POWER SYSTEMS

For
ELECTRICAL ENGINEERING

POWER SYSTEMS

SYLLABUS

Power generation concepts, ac and dc transmission concepts, Models and performance of transmission lines and cables, Series and shunt compensation, Electric field distribution and insulators, Distribution systems, Per-unit quantities, Bus admittance matrix, Gauss Seidel and Newton-Raphson load flow methods, Voltage and Frequency control, Power factor correction, Symmetrical components, Symmetrical and unsymmetrical fault analysis, Principles of over-current, differential and distance protection; Circuit breakers, System stability concepts, Equal area criterion.

ANALYSIS OF GATE PAPERS

Exam Year	1 Mark Ques.	2 Mark Ques.	Total
2003	4	11	26
2004	6	9	24
2005	4	7	18
2006	4	10	24
2007	4	9	22
2008	3	8	19
2009	2	5	12
2010	3	5	13
2011	5	4	13
2012	3	2	7
2013	1	3	7
2014 Set-1	3	5	13
2014 Set-2	2	4	10
2014 Set-3	3	3	9
2015 Set-1	1	4	9
2015 Set-2	2	3	8
2016 Set-1	2	4	10
2016 Set-2	4	3	10
2017 Set-1	2	3	8
2017 Set-2	3	3	9
2018	5	3	11

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1 TRANSMISSION LINE MODEL & PERFORMANCE

1.1 INTRODUCTION

An electric transmission line can be represented by a series combination of resistance, inductance and shunt combination of conductance and capacitance. These parameters are symbolized as R, L, G and C respectively. Of these R and G are least important in the sense that they do not affect much the total equivalent impedance of the line and hence the transmission capacity.

The effective resistance is equal to the d.c. resistance of the conductor only if the current is uniformly distributed throughout the section of the conductor. The loss on the overhead line is due to (i) ohmic loss in the power conductors, (ii) corona los and (iii) leakage at the insulators

1.1.1 MAGNETIC FLUX DENSIT

A current carrying conductor produces a magnetic field which is in the form of closed circular loops around the conductor.

$$H = \frac{B}{\mu}$$

1.1.2 INDUCTORS AND INDUCTANCE

An inductor is a device which stores energy in a magnetic field. By definition, the inductance L of an inductor is the ratio of its total magnetic flux linkages to the current I through the inductor or

$$L = \frac{N\Psi_m}{I} = \frac{\lambda}{I}$$

For a medium permeability is constant ferrous media

$$L = \frac{d\lambda}{dI}$$

1.1.3 MAGNETIC FIELD INTENSITY DUE TO A LONG CURRENT CARRYING CONDUCTOR

The current is uniformly distributed across the section of the conductor. The flux linkages here will be both due to internal flux and external flux.

Cylinder with radius r < R

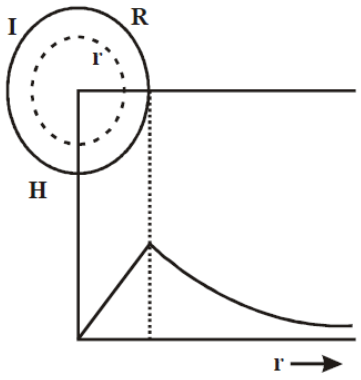

Fig. Variation of H due to current in the conductor for r ≤ R and r > R

$$I' = I\left(\frac{r}{R}\right)^2$$

$$H_r = \frac{Ir}{2\pi R^2}$$

A cylinder with radius r > R

$$H_r = \frac{I}{2\pi r}$$

1.2 FLUX LINKAGES

1.2.1 INTERNAL FLUX LINKAGES

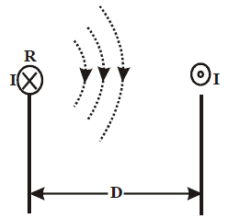

Fig. Magnetic field due to one conductor of a 1-ϕ transmission line

$$H = \frac{Ir}{2\pi R^2}$$

$$B = \mu H = \mu_0 H$$

$$= \frac{\mu_0 I}{2\pi R^2}.r \,(\text{as}\,\mu_r = 1)\,\text{for conductors}$$

$d\varphi = B.$ Area normal to flux density B

$= B.dr.l$

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Total internal flux linkages $\lambda = \int_0^R d\lambda$

$= \frac{\mu_0 I}{2\pi R^4}\int_0^R r^3 dr = \frac{\mu_0 I}{8\pi}$

1.2.2 EXTERNAL FLUX LINKAGES

$R \le r < D$

The total external flux linkages due to current flow
in one conductor

$\lambda = \int_R^{D-R} d\lambda$

$\lambda = \frac{\mu_0 I}{2\pi}\ln\frac{D}{R}$

Total flux linkages due to one conductor
= Total internal flux linkage + Total external flux
linkages

$= \frac{\mu_0 I}{8\pi} + \frac{\mu_0 I}{2\pi}\ln\frac{D}{R}$

Total flux linkage due to both the conductors $= 2\left[\frac{\mu_0 I}{8\pi} + \frac{\mu_0 I}{2\pi}\ln\frac{D}{R}\right]$

Inductance L per unit length

$= \left[\frac{\mu_0}{4\pi} + \frac{\mu_0}{2\pi}\ln\frac{D}{R}\right]$ Henry / metre

Since $\mu_0 = 4\pi\times10^{-7}$,

$L = \left[1 + 4\ln\frac{D}{R}\right]\times10^{-7}$ Henry / metre

$= 4\times10^{-7}\times\left[\frac{1}{4} + \ln\frac{D}{R}\right]$ Henry / metre

Since $\ln e^{1/4} = \frac{1}{4}$

$\therefore L = 4\times10^{-7}\left(\ln e^{1/4} + \ln\frac{D}{R}\right)$

$= 4\times10^{-7}\ln\frac{D}{Re^{-1/4}}$

$= 4\times10^{-7}\ln\frac{D}{R'}$ Henry / metre

1.2.3FLUX LINKAGES OF ONE CONDUCTOR IN A GROUP OF CONDUCTORS

Find out the flux linkages of one conductor due to current flowing in the conductor self and the current flowing in the other conductors. It is assumed here that the sum of the currents in various conductors is zero.

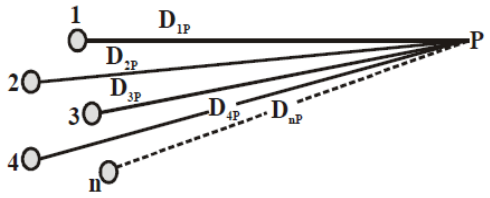

Fig. Cross-sectional view of a group of n conductors Point P is remote from the group of conductors

Assume here that P is a point very far from the group of the conductors. The objective here is to calculate the flux linkages of say conductor 1 due to the current I_1, carried by the conductor itself and flux linkage to conductor 1 due to the current carried by conductors 2, 3,…….n.

Due to the current I_1

$\lambda_{1p_1} = \frac{\mu_0 I_1}{8\pi} + \frac{\mu_0 I_1}{2\pi}\ln\frac{D_{1p}}{R_1}$

Due to current in conductor 2 are

$\lambda_{1p_2} = 2\times10^{-7}.I_2\ln\frac{D_{2p}}{D_{12}}$

Since $I_1 + I_2 + \ldots\ldots\ldots + I_n = 0$,

The net flux linkages λ_{1p}

$\lambda_{1p} = 2\times10^{-7}\left[I_1\ln\frac{1}{R_1} + I_2\ln\frac{1}{D_{12}} + \ldots\ldots + I_n\ln\frac{1}{D_{1n}}\right]$

wb-turns/metre

1.3 INDUCTANCE OF TWO-WIRE (1-ø) TRANSMISSION LINE

1.3.1 INDUCTANCE OF 3-ϕ UNSYMMETRICALLY SPACED TRANSMISSION LINE

$a \ne b \ne c$ and each has a radius of R metres

$\lambda_a = 2\times10^{-7}\left[I_a\ln\frac{1}{R`} + I_b\ln\frac{1}{c} + I_c\ln\frac{1}{b}\right]$

$\lambda_b = 2\times10^{-7}\left[I_a\ln\frac{1}{c} + I_b\ln\frac{1}{R'} + I_c\ln\frac{1}{a}\right]$

$\lambda_c = 2\times10^{-7}\left[I_a\ln\frac{1}{b} + I_b\ln\frac{1}{a} + I_c\ln\frac{1}{R'}\right]$

I_a as reference

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$$I_b = k^2 I_a \text{ and } I_c = kI_a$$
$$\text{where } k = (-0.5 + j0.866)$$

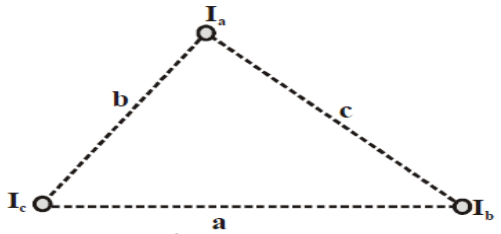

Fig. 3-ϕ transmission line with unsymmetrical spacing

In case the transmission line is transposed i.e., each conductor takes all the three position of the conductors

$$L = \frac{L_a + L_b + L_c}{3}$$

$$= \frac{1}{3}\left[2\times10^{-7}\left(3\ln\frac{1}{R'} - \ln\frac{1}{abc} - j\frac{\sqrt{3}}{2}\ln 1\right)\right]$$

$$= 2\times10^{-7}\ln\frac{3\sqrt{abc}}{R'} \text{ Henry / metre}$$

$$L = 2\times10^{-7}\ln\frac{d}{R'} \text{ Henry / metre}$$

1.3.2 INDUCTANCE OF COMPOSITE CONDUCTORS

The current is assumed to be equally divided amongst the strands. One group of conductors act as a 'go' conductor for the single-phase line and the other as the 'return'. The current per strand is I/m ampere in one group and –I/n ampere in the other.

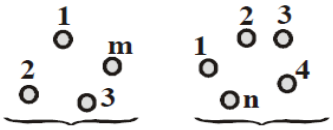

Fig. Inductance of composite conductor-1-ϕtransmission line

$$L_{av} = \frac{L_1 + L_2 + \ldots\ldots + L_m}{m}$$

Since all the strands of conductor A are electrically parallel, the inductance of conductor will be

$$L_A = \frac{L_{av}}{m} = \frac{L_1 + L_2 + \ldots\ldots + L_m}{m^2}$$

Substituting the values of L_1, L_2,……,L_m in equation

$$L_A = 2\times10^{-7}\ln\frac{\sqrt[mn]{(D'_{11}D'_{12}\ldots.D_{1n})(D'_{21}D'_{22}\ldots.D'_{2n})\ldots.(D'_{m1}D'_{m2}\ldots D'_{mn}}}{\sqrt[m^2]{(R'D_{12}D_{13}\ldots.D_{1m})(R'D_{21}D_{23}\ldots.D_{2m})\ldots.(R'D_{m1}D_{m2}\ldots D_{mn})}}$$

The mnth root of the product of the mn distances between m strands of conductor A and n strands of conductor B is called geometric mean distance (GMD) and is denoted as D_m and the m^2th root of m^2 distance i.e., the distance of the various strands from one of the strands and the radius of the same strand, geometric mean radius (GMR) or self GMD.

$$L = L_A + L_B$$

1.3.3 INDUCTANCE OF DOUBLE 3-Φ LINE

Conductors α and α' are electrically parallel and constitute one phase.

The conductors of two phases are placed diagonally opposite rather than in the same horizontal plane, in all the three positions. By doing this the self GMD of the conductors is increased whereas the GMD reduced, thereby the inductance per phase in lowered.

1.4 TRANSPOSITION OF POWER LINES

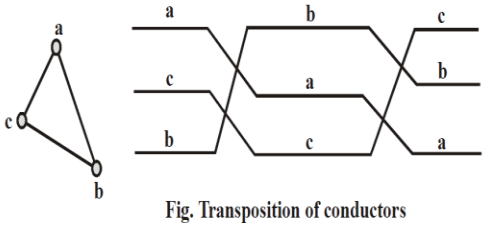

Fig. Transposition of conductors

By transposition of conductors is meant the exchanging of position of the power conductors at regular intervals along the line, so that each conductor occupies the original position of every other conductor over an equal distance.

If the spacing is unsymmetrical even though the system operates under balanced condition, voltage drops of different magnitude will be there in the three conductors due to unequal inductance of the three phases. The magnetic field external to the conductors is not zero, thereby causing induced voltages in adjacent electrical circuits, particularly telephone lines that may result in

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telephone interferenceIt is enough to transpose either power line or the communication lines. Under balanced operating condition, the magnetic field linking an adjacent telephone line is shifted 120° in time phase with each rotation of the conductor positions in the net voltage induced in the telephone line is zero as it is the sum of three induced voltage which are displaced by 120° in time phase.

The transposition, however, may be effected at the intermediate switching station.

1.5 COMPOSITE CONDUCTORS

For transmission lines operating at high voltages normally stranded conductors are used. These conductors are known as composite conductors as they compose of two or more elements or strands electrically in parallel. By using different Steel cored, reinforced aluminium conductors (ASCR) which combine the lightness, electriJcal conductivity and restlessness of aluminum with the high tensile strength of steel

1. Aluminium conductors steel reinforced cheaper
2. The superior mechanical strength
3. A reduction in the number of supports
4. The increase in span length5. Corona losses reduced

1.6 CONCEPT OF GEOMETRIC MEAN DISTANCE

Geometric mean distance is a mathematical concept used for the calculation of inductance.

On the circle is

$$GMD_p = 5\sqrt{D_1D_2D_3D_4D_5}$$

Number of points on the circle are increased to infinity, the distance between the point P and centre of the circle.

The GMD between two circular areas will be the distance between the centres of the two areas and so on. For voltages in excess of 230 kV. It is preferable to use more than one conductor per phase which is known as bundling of conductors. A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor.

The advantages in using bundle conductors

i) Reduced reactance
ii) Reduced voltage gradient
iii) Reduced corona loss
iv) Reduced radio interference
v) Reduced surge impedance

The self GMD of the conductors is increased.

$$\text{Reactance} = K \ln \frac{GMD}{GMR}$$

Since the voltage gradient is reduced by using bundled conductors the radio interference is also reduced.

Surge impedance $\sqrt{L/C}$. Since by bundling, the self GMD is increased, the inductance is reduced and capacitance increased, as a result the surge impedance is reduced. The maximum power that can be transmitted is increased.

The basic difference between a composite conductor and bundled conductor is that the sub-conductors of a bundled conductor are separated from each other by a distance of almost 30 cms or more and the wires of a composite conductor touch each other.

1.7 SKIN AND PROXIMITY EFFECT

When direct current flows in the conductor, the current is uniformly distributed across the section of the conductor whereas flow of alternating current is non-uniform, with the outer filaments of the conductor carrying more current than the filaments closer to the centre.

A higher resistance to alternating current than to direct current and is commonly known as skin effect. This effect is more, the more is the frequency of supply and the size of the conductor.

The flux linkages per ampere to inner strands is greater than those of outer strands. Hence the inductance/impedance of the inner strands is greater than those of

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outer strands which results in more current in the outer strands as compared to the inner strands. This non-uniformity of flux linkage is the main cause of skin effect.
The alternating magnetic flux in a conductor caused by the current flowing in a neighboring conductor gives rise to circulating currents which cause an apparent increased in the resistance of a conductor. This phenomenon is called proximity effect. In a two-wire system more lines of flux link elements farther apart than the elements nearest each other. Therefore, the inductance of the elements farther apart is more as compared to the elements near each other and the current density is less in the elements farther apart than the current density in the elements near each other. The effective resistance is, therefore, increased due to non-uniform distribution of current. The proximity effect is pronounced in case of cables where the distance between the conductors is small whereas for overhead lines with usual spacing the proximity effect is negligibly small.

