/dt$ & $d\omega/dt$.

Step 3: Compute first estimate of δ & ω.

$$\delta^{(t+\Delta t)} = \delta^{(t)} + \Delta t \, d\delta/dt$$

$$\omega^{(t+\Delta t)} = \omega^{(t)} + \Delta t \, d\omega/dt$$

Step 4: Compute $d\delta/dt$ & $d\omega/dt$.

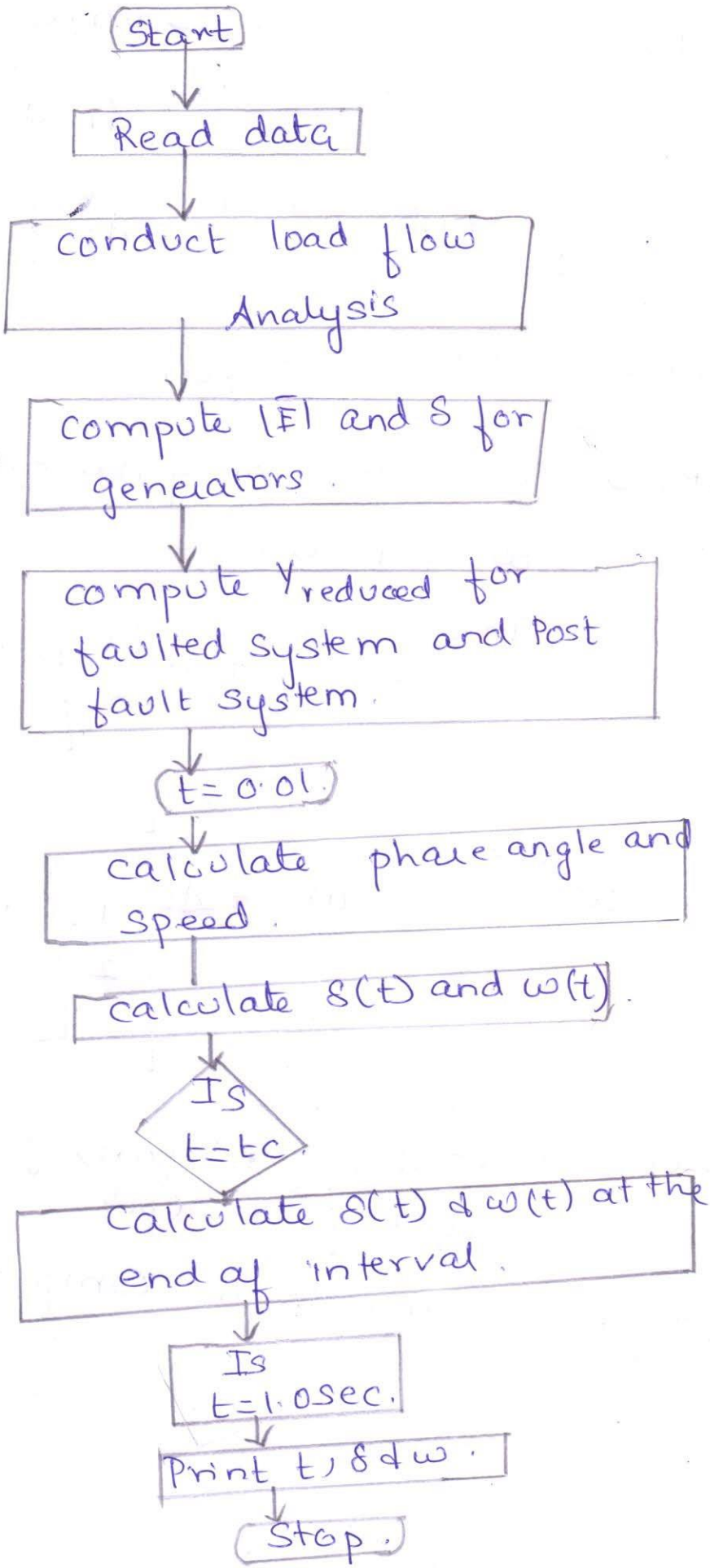
Step 5: Evaluate the final estimate of δ & ω.

$$\delta^{(t+\Delta t)} = \delta^{(t)} + \Delta t \left[\frac{1}{2} \left[d\delta/dt_{t=to} \right] \right]$$

$$\omega^{(t+\Delta t)} = \omega^{(t)} + \Delta t \left[\frac{1}{2} \left[d\omega/dt_{t=to} \right] \right]$$

Step 6: $t = t + \Delta t$; If $t > t_{max}$ go to next step (or) go to step 2.

Step 7: Terminate the computation.


Start
Read data
conduct load flow Analysis
compute |E| and δ for generators.
compute Y reduced for faulted system and Post fault system.
t = 0.01
calculate phase angle and speed.
calculate δ(t) and ω(t).
Is t = tc
Calculate δ(t) & ω(t) at the end of interval.
Is t = 1.0 sec.
Print t, δ & ω.
Stop.

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