1.8 CAPACITANCE OF TRANSMISSION LINES

The flow of current through a conductor gives rise to a magnetic field and charging of conductor results in an electric field. A charge if brought in the vicinity of this electric field experiences a force as electric field intensity E. Newton per coulomb or volts per metre.

$$E_r = \frac{\rho L}{2\pi\varepsilon_0 r}$$

$$V = \frac{\rho L}{2\pi\varepsilon_0}\ln\frac{r_2}{r_1}$$

1.8.1 CAPACITANCE OF 1-Φ TRANSMISSION LINE

The charge ρ_L coulomb/metre is distributed on the surface of the conductor which is non-uniformly distributed over the surface such that it has higher density on the adjacent sides of the conductors. If operating voltage V, distance of separation h and radius of the equipotential surface r.

$$E_r = \frac{\rho L}{\pi\varepsilon_0}\ln\frac{h}{r}$$

$$C = \frac{\pi\varepsilon_0}{\ln h/r}\ F/\text{metre}$$

Equation for inductance contains a constant term corresponding to the internal flux linkages whereas since charges reside on the surface of the conductor, similar term is absent in the capacitance expression.
The concept of self GMD is applicable for inductance calculation and not for the capacitance. The capacitance between one conductor and a neutral point

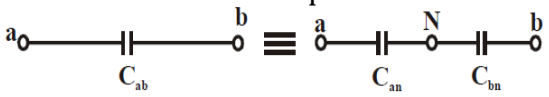

Fig.

$$C_{an} = 2C_{ab} = \frac{2\pi\varepsilon_0}{\ln\frac{h}{r}}$$

1.8.2 CAPACITANCE OF A3-PHASE UNSYMMETRICALLY SPACED TRANSMISSION LINE

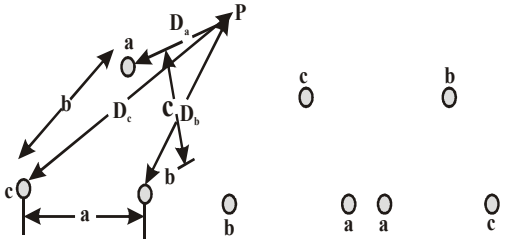

Fig. Unsymmetrically spaced transposed 3-phase transmission line

For an untransposed line the capacitances between conductors to neutral of the three conductors are unequal. In transposed lines the average capacitance of each conductor to neutral is the same as the capacitance to neutral of any other phase.
3-phase balanced system, ρ_α reference charge,

$$V_a' = \frac{1}{2\pi\varepsilon_0}\left[\rho_a\ln\frac{D_a}{r} + \rho_b\ln\frac{D_b}{c} + \rho_c\ln\frac{D_c}{b}\right]$$

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$$V_a'' = \frac{1}{2\pi\varepsilon_0}\left[\rho_a \ln\frac{D_b}{r} + \rho_b \ln\frac{D_c}{a} + \rho_c \ln\frac{D_a}{c}\right]$$

$$V_a''' = \frac{1}{2\pi\varepsilon_0}\left[\rho_a \ln\frac{D_c}{r} + \rho_b \ln\frac{D_a}{b} + \rho_c \ln\frac{D_b}{a}\right]$$

Average

$$V_a = \frac{V_a' + V_a'' + V_a'''}{3}$$

$$\rho_a + \rho_b + \rho_c = 0$$

$$V_a = \frac{\rho_\alpha}{2\pi\varepsilon_0}\ln\frac{\sqrt[3]{abc}}{r} = \frac{\rho_\alpha}{2\pi\varepsilon_0}\ln\frac{GMD}{r}$$

$$C = \frac{\rho_\alpha}{V_a} = \frac{2\pi\varepsilon_0}{\ln\frac{GMD}{r}}\ F/\text{metre}$$

For a symmetrical spacing of the conductors, a = b = c = h

$$C = \frac{2\pi\varepsilon_0}{\ln\frac{h}{r}}$$

1.8.3 EFFECT OF EARTH ON THE CAPACITANCE OF CONDUCTORS

The electric flux lines and the equipotential lines are orthogonal to each other. The earth is considered to be conducting and an equipotential plane of infinite extent. The positive charge on the conductor induces negative charges on the earth surface. This distribution of charge on the surface of the earth should be replaced by an equivalent charge for the calculation of electric field potential and other related quantities due to this isolated charged conductor.

Since earth is an equipotential plane which is possible only if we assume the presence of an imaginary conductor below the surface of the earth at a depth equal to the height of the actual conductor above the surface of the earth.

1.8.4 CAPACITANCE OF SINGLE CONDUCTOR

The single conductor with the earth is equivalent to a single-phase transmission line.

$$C = \frac{\pi\varepsilon_0}{\ln\frac{D_{ab}}{r}\frac{D_{aa'}}{D_{ab'}}}$$

Ratio $\frac{D_{aa'}}{D_{ab'}} < 1$, the effect of earth on capacitance of the system is to increase it.

The effect of earth is to increase the capacitance.

1.9 PERFORMANCE OF LINES

By performance of lines determination of efficiency and regulation of lines

The efficiency of lines is defined as

$$\%\ \text{efficiency} = \frac{\text{Power delivered at the receiving end}}{\text{Power sent from the sending end}} \times 100$$

$$\%\ \text{efficiency} = \frac{\text{Power delivered at the receiving end}}{\text{Power delivered at the receiving end} + \text{losses}} \times 100$$

Receiving end and sending end

The regulation change in the receiving end voltage, expressing in per cent of full load voltage, from no load to full load, the sending end voltage and frequency constant

$$\%\text{regulation} = \frac{V_r' - V_r}{V_r} \times 100$$

V_r' is the receiving end voltage under no load condition and V_r' the receiving end voltage under full load condition.

1.9.1 REPRESENTATION OF LINES

Four distributed parameters, series resistance and inductance, and shunt capacitance and conductance

Electrical power transmitted at approximately the speed of light. One full wave variation of voltage or current

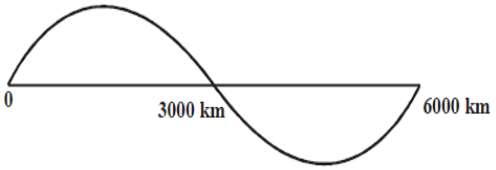

Fig. Voltage distribution of 50 Hz supply

$$f.\lambda = \upsilon$$

$$f = 50 \text{ and } \upsilon = 3\times10^8\ \text{m/sec}.$$

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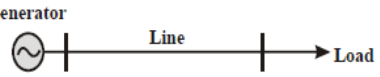
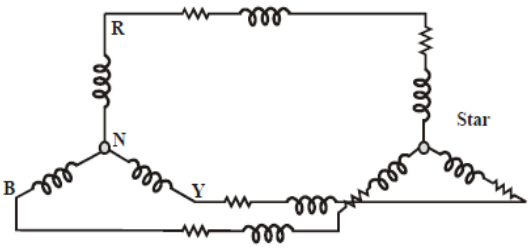
$$\lambda = \frac{v}{f} = \frac{3\times10^8}{50} = 6\times10^6 \text{ metres}$$

=6000 Km



(a) Single-line diagram of a 3-phase system



(b) 3-phase diagram of (a)

Less than about 160 km, the voltage or current variation on the line is not much parameters assumed to be lumbed and not distributed.

Short categorized as short transmission lines and medium transmission lines. The lines upto about 80 km short effect of shunt capacitance is neglected above 80 and below 160 km as medium length the shunt capacitance can be assumed to be lumped at the middle of the line or half of the shunt capacitance may be considered to be lumped at each end of the line. Nominal-T and nominal-π respectively, more than 160 km the parameters are distributed and rigorous calculations are required.

The 3-phase system is normally balanced system irrespective of the fact that the conductors are not transposed, as the untransposed conductors introduce slight dissymmetry which can be ignored for all practical purposes.

The currents in a balanced polyphase network is zero and, therefore, the current through the wire connected between the star point of the load and neutral of the system is zero. The star point of the load and neutral of the system are at the same potential.

A 3-phase balanced system can, therefore, be analysed on single-phase basis in which the neutral wire is of zero impedance.

A 3-phase balanced system can, therefore, be analysed on single-phase basis in which the neutral wire is of zero impedance.

1.9.2 SHORT TRANSMISSION LINE

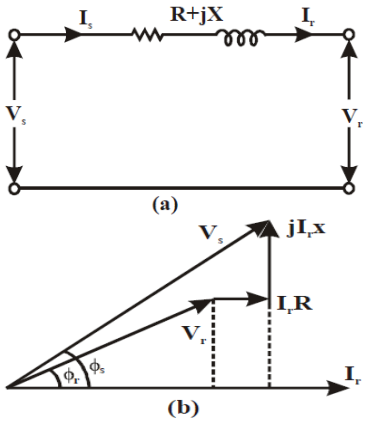


Fig. Short-transmission line (a) equivalent circuit,

$$V_s\cos\varphi_s = V_r\cos\varphi_r + I_rR$$

$$V_s\sin\varphi_s = V_r\sin\varphi_r + I_rX$$

Squaring and adding

$$V_s^2 = V_r^2 + 2I_rRV_r\cos\varphi_r + 2I_rXV_r\sin\varphi_r + I_r^2(R^2+X^2)$$

Last term

$$V_s \approx V_r + I_rR\cos\varphi_r + I_rX\sin\varphi_r$$

$$V_r' = V_s$$

$$\%\,\text{regulation} = \frac{V_s - V_r}{V_r}\times100$$

$$= \left(\frac{I_rR}{V_r}\cos\varphi_r + \frac{I_rX}{V_r}\sin\varphi_r\right)\times100$$

$$\text{regulation per unit} = \frac{I_rR}{V_r}\cos\varphi_r + \frac{I_rX}{V_r}\sin\varphi_r$$

$$= v_r\cos\varphi_r + v_x\sin\varphi_r$$

v_r and v_x are the per unit values of resistance and reactance of the line.

Constants of the network dimensionaless

The constants A, B, C and D are related for a passive network as follows

$$V_s = V_r + I_rZ$$

$$I_s = I_r$$

$$A = 1$$

$$B = Z$$

$$C = 0$$

$$D = 1$$

1.1 – Z.0 = 1

1.2 $V_r' = \frac{V_s}{A}$ when $I_r = 0$

1.3 $\%\,\text{regulation} = \frac{V_s/A - V_r}{V_r}\times100$

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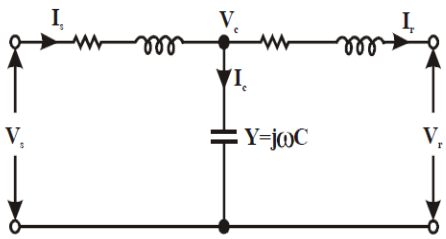
% η of transmission

$$\%\eta = \frac{\text{Power received at the receiving end}}{\text{Power received at the receiving end+losses}} \times 100$$

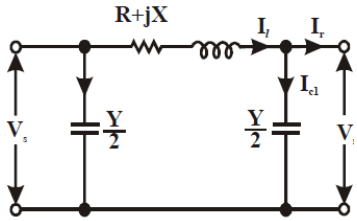
$$= \frac{P}{P+3I_r^2R} \times 100$$

R is the resistance per phase of the line

1.9.3 MEDIUM LENGTH LINES



(a) Nominal-T



(b)Nominal-π

The parameters are assumed to be lumped. The shunt capacitance at the middle at each end. Noted that two representations are approximate to the exact representation of the actual line

Nominal-T

For lagging power factor load receiving end current reference vector.

To calculate regulation

$$V_r' = \frac{|V_s|\left(-\frac{j}{\omega C}\right)}{\frac{R}{2}+j\frac{X}{2}-\frac{j}{\omega C}}$$

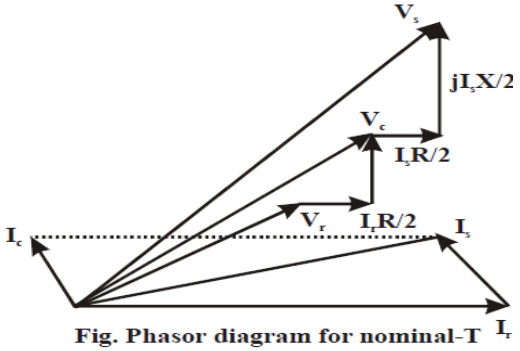


Fig. Phasor diagram for nominal-T

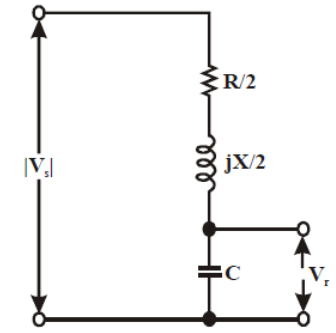


Fig. Equivalent circuit under no load

An small error in evaluating phase angle inaccurate calculation of efficiency

$$\%\eta = \frac{P}{P+3\frac{R}{2}(I_r^2+I_s^2)} \times 100$$

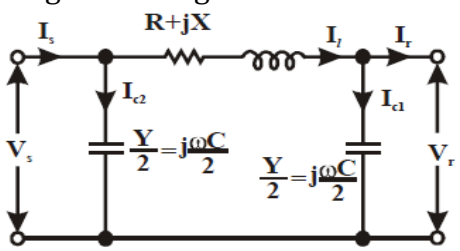
$$V_s = V_r\left(1+\frac{YZ}{2}\right)+I_rZ\left(1+\frac{YZ}{4}\right)$$

$$I_s = I_r\left(1+\frac{YZ}{2}\right)+V_rY$$

$$= YV_r+\left(1+\frac{YZ}{2}\right)I_r \quad A = D \text{ and } AD-BC=1$$

Nominal-π

Receiving end voltage as the reference or



(a)Nominal-π

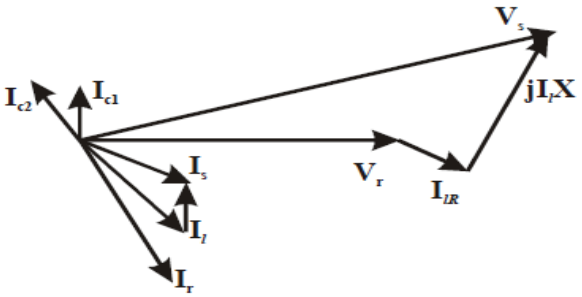


Fig. (b) Phasor diaram for nominal-π

$$V_r' = \frac{|V_s|\left(-\frac{2j}{\omega C}\right)}{R+jX-\frac{j}{\omega C/2}}$$

$$\%\eta = \frac{P}{P+3I_l^2R} \times 100$$

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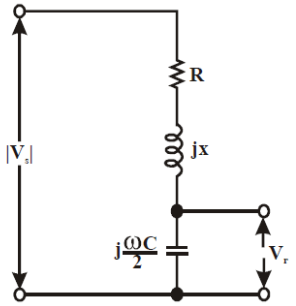

Fig. Equivalent circuit under no load

$$V_s = V_r' + I_l Z = V_r + \left(I_r + V_r \frac{Y}{2}\right) Z$$

$$= \left(1 + \frac{YZ}{2}\right) V_r + ZI_r$$

$$= \left(1 + \frac{Y^2 Z}{4}\right) + \left(1 + \frac{YZ}{2}\right) I_r$$

$$A = D$$

1.9.3 LONG TRANSMISSION LINES

The receiving end as the reference for measuring distances

When $\Delta x \to 0$ reduce to

$$V = A\exp\left(\sqrt{yz}.x\right) + B\exp\left(-\sqrt{yz}.x\right)$$

$$Z_c = \sqrt{\frac{z}{y}} \text{ and } \gamma = \sqrt{yz} = \alpha + j\beta$$

Z_c characteristic impedance and γ the propagation constant

$$V = Ae^{\gamma x} + Be^{-\gamma x}$$

$$1 = \frac{1}{Z_c}(Ae^{yx} - Be^{-yx})$$

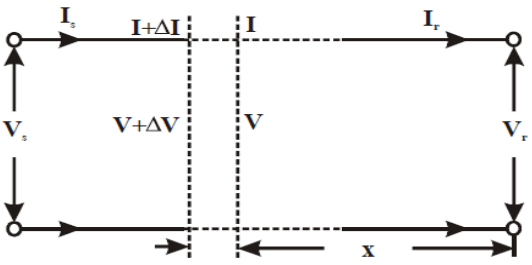

Fig. Long transmission line

Two constants are to be determined, two boundary conditions

At x = 0

$$A = \frac{V_r + I_r + Z_c}{2} \text{ and } B = \frac{V_r - I_r Z_c}{2}$$

V and I (magnitude and phase) are functions of the distance x, receiving end voltage V_r and current I_r and the parameters of the line.

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{r + j\omega L}{g + j\omega C}}$$

For a lossless line $r = 0, \quad g = 0,$

$$Z_c = \sqrt{\frac{L}{C}}$$

Pure resistance surge impedance of the line. When dealing with frequencies or surges normally the losses are neglected and, therefore, the characteristic impedance becomes the surge impedance. Surge impedance loading of a line is the power about 40 ohms. The phase angle of Z_c between 0° and -15^oA. Line of infinite length cannot have a reflected wave.

Lower value cable, relatively large and low inductances of the cables

The propagation constant

$$V = \frac{V_r + I_r Z_c}{2} e^{ax}.e^{j\beta x} + \frac{V_r - I_r Z_c}{2} e^{-ax}.e^{-j\beta x}$$

The first term the incident voltage wave as Its value increases as x is increased. A voltage wave decreases in magnitude as it travels from the sending end towards the receiving end.

Second part reflected voltage. At any point along the line, voltage is the sum of these two components i.e.

sums of incident and reflected voltages

$$V = V_r.\frac{e^{\gamma x} + e^{-\gamma x}}{2} + I_r Z_c \frac{e^{\gamma x} - e^{-\gamma x}}{2}$$

$$= V_r \cosh \gamma x + I_l Z_c \sinh \gamma x$$

$$= \frac{1}{Z_c}[V_r \sinh \gamma x + I_r Z_c \cosh \gamma x]$$

$$\frac{V_r}{Z_c} \sinh \gamma x + I_r \cosh \gamma x$$

$$V_s = V_r \cos \gamma x + I_r Z_c \sin \gamma l$$

A = D = cos γl

ABCD Constants

$$V_s = AV_r + BI_r$$

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$I_s = CV_r + DI_r$

Similar relations for V_r and I_r

Since AD – BC = 1 and A = D,

$I_r - CV_s + DI_s$

$V_r = DV_s - BI_s = AV_s - BI_s$

1.10 CONSTANTS FOR TWO NETWORKS IN TANDEM

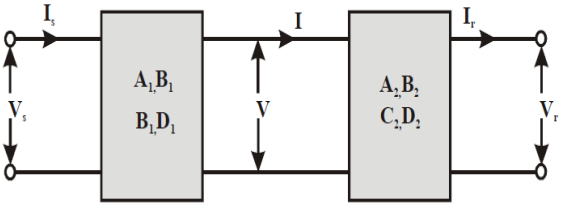

Fig. Two networks in tandem

$V = D_1V_s - B_1I_s$

$I = -C_1V_s + A_1I_s$

$V = A_2V_r + B_2I_r$

$I = C_2V_r + D_2I_r$

$D_1V_s - B_1I_s = A_2V_r + B_2I_r$

$-C_1V_s + A_1I_s = C_2V_s + D_2I_r$

Multiplying by A_1 and by B_1 and adding

$(A_1D_1 - B_1C_1)I_s = (A_2C_1 + C_2D_1)$

$V_r + (B_2C_1 + D_1D_2)I_r$

$A = A_1A_2 + B_1C_2$

$B = A_1B_2 + B_1D_2$

$C = A_2C_1 + C_2D_1$

$D = B_2C_1 + D_1D_2$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}$$

1.11 CONSTANTS FOR TWO NETWORKS IN PARALLEL

The derivation is based on the fact that transmission line is a reciprocal network (symmetrical network) and when two reciprocal networks are connected in parallel, the resulting network is also reciprocal (The resulting networks is not reciprocal in case the two networks are connected in tandem).

$V_s = A_1V_r + B_1I_{r_1}$

$V_s = A_2V_r + B_2I_{r_2}$

Where $I_r = I_{r_1} + I_{r_2}$

Multiplying by B_2 and B_1

$(B_1 + B_2)V_s = (A_1B_2 + A_2B_1)V_r + B_1B_2(I_{r_1} + I_{r_2})$

$$V_s = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} V_r + \frac{B_1B_2}{B_1 + B_2} I_r$$

$$A = D = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} = \frac{D_1B_2 + D_2B_1}{B_1 + B_2}$$

$AD - BC = 1$

Measured by conducting the open circuit and short circuit tests at the two ends of the line

$$Z_{so} = \frac{A}{C}$$

$$Z_{ss} = \frac{B}{D}$$

Since the direction of sending end current according to the above equation enters the network whereas while performing the tests on receiving end side, the direction of the current will be leaving the network, therefore

$I_{r_1} = DV_s + BI_s$

$-I_r = -CV_s - AI_s \text{ or } I_r = CV_s + AI_s]$

$$Z_{ro} = \frac{V_r}{I_r} = \frac{D}{C}$$

$$Z_{rs} = \frac{V_r}{I_r} = \frac{B}{A}$$

$$A = \sqrt{\frac{Z_{so}}{Z_{ro} - Z_{rs}}}$$

$B = AZ_{rs}$

$$C = \frac{A}{Z_{so}}$$

$D = A$

1.12 FERRANTI-EFFECT

When a long line is operating under no load or light load condition, the receiving end voltage is greater than the sending end voltage.

Ferranti-effect

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i) No load condition
When x = *l* and $I_r = 0$
At *l* = 0

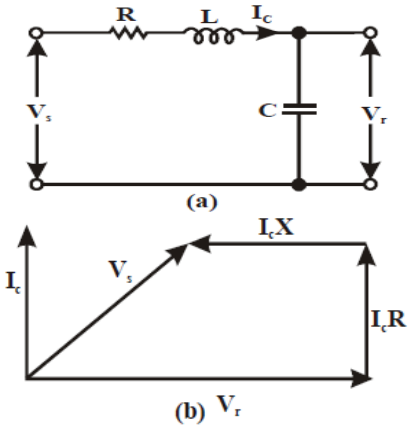

Fig. (a) Line representation (Lumped) under no load condition (b) its phasor diagram

As *l* increases, the incident component of sending end voltage increases and turns the vector anti-clockwise through an angle β1 whereas the reflected part. Rotated clockwise through the same angle.
Sum sending end voltage gives a voltage which is smaller than V_r

ii) A simple explanation of Ferranti-effect
Since usually the capacitive reactance of the line is quite large as compared to the inductive reactance, under no load or lightly loaded condition the line current is of leading p.f.
The phasor diagram is given below for this operating condition
The charging current produces drop in the reactance of the line which is in phase opposition to the receiving end voltage and hence the sending end voltage becomes smaller than the receiving end voltage.

The Ferranti-effect is based on the net reactive power flow on the line. It is known that if the reactive power generated at a point is more than the reactive power absorbed, the voltage at that point becomes higher than the normal value and vice versa. The inductive reactance of the line is a sink for the reactive power whereas the shunt capacitances generate reactive power. In fact, if the line loading corresponds to the surge impedance loading, the voltage is same everywhere as the reactive power absorbed then the equals the reactive power generated by the line. The SIL lightly loaded or fully loaded lines. If the loading is less than SIL, the reactive power generated is more than absorbed, therefore, the receiving end voltage is greater than the sending end voltage.

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2 CORONA/INSULATORS/CABLES

2.1 INSULATION

The insulators for overhead lines provide insulation to the power conductor from the ground. The insulators are connected to the cross arm of the supporting structure and the power conductor passes through the clamp of the insulator. Made of either glazed porcelain. The materials used for porcelain are silica 20% feldspar 30% and clay 50%. The porcelain should be ivory white, sound and free from defects. It should be vitrified because the presence of pores or air in the porcelain will lower down its dielectric strength. Air-free and impervious to the entrance of liquids and gases. The dielectric strength 15 kV to 17 kV for every one-tenth inch thickness.

Porcelain is mechanically strong, less affected by temperature and has minimum leakage problem. Toughened glass higher dielectric strength (35 kV for one-tenth inch thickness). Easy to detect any flaw like trapping of air etc. It has lower coefficient of thermal expansion and; as a result, the strains due to temperature changes are minimized. Drawback moisture condenses very easily on its surface and use is limited to about 33 kV. It is desirable not to allow porcelain to come in direct contact with a hard metal screw thread. Normally cement is used between metal and the porcelain.

2.1.1 TYPES OF INSULATIONS

The types of insulators are

i) Pin type
ii) Suspension type
iii) Strain type
iv) Shackle type

Pin type a single or multiple shells (petticoats or rain sheds) adapted to be mounted on a spindle to be fixed to the cross arm of the supporting structure. Multiple shells are provided in order to obtain sufficient length of leakage path so that the flash over voltage between the power conductor and the pin of the insulator is increased. Sufficient leakage resistance. It is desirable that the horizontal distance between the tip of the lowermost shell should be less as compared with the vertical distance between the same tip and the cross-arm, otherwise in case of an arc-over, the discharge will take place between the power conductor and cross-arm rather than power conductor and the pin of the insulator. Power conductor the top of the insulator and is tied to the insulator by the annealed wire of the same material as the conductor. Upto 33 kV not desirable beyond 50 kV as the cost of such insulators then increases much faster than the voltage. Cost α V^x

Where $x > 2$

Pin type replacement of these insulators is expensive. Against higher voltages, suspension insulators. One or more insulator units flexibly connected together and adapted to be hung for the cross arm of the supporting structure and to carry a power conductor at its lowest extremity. String insulators porcelain grooved on the undersurface to increase the surface leakage path between the metal cap at the top and the metal pin at the bottom of the insulators.

The standard unit is $10" \times 5\frac{3}{4}"$. in size. The diameter is taken as 10" as it gives optimum spark over to puncture voltage ratio. Increasing the diameter further increases the flash over or spark over voltage but it lowers the above ratio which is undesirable.

Free to swing, clearances required, more cross arm, more advandages.

i) Each insulator for 11kV , 132kV is 12 (maximum)

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ii) Failure of one of the units replacement.
iii) String swing together mechanical stresses at the point of attachment are reduced.
iv) Operating voltage can be increased by adding suitable number of discs.

The strain insulators are exactly identical in shape with the suspension insulators. These strings are placed in the horizontal plane rather than the vertical plane. There are used to take the tension of the conductors at line terminals, at angle towers, at road crossings and at junction of overhead lines with cables. Known as tension or strain insulators. For low voltages of the order of 11 kV, shackle insulators are used.

Sometimes two, even three, strings of insulators in parallel have bee used.

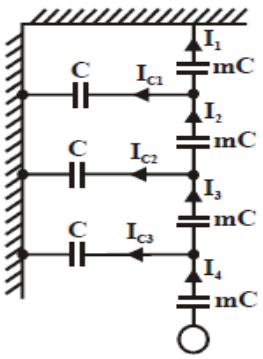
Voltage kV	66	132	220	400
No. of discs	4-5	9-10	15-16	22-23

2.1.2 POTENTIAL DISTRIBUTION OVER A STRING OF SUSPENSION INSULATORS

This does not mean that the voltage across the discs of the string is uniformly distributed. Because of the capacitances formed between the metal parts of the insulators and the tower structure.

Bigger size of the towers uneconomical. Capacitances affect the voltage distribution across the string. The capacitance of each unit is known as, mutual capacitance.

$$m = \frac{\text{mutual capacity}}{\text{Capaci tan ce to ground}} = \frac{mC}{C}$$



Potential distribution over a string of four insulators.

The insulator discs are identical. V be the operating voltage and V_1, V_2, V_3, and V_4 across the units.

$V_1 < V_2 < V_3 < V_4$

The voltage drop across the unit nearest the cross arm is minimum and it goes on increasing as we go towards the power conductor. The voltage drop across the unit nearest the power conductor is maximum.

Since the mutual capacity of each disc is same and the current through the topmost unit is minimum, the voltage drop across that unit will be minimum.

$I_1 < I_2 < I_3 < I_4$

The current goes on increasing being the maximum in the lowest unit; the voltage drop is maximum there.

The lowermost unit in a string of insulators is fully stressed or utilized. String efficiency is a measure of the utilization of material in the string.

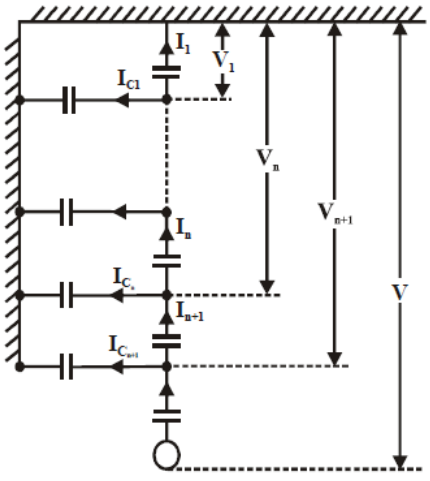
$$\eta = \frac{\text{Voltage across the string}}{n \times \text{voltage across the unit near the power conductor}}$$

$$\eta = \frac{\text{S.O.V. for the string}}{n \times \text{S.O.V. of one disc}}$$

S.O.V. spark over voltage potential distribution

At junction n,

$$v_{n+1} = \frac{V_n}{m} + v_n$$



Potential distribution over a string of (n+1) units equal capacities.

V_n is the voltage across n units from the top and v_n is the drop across nth unit. The total voltage across the string is the sum of

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voltages across all the units (which have been obtained in terms of v_n), the value of v_n can be obtained and hence by back substitution the value of voltage across every unit can be calculated.

$$v_5 = 3.657 \times 6.67 = 24.3\,\text{kV}$$

$$\%\,\text{string efficiency} = \frac{66 \times 100}{5 \times 24.3} 54.4\%$$

The voltage drops across various units will tend to be equal in case the value of m is large. The value of m will go on increasing with operating voltage. This is because mutual capacity being fixed the ground capacitance goes on decreasing with larger clearances and hence the ratio of the two capacitances goes on increasing.

2.2 METHODS OF EQUALISING THE POTENTIAL

1. Selection of m:- Needs longer cross arms, taller supporting structures, m =10 maximum.
2. Grading of Units: Unequal distribution of voltage is due to the leakage current from the insulator pin to the tower structure. Disc of different capacities could be used such that the product of their capacitive reactance and the current flowing through the respective unit is same.
   Unit nearest the cross arm should have the minimum capacitance (maximum capacitive reactance towards the power conductor the capacitance should increase.
   $C_1 < C_2 <$ -----$< C_n \rightarrow XC_1 > XC_2 >$ --$\rightarrow XC_n$
   $$I_{c_1} = \frac{I_{c_n}}{n}$$
   At junction n
   $$C_{n+1} = C_n + nC$$
   Requires large stocks of different sized units, which is uneconomical and impractical.
3. Static Shielding: In static shielding the idea is to cancel exactly the pint to tower charging currents so that the same current flows through the units of identical capacities to produce equal voltage drops across each unit. A guard ring or grading ring is connected round to the power conductor such that this surrounds the bottom unit.

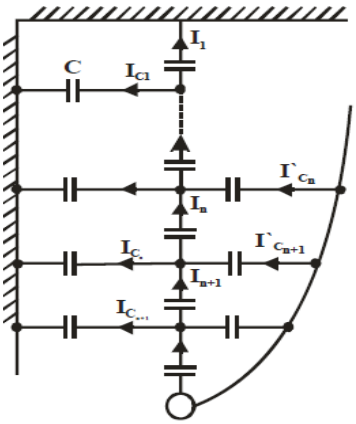

Fig. Static shielding

The design of the ring should be such that this gives rise to the capacitances which will cancel exactly the charging current in that particular section.

$$I_{c_n} = I'_{c_n}$$

C_n is the capacitance between the guard ring and the pin of the nth unit.

$$nC = (k-n)v\omega C_n$$

$$C_n = \frac{n}{k-n} C$$

In practice it is very difficult to achieve this condition. For a 14 unit string the voltage across the bottom unit without guard ring was 18.3% of the operating voltage and with guard it was 11.8% which is a great improvement.

Two purposes: (i) Equalization of voltage drop across the units, and (ii) when used with arcing horn (which is fixed at the top end of the string) It protects the insulator string from flashover whenever an over voltage (under normal or abnormal condition) appears between the tower structure and the power conductor. The combination of the two provides path through the air medium to discharge the energy contained in the abnormal voltage and thus the insulator string is saved.

2.3 INSULATED CABLES

Three essential points

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a) Conductor
b) Insulation
c) External Protection

The successive layers usually are stranded in opposite direction. Standard stranding 6 wires around 1, 12 wire around 6, followed by 18, 24 and so on as 19/0.1. The first number of strands, second diameter of each strand in mm. Gauge three strands each of 20 SWG.

2.3.1 THE INSULATION

Main requirements

1. High insulation resistance
2. High dielectric strength
3. Good mechanical properties
4. Not be affected by chemicals
5. Non-hygroscopic the dielectric strength of any material goes very much down with moisture content.

Vulcanized rubber: Rubber in its natural form is highly insulating but it absorbs moisture. Thereby it loses insulating properties. When it is mixed with sulphur is subjected to a particular temperature it change into vulcanized rubber. Not absorb moisture better insulating properties.

Vulcanized rubber insulated cables are used for wiring of houses, buildings and factories for low power work.

Butyl rubber: Butyl rubber subjected is 85°C whereas for natural rubber it is 60°C.

Polyvinyl chloride (pvc): It is a polymer derived generally from acetylene and it can be produced in different grades depending upon the polymerization process.

Heating resistance PVC is 80°C – 100°C. PVC compounds are normally costlier than the rubber compounds.

Polythene: Used for high frequency cables. Used to a limited extent for power cables also.

Maximum operating temperature

Cross-linked polythene: The use of polythene for cables has been limited by its low melting point. By cross-linking the molecules a new material is produced which does not melt but carbonizes at 250°C to 300°C Vulcanised or "cross-linked" polythene.

Impregnated paper: A suitable layer of the paper is lapped on the conductor depending upon the operating voltage. It is then dried by combined application of heat and vacuum.

The temperature is 120° – 130°C before vacuum is created. In many cases the failures of the cables have been due to the void formation at the higher levels or due to the bursting of the sheath at the lower levels because of the excessive internal pressure of the head of compound.

Protective coverings: Cables are protected against mechanical demage by armouring the cables with steels tapes or galvanized steel wires. Armouring is necessary, non-magnetic materials should be used.

2.4 EXTRA HIGH VOLTAGE CABLES

The dielectric material surrounds the conductor and we know that every dielectric material has certain dielectric strength which, if exceeded, will result in rupture of the dielectric.

The maximum electric stress (which occurs at the surface of the conductor) is below that required for short time puncture of dielectric. In case the potential gradient is taken a low value, the overall size of the cable above 11 kV becomes relatively large. Also, if the gradient is taken large t reduce the overall size of cable the dielectric losses increase very much which may results in thermal breakdown of the cable.

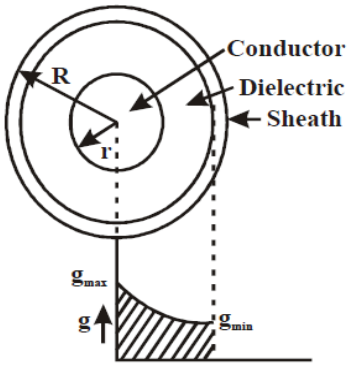

Fig. Electric stress in a single core cable

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2.4.1 ELECTROSTATIC STRESSES IN SINGLE CORE CABLE

r radius of the conductor, R the inner radius of the sheath, ε the permittivity of the dielectric, λ the charge per unit length, V the potential of the conductor with respect to the sheath and g the gradient at a distance x from the centre of the

$$g = \frac{\lambda}{2\pi\varepsilon x} = E \text{ where } E \text{ isf}$$

$$g = \frac{V}{x \ln \frac{R}{r}}$$

The gradient is maximum when x = r at the surface of conductor

$$g_{max} = \frac{V}{r \ln \frac{R}{r}}$$

and the gradient is minimum at the inner radius of the sheath where it is given by

$$g_{min} = \frac{V}{R \ln \frac{R}{r}}$$

In order to keep a fixed overall size of the cable (R) for a particular operating voltage V, there is a particular value of the radius of the conductor which gives minimum gradient at the surface of the conductor. The objective here is to find the minimum value of g_{max} i.e. to maximize.

V is fixed

Or $\frac{R}{r} = e$

To have minimum value of gradient at the surface of the conductor the inner radius of the sheath and the conductor radius are related by the equation.

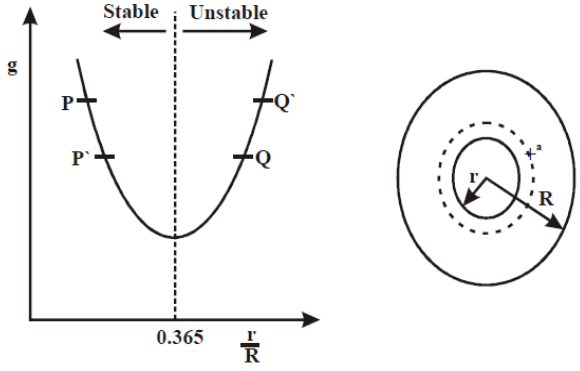

Fig. Variation of g as a function of r/R

Since the working dielectric strength of the insulating material is taken about 40-50 kV/cm to which now air surrounding the conductor is stressed, which will get ionized, effective radius (r + a) units ratio will be (r + a)/R. The stress to which the dielectric material is subjected is increased and this may finally lead to rupture of the material.

Therefore it can be seen that for all ratios r/R less than the minimum 1/e the cable operates satisfactorily. This means for satisfactory operation of the cable.

Now if this principle is used for the design of cables then we see that there will be large difference between the stress at the surface of the conductor and the stress at the inner radius of the sheath, which means the dielectric material will not be fully utilized.

2.5 GRADING OF CABLES

The distribution of dielectric material such that the difference between the maximum gradient and the minimum is reduced, thereby a cable of the same size could be operated at higher voltages or for the same operating voltage a cable of relatively smaller size.

Two methods

i) Capacitance grading more than one dielectric material
ii) Intersheath grading the same dielectric material by interposing thin metal sheaths.

2.5.1 CAPACITANCE GRADING

An infinite number of materials

$$g = \frac{\lambda}{2\pi.\frac{k}{x}.x} = \frac{\lambda}{2\pi k} = \text{cons tan t}$$

Dielectric strength and working stresses of this material be G_1, G_2, G_3 and g_1, g_2, and g_3 respectively. The objective now is to find out the locations of these materials with respect.

Two possibilities

i) The factor of safety for all the materials be same, working stress different.

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ii) Same working stress

Where *f* is the factor of safety

$\varepsilon_1 G_1 > \varepsilon_2 G_2 > \varepsilon_3 G_3$

Highest product of dielectric strength and permittivity should be placed nearest to the conductor and the other layers should be in the descending order of the product of dielectric strength and permittivity.

$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

2.5.2 INTERSHEATH GRADING

Objective the gradient with intersheath will be smaller than the gradient without intersheath for the same overall radius and the operating voltage.

$$\frac{g_{max}}{g} = \frac{3}{1+\alpha+\alpha^2}$$

The gradient with intersheath is lower than without intersheath for the same overall size and operating voltage of the cabl

$r_1 = r + d, r_2 = r + 2d \text{ and } R = r + 3d$

The grading theory is more of theoretical interest than practical reasons. Capacitance grading is difficult of non-availability of matrials. In case of intersheath, damage of intersheath.

For these reasons the modern practice is to avoid grading in favour of oil and gas filled cables.

2.6 INSULATION RESISTANCE OF A CABLE

The usual load current flows the core of the cable whereas leakage current i.e. the current which is not useful flows radially i.e. from the conductor to the sheath through the dielectric material.

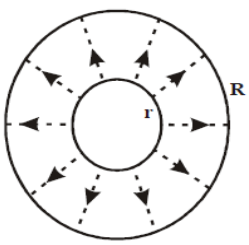


Fig. Insulation resistance of a cable

Dotted lines

ρ is the specific resistance of the material, an annular cylinder with radii x and (x+dx)

Unit length

$$R = \frac{\rho}{2\pi l} \ln \frac{R}{r} \text{ ohms}$$

Noted that whereas the resistance of the core of the cable is directly proportional to the length of the cable, the leakage resistance is inversely proportional to the length of the cable.

2.7 CAPACITANCE OF A SINGLE CABLE

A single core cable is in effect an electrostatic capacitor because it has two electrodes, the core of the cable and the sheath separated by a dielectric material. Let λ be the charge per unit length. By definition capacitance is the ratio of the charge on one of the electrodes to the potential difference between the electrodes.

$$\frac{\lambda}{V} = C = \frac{2\pi\varepsilon}{\ln R/r} \text{ F/metre}$$

To find the capacitance by measurements.

In a 3-core cable, sheath is at earth potential and the three conductors at supply potentials.

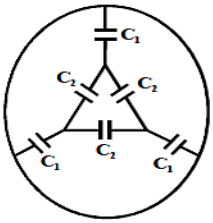


Fig. Capacitance of a 3-core cable

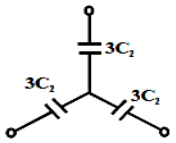
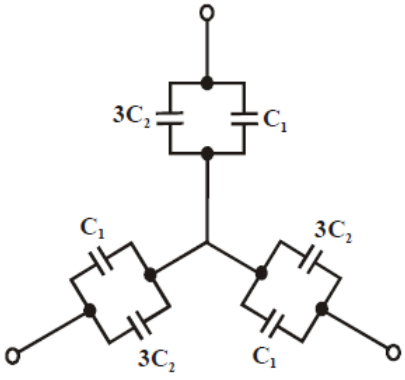


Fig. Star equivalent of delta

Let C_1 be the capacitance between sheath and the conductor and C_2 the capacitance between each conductor. An equivalent star connection.

Since the star point is at sheath potential and the terminals correspond to the conductors of the cable.



(a)

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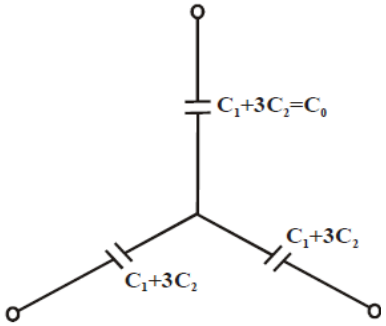

(b)

Fig. (a) and (b) Equivalent capacitance of a 3-core cable

Two measurements (i) Bunch the three cores (ii) connect any two cores to the sheath

$C_y = C_1 + 2C_2$

$C_0 = C_1 + 3C_2$

Empirical formula due to Simon

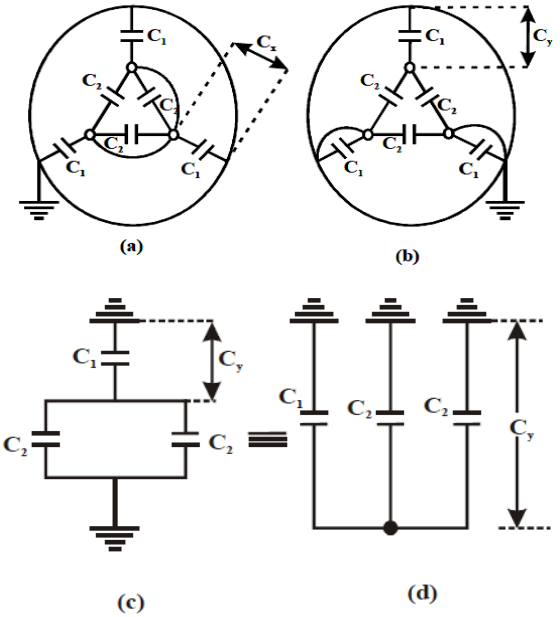

Fig (a) and (b) Capaciatance calculations by measurement;
Fig (c) and (d) Equivalent of (b)

2.8 HEATING OF CABLES

The temperature rise of a body depends upon the rate of generation and dissipation of heat by the body. If the rate of generation is greater than the rate of dissipation, the temperature goes on rising and vice versa. Sources of heat generation are

i) Core loss
ii) Dielectric loss
iii) Sheath losses

$R_{65} = R_{20}(1+\alpha t)$

The resistance of the cable the core loss is calculated as I^2R where I is the current carried by the cable.

2.8.1 DIELECTRIC LOSS

The equivalent circuit for this system is represented by a parallel combination of leakage resistance R and a capacitance C.

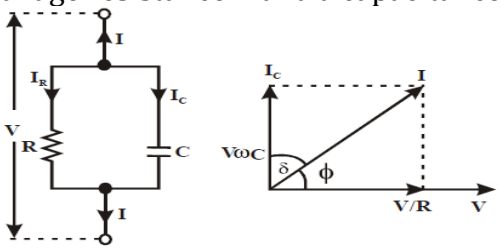

Fig. Equivalent of a cable, (b) Phaser diagram of (a)

Loss in the dielectric

$P = V^2\omega C \tan\delta$

δ is the dielectric loss angle and ω is the power supply frequency.

$P = V^2\omega C\delta$ watts

Power factor angle

$\cos\varphi = \cos(90-\delta) = \sin\delta$

The power factor of a dielectric is a function of the temperature of the dielectric and also depends upon the voltage stress to which the dielectric is stressed.

2.8.2 VARIATION OF DIELECTRIC POWER FACTOR WITH TEMPERATURE

It decreases with increase in temperature to a minimum value and rises again with increase of temperature. The minimum point lies somewhere between 30°C and 60°C depending upon the type of impregnating compound.

2.8.3 THERMAL RESISTANCE OF A SINGLE CORE CABL

The thermal resistance of the dielectric material

$\frac{g}{2\pi}\ln\frac{R}{r}$ thermal ohms / m

g thermal resistivity of the dielectric

2.9 OVERHEAD LINES VERSUS UNDERGROUND CABLES

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The inductance is more predominant in case of overhead lines whereas capacitance is in case of underground cables.

1. The large charging current on very high voltage cables limits the use of cable for long length transmission.
2. Overhead line is less expensive
3. Insulation cost is more in case of cables.
4. Erection cost of an overhead line is much less.

Underground cables

(i) Greater safety to the public, less interference
(ii) Connections or a link in overhead lines.
(iii)Submarine crossings

Oil filled cables require relatively smaller amount of insulation as compared to solid type for the same operating voltage and are recommended for all voltages ranging between 66 kV and 400 kV.

Good thermal characteristic and high dielectric strength of the gas SF_6, it is used for insulating the cables. The conventional cables are limited to 1000 MVA and 500 kV.

2.10 CORONA

Corona phenomenon is the ionization of air surrounding the power conductor. Free electrons are normally present in free space because of radioactivity and cosmic rays. As the potential between the conductors is increased, the gradient around the surface of the conductor increases.

The free electrons will move with certain velocity depending upon the field strength. These electrons will collide with the molecules of air and incase the speed is large, they will dislodge electrons from these molecules, thereby the number of electrons will increase. The process of ionization is thus cumulative and ultimately forms an electron avalanche. This results in ionization of the air surrounding the conductor. In case the ratio of spacing between conductors to the radius of the conductor is less than 15, flash over will occur between the conductors before corona phenomenon occurs.

A self-sustained electric discharge in which the field intensified ionization is localized only over a portion of the distance between the electrodes.

When a voltage higher than the critical voltage is applied between two parallel polished wires, the glow is quite even.

Conductors are examined through a stroboscope, reddish tufts conductor is negative smoother bluish white glow. Conductor is positive. The a.c. corona, viewed through a stroboscope, has the same appearance as direct current corona. As corona phenomenon is initiated, a hissing noise is heard and ozone gas is formed which can be detected by its characteristic out dour.

2.10.1 CRITICAL DISROPTIVE VOLTAGE

q is the charge per unit length, operating voltage is V, a point P at a distance x to find the electric field intensity. A unit positive charge at P.

$$V = -\int_{d-r}^{r} E_x dx$$

$$V = \frac{q}{\pi\varepsilon_0} \ln \frac{d}{r}$$

Now gradient at any point x

V' is the line to neutral 3-phase

$$V' = \frac{V_L}{\sqrt{3}}$$

The gradient increases as x decreases i.e., the gradient is maximum when x = r, the surface of the conductor,

$$V' = r g_{max} \ln \frac{d}{r}$$

Critical disruptive voltage is defined as the voltage at which complete disruption of dielectric occurs. The voltage corresponds to the gradient at the surface equal to the breakdown strength of air. This dielectric

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strength is normally denoted by g_0 and is equal to 30 kV/cm peak at NTP.

$$g_0' = g_0.\delta$$

$$\delta = \frac{3.92b}{273+t}$$

b is the barometric pressure in cm of Hg and t the temperature in ^oC.

$$V' = rg_0\delta \ln\frac{d}{r} kV$$

In deriving the above expression, an assumption is made that the conductor is solid and the surface is smooth. For higher voltages ACSR conductors are used.

The potential gradient for such a conductor will, in consequence, be greater than for the equivalent smooth conductor, so that the breakdown voltage for a stranded conductor will be somewhat less than for a smooth conductor. The irregularities on the surface of such a conductor are increased further because of the deposition of dust and dirt on its surface and the breakdown voltage is further reduced. An average value for the ratio of breakdown voltage for such a conductor and a smooth conductor lies between 0.85 to unity and is denoted by m_0.

The atmospheric conditions and the surface of the conductor is given by

$$V' = rg_0\delta m_0 \ln\frac{d}{r} kV$$

When the voltage applied corresponds to the critical disruptive voltage, corona phenomenon starts but it is not visible because the charged ions in the air must receive some finite energy to cause further ionization by collisions. For radial field, it must reach a gradient g_v at the surface of the conductor to cause a gradient g_0, a finite distance away from the surface of the conductor. The distance between g_v and g_0 is called the energy distance.

Equal to $(r + 0.301\sqrt{r})$ for two parallel conductors and $(r + 0.308\sqrt{r})$ for co-axial conductors.

Critical visual disruptive voltage, then

$$V_v = g_v r \ln\frac{d}{r}$$

$$V_v = g_0 m_v \delta r\left[1 + \frac{0.3}{\sqrt{r\delta}}\right]\ln\frac{d}{r}$$

$$= 21.1 m_v \delta r\left[1 + \frac{0.3}{\sqrt{r\delta}}\right]\ln\frac{d}{r} kV \text{ r.m.s}$$

m_v = 0.98 to 0.93 rough conductor
=0.72 for local corona

Since the surface of the conductor is irregular, the corona does not start simultaneously on the whole surface. Local corona m_v = 0.72 and decided corona or general corona m_v = 0.82.

2.10.2 CORONA LOSS

The ions produced by the electric field result in space charges which move round the conductor. The energy required for the charges to remain in motion is derived from the supply system.

The space surrounding the conductor is lossy. In order to maintain the flow of energy over the conductor in the field wherein this additional energy would have been otherwise absent, it is necessary to supply this additional loss from the supply system. This additional power is referred to as corona loss.

Peak empirical relation

$$P = 241\times10^{-5}\frac{(f+25)}{\delta}\sqrt{\frac{r}{d}}(V_p - V_0)^2 \text{ kW/km/phase}$$

V_p the operating voltage in kV and V_0 the critical disruptive voltage a fair weather condition. The approximate loss under foul weather condition is obtained by taking V_0 as 0.8 times the fair weather value. With perfectly smooth and cylindrical conductors no corona loss occurs until visual critical voltage is reached when the loss suddenly takes a definite value by peak limitations.

Supply frequency 25 to 120 Hz $\frac{V_p}{V_0} > 1.8$

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2.11 FACTORS AFFECTING CORONA LOSS

i) Electrical factors
ii) Atmospheric factors,
iii) Factors connected with the conductors

2.11.1 ELECTRICAL FACTORS

a) Frequency and waveform of supply
Higher the frequency of supply the higher are corona losses. d.c. corona loss is less as compared with a.c. corona. a.c. third harmonics are always present.

b) Field around the conductor
Depends upon the configuration of conductors. The formation is horizontal the field near the middle conductor is large as compared to the outer conductors i.e., the critical disruptive voltage is lower for the middle conductors and hence the corona loss on the middle conductors and hence the corona loss on the middle conductor is more as compared with the two outer conductors.
The smaller the height, the greater the corona loss.

2.11.2 ATMOSPHERIC FACTORS

a) Pressure and temperature effect
δ which appears directly in the denominator

$$V_0 = 21.1 m_0 \delta r \ln \frac{d}{r} kV$$

The lower the value of δ the higher the loss is $\alpha (V - V_0)^2$. For lower values the pressure should be low and temperature higher. The corona loss is more on hilly areas on plain areas.

b) Dust, Rain, Snow and Hail Effect
The critical voltage for local corona reduces which increases corona loss. Rains, snow and hailstorm reduce the critical disruptive voltage and hence increase the corona loss.

2.11.3 FACTORS CONNECTED WITH THE CONDUCTOR

$$\text{loss} \alpha \sqrt{\frac{r}{d}}$$

$$\text{loss} \alpha (V - V_0)^2$$

Larger the dia of the conductor larger will be the loss. Second expression as V_0 is approximately directly proportional to the size of the conductor, hence larger the size of the conductor larger will be the critical disruptive voltage and hence smaller will be the factor $(V-V_0)^2$. It is found in practice that the effect of the second proportionality is much more than the first on the corona losses, and hence larger the size of the conductor lower is the corona loss.

a) Number of conductors/phases:
For operating voltages 380 kV and above it is found that one conductor per phase gives large corona loss, large radio interference (RI) level solved by using two or more than two conductors per phase bundling of conductors. By bundling the conductors the self GMD of the conductors is increased thereby; the critical disruptive voltage is increased and hence corona loss is reduced.

b) Profile of the conductor:
Because of field uniformality in case of cylindrical conductor the corona loss is less.

c) Surface conditions of the conductors
The surface would have dirt etc. deposited on it which will lower the disruptive voltage and increase corona loss.

d) Heating of the conductor by load current
An indirect reducing effect on the corona loss. In the absence of heating, dew in the form of tiny water drops would form on the conductor in foggy weather or at times of high humidity, which induces additional corona.

e) During rains:
The time during which the water drops remain on the surface is reduced and the loss is also reduced.

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2.11.4 METHODS OF REDUCING CORONA LOSS

i) Large dia conductors
ii) Hollow conductors
iii) Bundled conductors

Hollow conductors to have a large diameter without materially adding to its weight.

2.11.5 LINE DESIGN BASED ON CORONA

Bad weather conditions such as rain sleet greatly increase the corona loss and also lower the critical voltage of the line. If the lines are designed without corona even during bad weather conditions, the size of the towers and the conductors will be uneconomical. The average corona loss through the year will be very small. A fair weather loss of 1 kW per 3-phase, foul weather loss of 20 kW per three phase mile.

2.11.6 DISADVANTAGES OF CORONA

i) Definite loss of power
ii) Corona is present the effective capacitance of the conductors in increased because the effective dia of the conductor is increased. This effect increases the flow the charging current. Because of corona triple frequency currents flow through the ground in case of a grounded system and they give rise to a voltage of triple frequency in an ungrounded system. These triple frequency currents and voltages interfere with the communication circuits due to electromagnetic and electrostatic effects.

2.11.7 ADVANTAGES OF CORONA

Reduces the magnitude of high voltage steep fronted waves due to lighting or switching by partially dissipating as a corona loss

2.11.8 RADIO INTERFERENCE

The corona discharges emit radiation which may introduce noise signals in the communication lines, radio and television receivers. It is mainly due to the brush discharges on the surface irregularities of the conductor during positive half cycles. This leads to corona loss at voltages lower than the critical voltages. The negative discharges are less troublesome for radio reception. The amplitude of RI level varies inversely as the frequency at which the interference is measured.

Higher frequency band less affected. But the pressure of harmonics and multiples of third harmonics will not care as they are in phase in all the power conductors and therefore are dangerous for the communication circuits.

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3 PER UNIT SYSTEM / SYMMETRICAL COMPONENTS / FAULT ANALYSIS

3.1 INTRODUCTION

The p.u. value of any quantity is defined a $\frac{\text{the actual value of the quantity (in any unit)}}{\text{the base or reference value in the same unit}}$

The three basic quantities are voltage, current and impedance. If we choose any two to them as the base or reference quantity, the third one automatically will have a base or reference value depending upon the other two e.g., if V and I are the base voltage and current in a system, the base impedance of the system is fixed and is given by

$$Z = \frac{V}{I}$$

To select voltage and kVA as the base quantities V_b and kVA_b

$$V_{p.u.} = \frac{V_{actual}}{V_b}$$

The base current

$$= \frac{kVA_b \times 1000}{V_b}$$

$$\therefore p.u.\,current = \frac{\text{Actual current}}{\text{Base current}} = \frac{\text{Actual current}}{kVA_b \times 1000} \times V_b$$

$$p.u. \quad \frac{\text{Actual impedance}}{\text{Base impedance}}$$

$$= \frac{Z.kVA \times 1000}{V} \quad \frac{Z.MVA_b}{(kV_b)^2}$$

If the individual quantities $Z_{p.u\ old}$, kVA_{old} and the common base quantities are $Z_{p.u.new}$, kVA_{new} and V_{new}, then making use of the relation above,

$$Z_{p.u.new} = Z_{p.u.old} \cdot \frac{kVA_{new}}{kVA_{old}} \cdot \left(\frac{V_{old}}{V_{new}} \right)^2$$

The p.u. impedance of an equipment corresponding to its own rating is given by

$$Z_{p.u.} = \frac{IZ}{V}$$

Where Z is the absolute value of the impedance of the equipment

With p.u. system there is less chance of making mistake in phase and line voltages, single phase or three phase quantities. Also the p.u. impedance of the transformer is same whether referred on to primary or secondary side of the transformer which is not the case when considering absolute value of these impedances.

Let the impedance of the transformer referred to primary side be Z_p and that on the secondary side be Z_s, then

$$Z_p = \left(\frac{V_p}{V_s} \right)^2$$

Where V_p and V_s are the primary and secondary voltages of the transformer.

Now

$$Z_{pp.u.} = \frac{Z_p I_p}{V_p} \quad Z_s \left(\frac{V_p}{V_s} \right)^2 \frac{I_p}{V_p}$$

$$= Z_s \cdot \frac{V_p I_p}{V_s^2} = Z \cdot \frac{V_s I_s}{V_s^2} = \frac{Z_s I_s}{V_s}$$

$$= Z_{s.p.u.}$$

The p.u. impedance of the transformer referred to primary side $Z_{p\ p.u.}$ is equal to the p.u. impedance of the transformer referred to the secondary side $Z_{s\ p.u.}$. This is a great advantage of p.u. system of calculation.

The base values in a system are selected in such a way that the p.u. voltages and currents in system are approximately unity. Sometime the base kVA is chosen equal to the sum of the ratings of the various equipments on the system or equal to the capacity of the largest unit.

A voltage corresponding to any part of the system could be taken as a base and the base voltages in other parts of the circuit, separated from the original part by transformers is related through the turns ratio of the transformers. The base voltage on primary side is V_{pb} then on the secondary side of the transformer the base

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voltage will be $V_{sb} = V_{pb}(N_s/N_p)$, where N_s and N_p are the turns of the transformer on secondary and primary side respectively.

3.2 SYMMETRICAL FAULT ANALYSIS

This chapter is devoted to abnormal system behavior under conditions of symmetrical short circuit (symmetrical three-phase fault*). Such conditions are caused in the system accidentally through insulation failure of equipment or flashover of lines initiated by a lightning stroke or through accidental faulty operation. The system must be protected against flow of heavy short circuit currents by disconnecting the faulty part of the system by means of circuit breakers operated by protective relaying. For proper choice of circuit breakers and protective relaying, we must estimate the magnitude of currents that would flow under short circuit conditions – this is the scope of fault analysis (study)

Unsymmetrical faults requiring special tools like symmetrical components, the symmetrical fault analysis must be carried out, as this type of fault generally leads to most severe fault current flow against which the system must be protected.

Symmetrical fault may be a solid three-phase short circuit or may involve are impedance

The synchronous generator during short circuits has a characteristics time-varying behavior. In the event of a short circuit, the flux per pole undergoes dynamic change with associated transients in damper and field windings. The reactance of the circuit model of the machine changes in windings. The reactance of the circuit model of the machine changes in the first few cycles from a low sub transient reactance to a higher transient value, finally settling at a still higher synchronous (steady state) value. Depending upon the arc interruption time of circuit breakers, a suitable reactance value is used for the circuit model of synchronous generators for short circuit analysis.

3.3 TRANSIENT ON A TRANSMISSION LINE

Assumptions

i) The line is fed from a constant voltage source
ii) Short circuit takes place when the line is unloaded
iii) Line capacitance is negligible and the line can be represented by a lumped RL series circuit.

$i = i_s + i_i$

Short circuit current

$$i=\frac{\sqrt{2}V}{|Z|}\sin(\omega t+\alpha-\theta)+\frac{\sqrt{2}V}{|Z|}\sin(\theta-\alpha)e^{-(R/L)t}$$

Symmetrical short DC off-set current

Circuit current

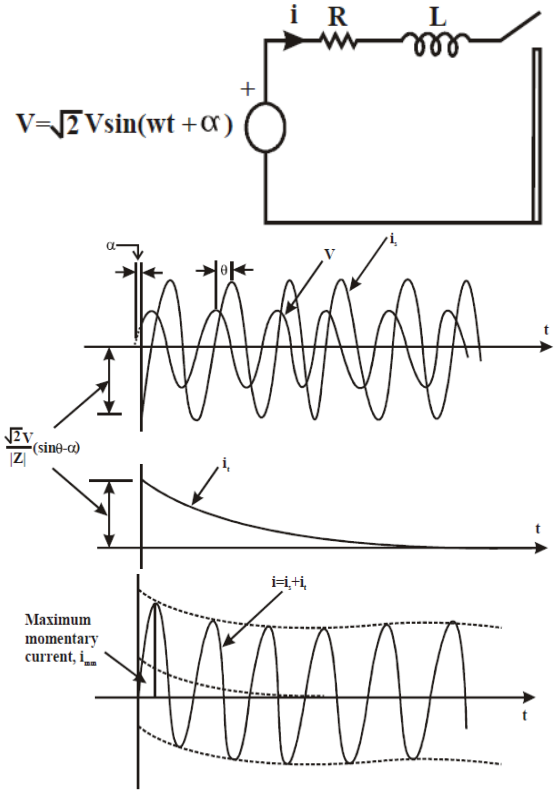

Fig. Waveform of a short circuit current on a transmission line

The maximum momentary short circuit current.

$$i_{mm}\frac{\sqrt{2}V}{|Z|}\sin(\theta-\alpha)+\frac{\sqrt{2}V}{|Z|}$$

$$i_{mm(\max possible)}=2\frac{\sqrt{2}V}{|Z|}$$

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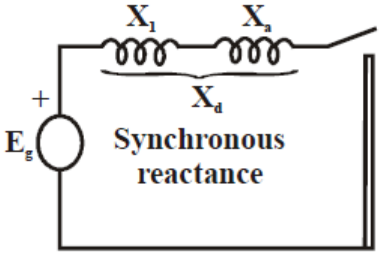
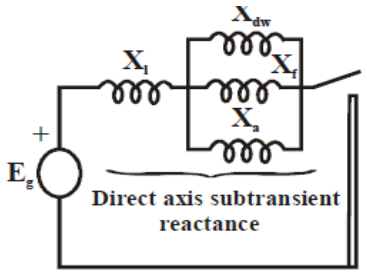
i_{mm} = twice the maximum of symmetrical short circuit current (doubling effect)
For the selection of circuit breakers, momentary short circuit current is taken corresponding to its maximum possible value (a safe choice)

3.4 SHORT CIRCUIT OF A SYNCHRONOUS MACHINE (ON NO LOAD)

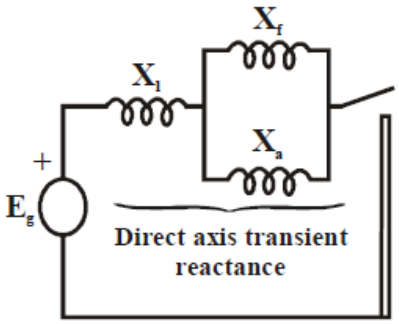
Under steady state short circuit conditions, the armature reaction of a synchronous generator produces a demagnetizing flux.
Modelled as reactace X_n, Combined with the leakage reactance X_1, synchronous reactance X_d (direct axis synchronous reactance. Armature resistance being small can be neglected.
Immediately in the event of a short circuit, the symmetrical short circuit current is limited only by the leakage reactance of the machine. Since the air gap flux cannot change instantaneously (theorem of constant flux linkages), to counter the demagnetization of the armature short circuit current, currents appear in the field winding as well as in the damper winding in a direction to help the main flux. These currents decay in accordance with the winding time constants. The time constant of the damper winding which has low leakage inductance is much less than that of the field winding, which has high leakage inductance. Thus during the initial part of the short circuit the damper and field windings have transformer currents induced in them so that in the circuit model their reactance-X_f of field winding and X_{dw} of damper winding – appear in parallel* with X_a



(a) Steady state short circuit model of a synchronous machine



(b) Approximate circuit model during subtransient period of short circuit



(C) Approximate circuit model during transient period of short circuit

The initial period of the short circuit

$$X_l + \frac{1}{(1/X_a + 1/X_f + 1/X_{dw})} = X_d''$$

Subtransient reactance of the machine, the reactance effective after the damper winding currents have died out,
$X_d' = X_1 + (X_a \,||\, X_f)$
Transient reactance of the machine. Under steady conditions is the synchronous reactance of the machine Obviously $X_d'' < X_d' < X_d$. The machine thus offers a time-varying reactance which changes from X_d'' to X_d' and finally to X_d.
The short circuit current can be divided into three periods-initial subtransient period when the current is large as the machine offers subtransient reactance, the middle transient period where the machine offers transient reactance, and finally the steady state period when the machine offers synchronous reactance.

$$|I| = \frac{|E_g|}{X_d}$$

$$|I'| = \frac{|E_g|}{X'_d}$$

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$$|I''| = \frac{|E_g|}{X_d''}$$

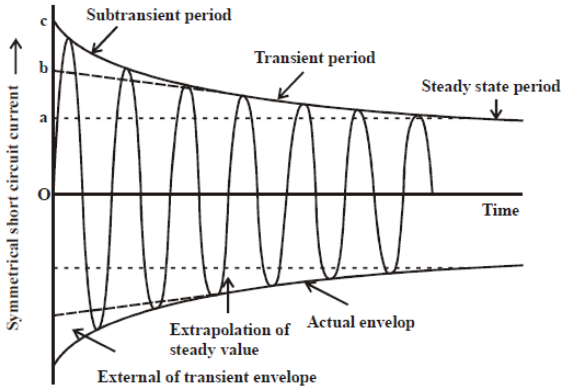

Fig. (a) Symmetrical short circuit armature current in synchronous machine

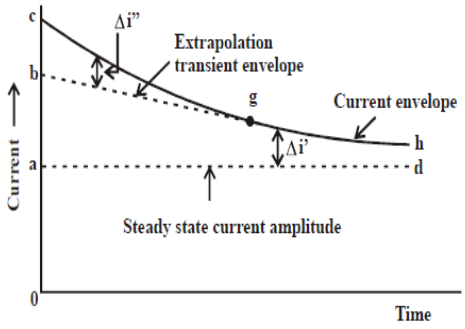

Fig. (b) Envelope of synchronous machine symmetrical short circuit current

| I | = Steady state current (rms)
| I'| = Transient current (rms) excluding DC component
| I"| = Subtransient current (rms) excluding DC component
X_d = direct axis synchronous reactance
X_d' = direct axis transient reactance
X_d'' = direct axis subtransient reactance
| E_g | = per phase no load voltage (rms)

3.5 SHORT CIRCUIT OF A LOADED SYNCHRONOUS MACHINE

The circuit model of a synchronous generator operating under steady conditions supplying a load current I^o to the bus emf under loaded condition and X_d is the direct axis synchronous reactance of the machine.

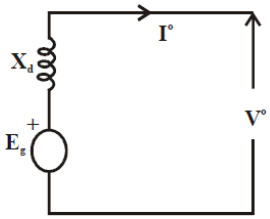

Fig. Circuit model of a loaded machine

$$E_g'' = V^o + jI^oX_d''$$

$$E_g' = V^o + jI^oX_d'$$

E_g'' is known as the voltage behind the subtransient reactance E_g' is the voltage behind the transient reactance. If I^o is zero (no load case), $E_g'' = E_g' = E_g$, the no load voltage,

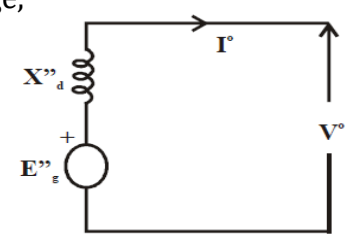

Fig. (a) Circuit model for computing subtransient current

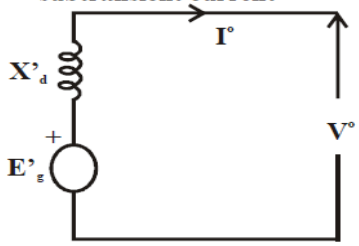

Fig.(b) Circuit model for computing transient current

$$E_m'' = V^o - jI\,X_d''$$

$$E_m' = V^o - jI^oX_d'$$

SHORT CIRCUIT (SC) CURRENT COMPUTATION THROUGH THE THEVENIN THEOREM

An alternate method of computing short circuit currents is through the applications of the Thevenin theorem. This method is faster and easily adopted to systematic computation for large networks.
Consider a synchronous generator feeding a synchronous motor over a line. Fault computations are to be made for a fault at F, at the motor terminals.
This change does not disturb the prefault current I^o and prefault voltage V^o (at F).
As seen from FG the Thevenin equivalent circuit of Fig. (b) is drawn in Fig. It comprises prefault voltage V^o in series with the passive Thevenin impedance network. It is noticed that the prefault current I^o does not appear in the passive Thevenin impedance network. It is therefore to be

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remembered that this current must be accounted for by superposition after the SC solution is obtained through use of the Thevenin equivalent.

Consider now a fault at F through an impedance Z^f.

$$I^f = \frac{V^o}{jX_{Th} + Z^f}$$

Current caused by fault in generator circuit

$$\Delta I_g = \frac{X'_{dm}}{(X'_{dg} + X + X'_{dm})} I^f$$

Current caused by fault in motor circuit

$$\Delta I_m = \frac{X'_{dg} + X}{(X'_{dm} + X + X'_{dg})} I^f$$

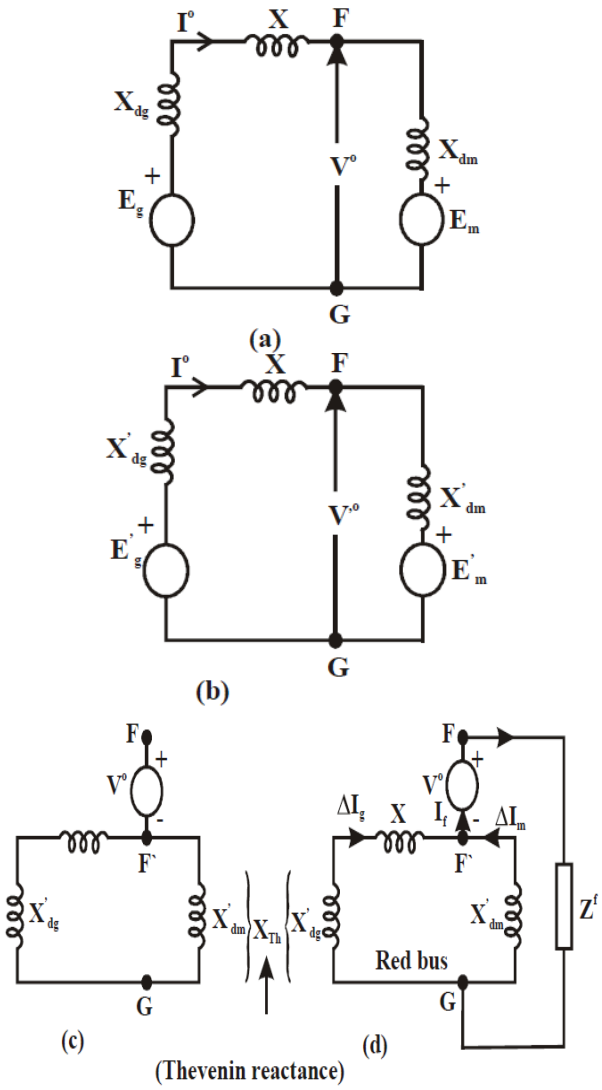

Fig. Computation of SC current by the Thevenin equivalent

Post fault currents and voltages by superposition:

$$I_g^f = I^o + \Delta I_g$$

$$I_m^f = -I^o + \Delta I_m \text{ (in the direction of } \Delta I_m)$$

Post fault voltage

$$V^f = V^o + (-jX_{Th} I^f) = V^o + \Delta V$$

$$\Delta V = -jX_{Th} I^f$$

3.6 FAULT ANALYSIS AND SYMMETRICAL COMPONENTS

3.6.1 INTRODUCTION

A system of n vectors or quantities may be resolved, when n is prime, into n different symmetrical groups or systems, one of which consists of n equal vectors and the remaining (n -1) systems consist of n equi-spaced vectors which with the first mentioned group of equal vectors forms an equal number of symmetrical n-phase systems…."

3.6.2 3-PHASE SYSTEMS

Any three coplanar vectors V_a, V_b and V_c can be expressed in terms of three new vectors V_1, V_2 and V_3 with constant coefficients.

Each of the original vectors has been replaced by a set of three vectors making a total of nine vectors. To simplify the calculations two conditions should be satisfied in selecting systems of components to replace 3- phase current and voltage vectors:

Fortescue's theorem, the three unbalanced vectors V_a, V_b and V_c can be replaced by a set of three balanced systems of vectors. Therefore, the solution is unique. A balanced system of three vectors is one in which the vectors are equal in magnitude and are equi-spaced.

1. Positive sequence component equal magnitude but displaced by 120° and same phase sequence as the original vectors.
2. Negative sequence component equal magnitude by 120° and the phase

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sequence opposite to the original vectors.

3. Zero sequence component equal magnitude and also are in phase with each other.

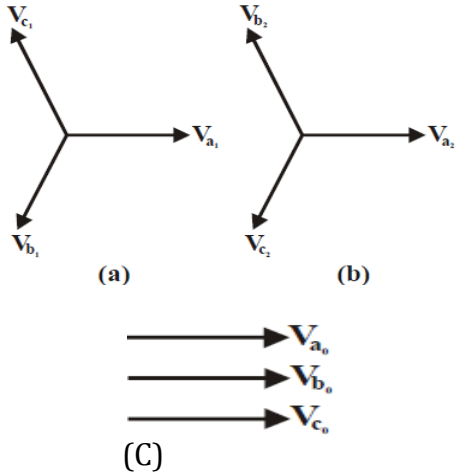

Fig.(a) Positive sequence component; (b)Negative sequence component; (c) Zero sequence component

3.6.3 SIGNIFICNACE OF POSITIVE, NEGATIVE AND ZERO SEQUENCE COMPNENTS

If a set of positive sequence voltages is applied to the stator winding of the alternator, the direction of rotation of the stator field is the same as the rotor, the direction of rotation of the stator field is opposite to that of the rotor, the set of voltages are negative sequence voltages. The zero sequence voltages are single phase voltages and, therefore, they give rise to an alternating field in space.

Relations between the original unbalanced vectors and their corresponding symmetrical components

$$V_a = V_{a1} + V_{a2} + V_{a0}$$
$$V_b = V_{b1} + V_{b2} + V_{b0}$$
$$V_c = V_{c1} + V_{c2} + V_{c0}$$

Phase a as the reference as shown in Fig. the following relations between the symmetrical components of phases b and c in terms of phase a can be written.

$$\lambda = 1\angle 120^o$$

In the complex form

$$\lambda = \cos 120^o + j\sin 120^o$$
$$= -0.5 + j0.866$$

Similarly

$$\lambda^2 = -0.5 + j0.866 = 1.0\angle 120^o$$
$$\lambda^2 = -0.5 - j0.866 = 1.0\angle -120^o$$
$$\lambda^3 = 1.0\angle 0^o$$
$$\lambda^4 = \lambda$$
$$\lambda^2 + \lambda + 1 = 0$$
$$V_{b1} = \lambda^2 V_{a1}$$
$$V_{c1} = \lambda V_{a1}$$

For negative sequence vectors

$$V_{b2} = \lambda V_{a2}, V_{c2} = \lambda^2 V_{a2}$$

For zero sequence vectors

$$V_{b0} = V_{a0} = V_{c0}$$

Substituting these relations in equations

$$V_a = V_{a1} + V_{a2} + V_{a0}$$
$$V_b = \lambda^2 V_{a1} + \lambda V_{a2} + V_{a0}$$
$$V_c = \lambda V_{a1} + \lambda^2 V_{a2} + V_{a0}$$

The problem is: given V_a, V_b, V_c, find out V_{a1}, V_{a2} and V_{a0}.

V_{a1}, multiply equations by 1, λ and λ^2 respectively

$$V_{a1} = \frac{1}{3}(V_a + \lambda V_b + \lambda^2 V_c)$$
$$V_{a2} = \frac{1}{3}(V_a + \lambda^2 V_b + \lambda V_c)$$
$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$

In the equations above V_a, V_b and V_c may be the line be the to ground voltages, line to neutral voltages, line to line voltages.

3.6.4 AVERAGE 3-PHASE POWER IN TERMS OF SYMMETRICAL COMPONENTS

$$P = V_a I_a \cos\varphi_a + V_b I_b \cos\varphi_b + V_c I_c \cos\varphi_c$$
$$= V_a.I_a + V_b.I_b + V_c.I_c$$
$$= 3(V_{a1}.I_{a1} + V_{a2}.I_{a2} + V_{a0}.I_{a0})$$
$$= 3[|V_{a1}|\,|I_{a1}|\cos\theta_1 + |V_{a2}|\,|I_{a2}|\cos\theta_2 + |V_{a0}|\,|I_{a0}|\cos\theta_0]$$

3.6.5 SEQUENCE IMPEDANCE

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The positive sequence impedance of an equipment is the impedance offered by the equipment to the flow of positive sequence currents. Similarly, the negative sequence or zero sequence impedance of the equipment is the impedance offered by the equipment to the flow of corresponding sequence current.
Since for a static device, the sequence has no significance, the positive- and negative-sequence impedances are equal; the zero sequence impedance which includes the impedance of the return path through the ground, in the general case, is different from the positive- and negative – sequence impedance.
The positive sequence impedance depends upon the working of the machine, i.e., whether it is working under subtransient, transient or steady state condition. The impedance under steady state condition. The impedance under steady state condition is known as the synchronous impedance

3.6.6 FAULT CALCULATIONS

Classified as:
1. Shunt faults (short circuits)
2. Series faults (open conductor)

Shunt type of faults involve power conductor or conductors-to-ground or short circuit between conductors. One or two phases opened other phases or phase is closed called series type of faults. Shunt faults are characterized by increase in current and fall in voltage and frequency whereas series faults are characterized by increase in voltage and frequency and fall in current in the faulted phases.
Shunt type of faults are classified as
i) Line-to-ground fault
ii) Line-to-line fault;
iii) Double line-to-ground fault
iv) 3-phase fault

The first three unsymmetrical faults. The method of symmetrical components will be utilized to analyses the unbalancing in the system. The 3-phase fault is a balanced fault
The series faults are classified
i) One open conductor
ii) Two open conductors

Faults symmetrical components for analyzing

3.6.7 VOLTAGE OF THE NEUTRAL

The potential of the neutral when it is grounded through some impedance or is isolated, will not be at ground potential under unbalanced conditions such as unsymmetrical faults. The potential of the neutral is given as $V_n = -I_nZ_n$ where Z_n is the neutral grounding impedance and I_n the neutral current. Here negative sign is used as the current flows from the ground to the neutral of the system and potential of the neutral is lower than the ground.
For a 3-phase system,

$$I_n = I_a + I_b + I_c$$
$$= (I_{a1} + I_{a2} + I_{a0}) + (\lambda^2 I_{a1} + \lambda I_{a2} + I_{a0}) + (\lambda I_{a1} + \lambda^2 {}_{a2} + I_{a0})$$
$$= I_{a1}(1 + \lambda + \lambda^2) + I_{a2}(1 + \lambda + \lambda^2) + 3I_{a0} = 3I_{a0}$$
$$V_n = -3I_{a0}Z_n$$

3.6.8 REFERENCE OF VOLTAGES

For the positive and negative sequence systems, therefore, the expressions voltage to neutral and voltage to ground may be used interchangeably but for the zero sequence system it is important to distinguish between the two terms.
Dissymmetry only at one point i.e., faults. In a 3-phase system, the unknown quantities are the 3-phase voltage V_a, V_b and V_c and the 3-phase currents I_a, I_b and I_c i.e., there are six unknowns. To determine these quantities, six linearly independent equations are required.
If conductor a is faulted to ground at some point, the voltage of this conductor at the faulted point is zero, i.e., $V_a = 0$. Instead of 3-pahse voltages and currents being unknown one can say that six symmetrical components V_{a0}, V_{a1}, V_{a2}, I_{a0}, I_{a1} and I_{a2} are

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unknown. In a 3-phase system, three equations at the point of dissymmetry.

3.6.9 SEQUNCE NETWORK EQUATIONS

For an unloaded alternator with neutral solidly grounded, assuming that the system is balanced, i.e., the generated voltages are of equal magnitude and displaced by 120°. Since the sequence impedance per phase are same for all three phases analysis on single phase basis. (as positive sequence current does not produce drop in negative or zero sequence impedance)

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

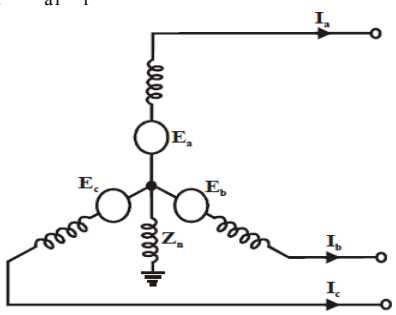


Fig: A balanced 3-phase system

A negative sequence current does not produce drop in positive or zero sequence impedance

$$V_{a2} = E_{a2} - I_{a2}Z_2$$

The negative sequence voltage generated is zero,

therefore

$$E_{a2} = 0$$

$$V_{a2} = -I_{a2}Z_2$$

Similarly for zero sequence voltages

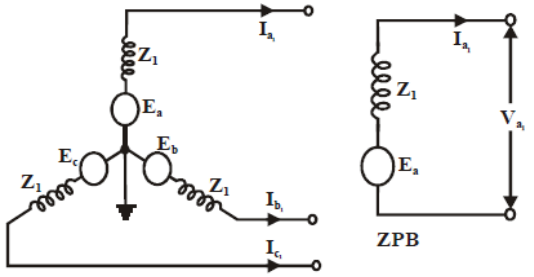
$$E_{a0} = 0$$

$$V_{a0} = V_n - I_{a0}Z_{g0} = -3I_{a0}Z_n - I_{a0}(Z_{g0} + 3Z_n)$$

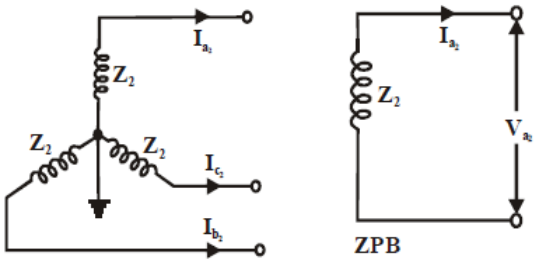
Z_{g0} is the zero sequence impedance of the generator and Z_n is the neutral impedance

$$Z_0 = Z_{g0} + 3Z_n$$

Simultaneous solution of the three sequence equations and the three boundary conditions equations in which the phase quantities have been replaced by their symmetrical components of currents and voltage, will give the six unknown symmetrical components of currents and voltages.



(a)



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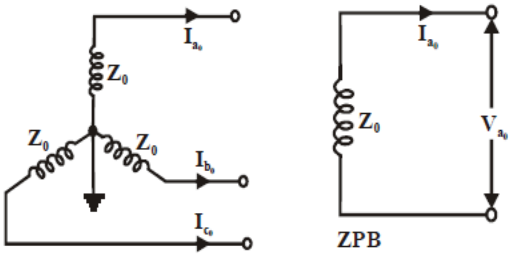

(c)

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

For all type of faults the sequence network equations will be as given by equation whereas the three equations describing the boundary conditions will be different for different types of faults.

i) neutral grounded through some impedance Z_n, and
ii) fault having some impedance Z_f.
Let the fault take place on phase a. The boundary conditions are

3.6.10 SINGLE LINE TO – GROUND FAULT

Sequence network equations are

$V_{a0} = - I_{a0}Z_0$

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

$V_{a2} = - I_{a2}Z_2$

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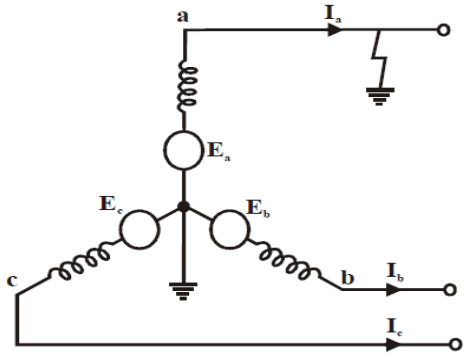

Fig: A Solidly grounded, unloaded alternator; L-G fault on phase a.

The solution of these six equations will give six unknowns V_{a0}, V_{a1}, V_{a2} and I_{a0}, I_{a1} and I_{a2}.

$I_{a1} = I_{a2} = I_{a0} = I_a/3$

$V_a = 0 = V_{a1} + V_{a2} + V_{a0}$

$E_a - I_{a1}Z_1 - I_{a2}Z_2 - I_{a0}Z_0 = 0$

$I_{a1} = I_{a2} = I_{a0}$

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

To simulate a L-G fault all the three sequence networks are required and since the currents are all equal in magnitude and phase angle, therefore, the three sequence networks must be connected in series.

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda & \lambda^2 \\ 1 & \lambda^2 & \lambda \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$I_n = I_a = I_{a1} + I_{a2} + I_{a0}$

$I_{a1} = I_{a2} = I_{a0}$

$I_n = 3I_{a0}$

In case the neutral is not grounded the zero sequence impedance Z_0 becomes infinite

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + \infty} = 0$$

The same result neutral is isolated, there is no return path for the current and, therefore $I_{a1} = I_{a2} = I_{a0} = 0$. For this system the fault current $I_a = 0$.

3.6.11 LINE – TO – LINE FAULT

The boundary conditions are

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c$$

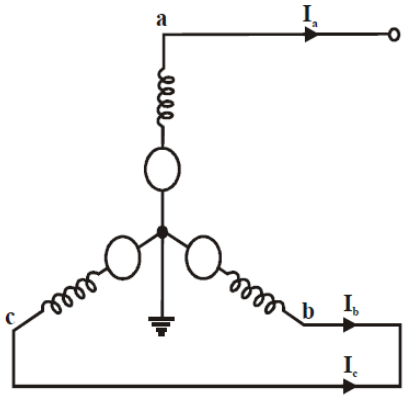

Fig: L-L fault on an unloaded and neutral grounded alternator.

Using the relations

$$I_{a1} = \frac{1}{3}\left(I_a + \lambda I_b + \lambda^2 I_c\right)$$

$$I_{a2} = \frac{1}{3}\left(I_a + \lambda^2 I_b + \lambda I_c\right)$$

$$I_{a0} = \frac{1}{3}\left(I_a + I_b + I_c\right)$$

and substituting for I_a, I_b and I_c

$$I_{a1} = \frac{1}{3}\left(0 + \lambda I_b - \lambda^2 I_b\right)$$

$$= \frac{1}{3}\left(\lambda - \lambda^2\right) I_b$$

$$I_{a2} = \frac{1}{3}\left(0 + \lambda^2 I_b - \lambda I_b\right)$$

$$= \frac{I_b}{3}\left(\lambda^2 - \lambda\right)$$

$$I_{a0} = \frac{1}{3}(0 + 0) = \upsilon$$

For a line-to-line fault the zero-sequence component of current is absent

$$I_{a1} = -I_{a2}$$

Zero-sequence network is not required

$$V_{a0} + \lambda^2 V_{a1} + \lambda V_{a2} = V_{a0} + \lambda V_{a1} + \lambda^2 V_{a2}$$

$$(\lambda^2 - \lambda) V_{a1} = (\lambda^2 - \lambda) V_{a2}$$

$$V_{a1} = V_{a2}$$

Two sequence networks are connected in opposition.

$$V_{a1} = V_{a2}$$

$$E_a - I_{a1}Z_1 = -I_{a2}Z_2 = I_{a1}Z_2$$

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

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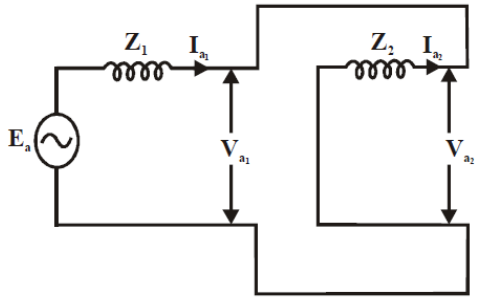

Fig: Interconnection of sequence networks for L-L fault.

System there is only one ground i.e., the grounded neutral of the system and since the fault does not involve ground the zero sequence currents which are single phase currents do not flow i.e., $I_{a0} = 0$.

3.6.12 DOUBLE LINE TO GROUND FAULT

On phases b and c

$$I_a = 0$$

$$V_b = 0$$

$$V_c = 0$$

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$

$$= V_a / 3$$

$$V_{a1} = \frac{1}{3}(V_a + \lambda V_b + \lambda^2 V_c)$$

$$= V_a / 3$$

$$V_{a2} = \frac{1}{3}(V_a + \lambda^2 V_b + \lambda V_c)$$

$$= V_a / 3$$

$$V_{a0} = V_{a1} = V_{a2}$$

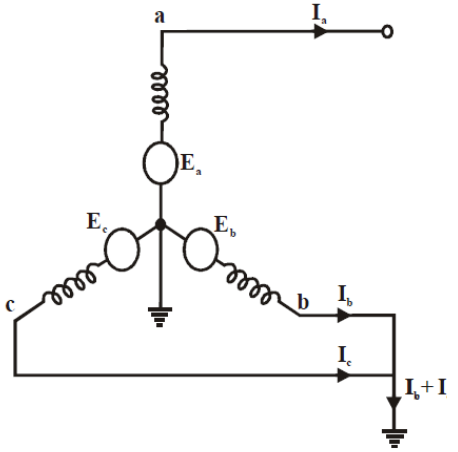

Fig: A Solidly grounded, unloaded alternator; L-L-G fault.

$$V_{a0} = V_{a1}$$

$$-I_{a0}Z_0 = E_a - I_{a1}Z_1$$

$$I_{a0} = -\frac{E_a - I_{a1}Z_1}{Z_0}$$

$$V_{a2} = V_{a1}$$

$$-I_{a2}Z_2 = E_a - I_{a1}Z_1$$

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

$$I_a = I_{a1} + I_{a2} + I_{a0} = 0$$

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

Rearranging the terms gives

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

All the three sequence networks are required to simulate L-L-G fault and also that the negative and zero-sequence networks are connected in parallel

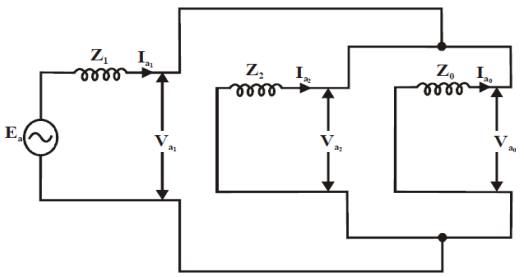

Fig: Interconnection of sequence networks for L-L-G fault.

The neutral current

$$I_n = I_b + I_c$$

$$= \lambda^2 I_{a1} + \lambda I_{a2} + I_{a0} + \lambda I_{a1} + \lambda\ I_{a2} + I_{a0}$$

$$= (\lambda^2 + \lambda) I_{a1} + (\lambda + \lambda\ ) I_{a2} + 2I_{a0}$$

$$= -I_{a1} - I_{a2} + 2I_{a0}$$

$$= I_{a0} + 2I_{a0} = 3I_{a0}$$

3.6.13 3-PHASE FAULT

Boundary conditions are

$$I_a + I_b + I_c = 0$$

$$V_a = V_b = V_c$$

Since $|I_a| = |I_b| = |I_c|$ and if I_a is taken as reference

$$I_b = \lambda^2 I_a \text{ and } I_c = \lambda I_a$$

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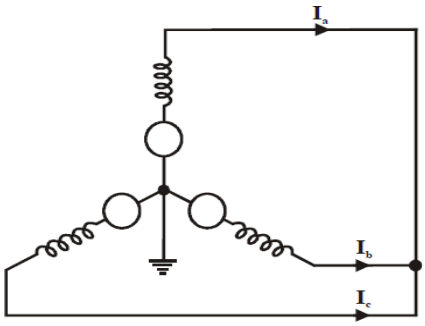


Fig: A 3-phase neutral grounded and unloaded alternator 3-phase shorted.

Using the relation

$$I_{a1}=\frac{1}{3}\left(I_a+\lambda I_b+\lambda^2 I_c\right)$$

and substituting the values of I_b and I_c,

$$I_{a1}=\frac{1}{3}\left(I_a+\lambda^3 I_b+\lambda^3 I_c\right)=I_a$$

$$I_{a2}=\frac{1}{3}\left(I_a+\lambda^2 I_b+\lambda I_c\right)$$

Substituting for I_b and I_c in terms of I_a,

$$I_{a2}=\frac{1}{3}\left(I_a+\lambda^2 I_b+\lambda I_c\right)$$

$$=\frac{1}{3}\left(I_a+\lambda I_a+\lambda^2 I_a\right)$$

$$=\frac{I_a}{3}\left(1+\lambda+\lambda^2\right)$$

$$=0$$

Similarly,

$$I_{a0}=\frac{1}{3}(I_a+I_b+I_c)=0$$

For a 3-phase fault zero-as well as negative-sequence components of current are absent and the positive-sequence component of current is equal to the phase current.

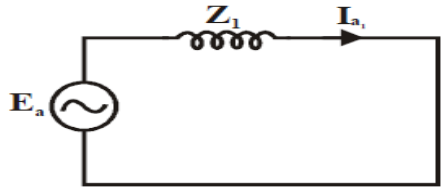


Fig: Interconnection of sequence network-3-phase fault

$$V_{a1}=\frac{1}{3}(V_a+\lambda V_b+\lambda^2 V_c)=\frac{1}{3}(V_a+\lambda V_a+\lambda^2 V_a)$$

$$=\frac{V_a}{3}(1+\lambda+\lambda^2)=0$$

$$V_{a2}=\frac{1}{3}(V_a+\lambda^2 V_b+\lambda V_c)=0$$

Since

$$V_{a1}=0=E_a-I_{a1}Z_1,$$

$$I_{a1}=\frac{E_a}{Z_1}$$

OBSERVATIONS

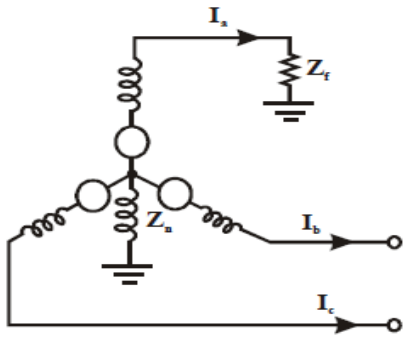
1. Positive sequence currents are present in all types of faults.
2. Negative sequence currents are present in all unsymmetrical faults.
3. Zero sequence currents are present when the neutral of the system is grounded and the fault also involves the ground, and magnitude of the neutral current is equal to $3I_{a0}$.

Since only the positive sequence voltage are generated in the synchronous machine.

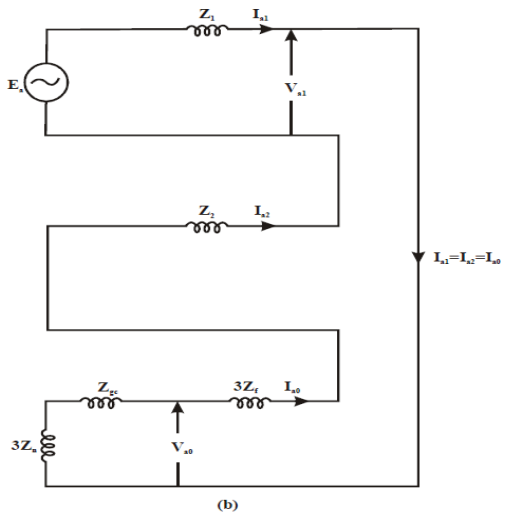
Any unbalanced condition gives rise to positive sequence currents.

These voltages are in general a maximum at the fault point and decreases as the neutral bus is approached.

3.6.14 LINE TO GROUND FAULT WITH Z_F



(a)



(b)

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a) A-3 phase unloaded alternator with neutral grounded through impedance Zn and fault impedance Zf, L – G fault;

b) Interconnection of sequence network for L-G fault

$$V_a = I_a Z_f$$

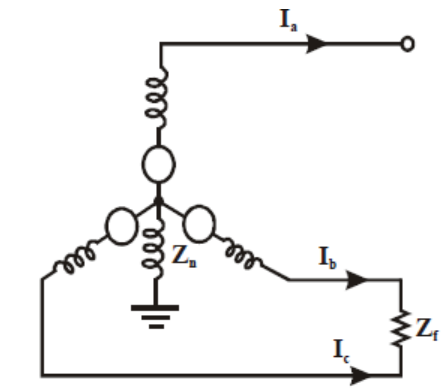
$$I_b = 0, I_c = 0$$

$$V_{a0} = -I_{a0}(Z_{g0} + 3Z_n)$$

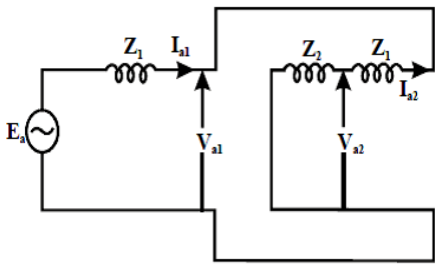
$$V_{a1} = E_a - I_{a1}Z_1, V_{a2} = -I_{a2}Z_2$$

$$I_{a1} = \frac{E_a}{Z_1 + Z_2 + (Z_0 + 3Z_n) + 3Z_f}$$

3.6.15 LINE TO LINE FAULT WITH Z_F



(a)



(b)

Fig. (A) L-L fault;

(b) Interconnection of sequence network, fault impedance Z_f, L-L fault

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c + I_b Z_f$$

$$V_{a1} = V_{a2} + I_{a1} Z_f$$

$$I_{a1} = \frac{E_a}{Z_1 + (Z_2 + Z_f)}$$

3.6.16 DOUBLE LINE TO GROUND FAULT WITH Z_F

$$I_b = 0$$

$$V_b = V_c = (I_b + I_c)Z_f$$

$$I_{a1} = \frac{E_a}{Z_1 \dfrac{Z_2(Z_0 + 3Z_n + 3Z_f)}{Z_2 + Z_0 + 3Z_n + 3Z_f}}$$

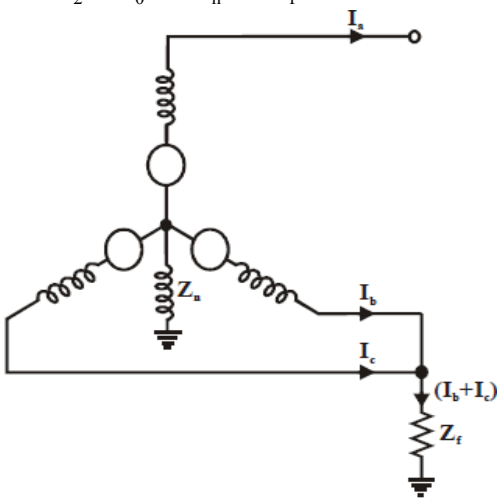


Fig: (a) L-L-G fault. Fault impedance Z_f and neutral impedance Z_n

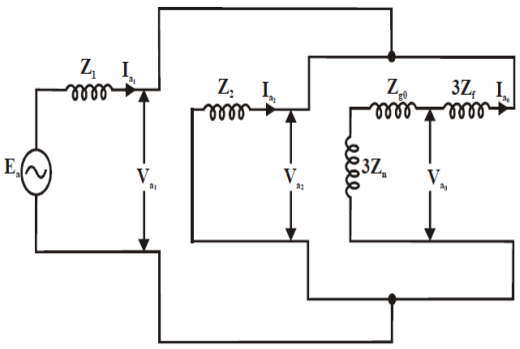


Fig: (b) Interconnection of sequence networks for Fig.(a).

3.6.17 SEQUENCE NETWORKS

The positive sequence network is in all respects identical with the usual networks considered. Each synchronous machine must be considered as a source of e.m.f. Which may vary in magnitude and phase position depending upon the distribution of power and reactive volt amperes just prior to the occurrence of the fault. The positive sequence voltage at the point of fault will drop, the amount being dependent upon

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the type of faults; for 3-phase faults it will be zero; for double line-to-ground fault, line-to-line fault and single line-to-ground fault, it will be higher in the order stated.

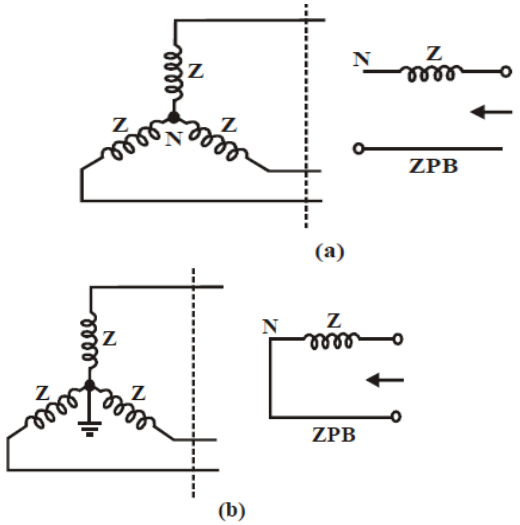
The negative sequence network similar no negative sequence voltages are generated, the source of e.m.f. is absent.

The zero sequence network will be free of internal voltages, the flow of current resulting form the voltage at the point of fault. The transformer and generator impedances will depend upon the type of connections whether star or delta connected; if star, whether grounded or not.

Equivalent circuit for the zero sequence network depends upon the impedances met by the zero sequence currents flowing through the three phases and their sum, $3I_{a0}$, flowing through the neutral impedance and returning through the ground or a neutral conductor. If there is not complete path for zero sequence currents in a circuit, the zero sequence impedance is infinite. Thus a Y-connected circuit with ungrounded neutral has infinite impedance to zero sequence currents

A current of $3I_{a0}$ produces a drop of $3I_a0Z_n$ and to show in the equivalent zero sequence network the same drop where current of I_{a0} flows, the impedance should be $3Z_n$.

A delta-connected circuit provides no path for zero sequence currents flowing in the line.



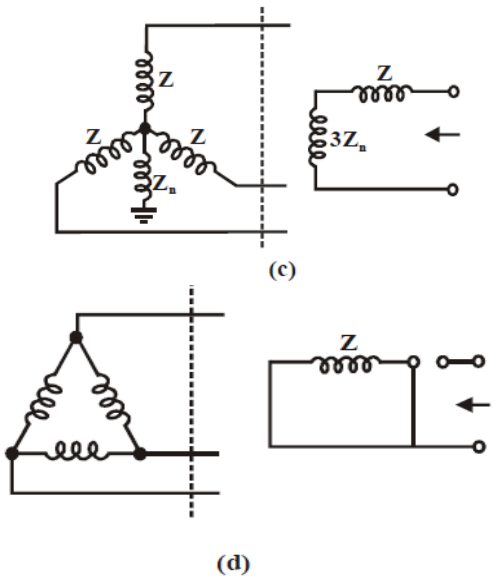


Fig: Zero sequence networks for a 3-phase load.

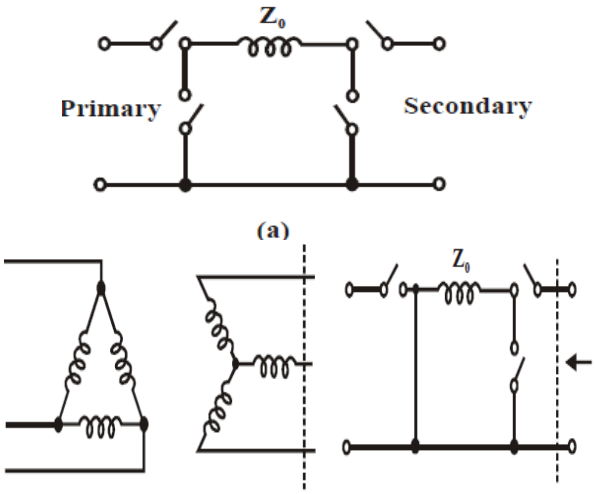
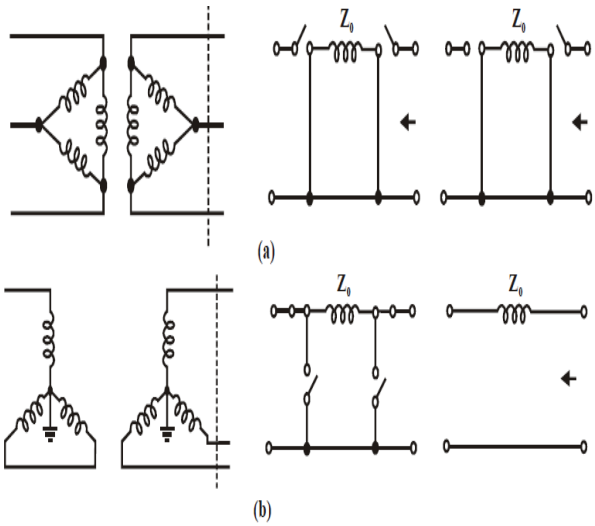


Fig: (a) Switch arrangements for a transformer
(b) Equivalent of Δ/Y.

3.6.18 3-PHASE TRANSFORMERS



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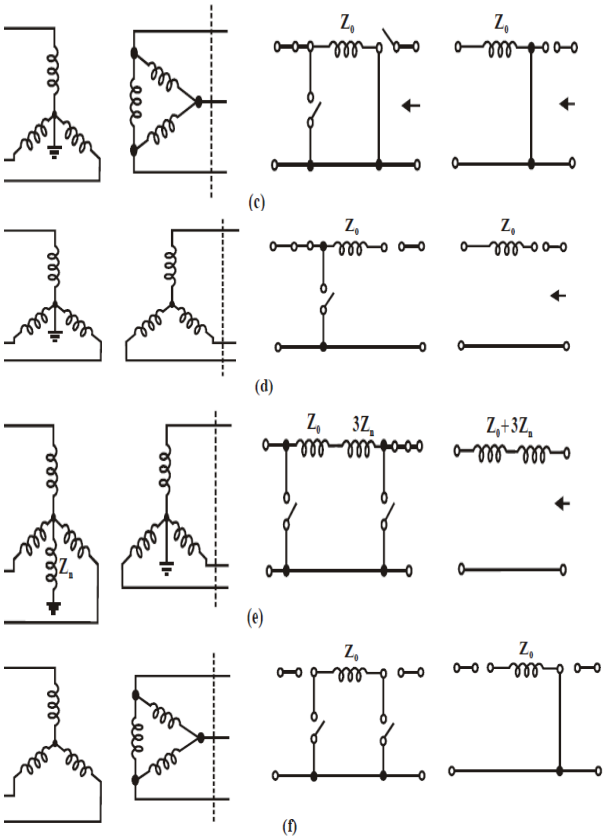

Fig: Zero sequence equivalent circuits of transformers.

Two series and two shunt switches. The series switch of a particular side is closed if it is star grounded and the shunt switch is closed if that side is delta connected, otherwise they are left open.

3.6.19 FAULTS ON POWER SYSTEM

The faults are analyze easily by making use of Thevenin's theorem. As the readers know that this theorem can be used for determining the changes that take place in currents and voltages of a linear network when an additional impedance is added between two nodes of the network. The theorem states that.

The changes that take place in the network voltages and currents due to the addition of an impedance (a short circuit) between two network nodes are identical with those voltages and currents that would be caused by an e.m.f. placed in series with impedance and having a magnitude and polarity equal to the pre-fault voltage that existed between the nodes in question and the impedance as seen between the nodes with all active voltage sources short circuited.

It is to be noted here that positive sequence impedance of the alternator or the synchronous machine depends upon the state of the machine i.e., whether it is sub-transient, transient or steady state.

Since the system is balanced, no negative or zero-sequence currents are flowing before the fault occurs. The prefault negative and zero-sequence voltages at the fault point are zero.

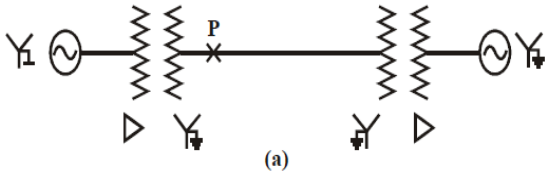

Fig:(a) Single line diagram of a balanced 3-phase system

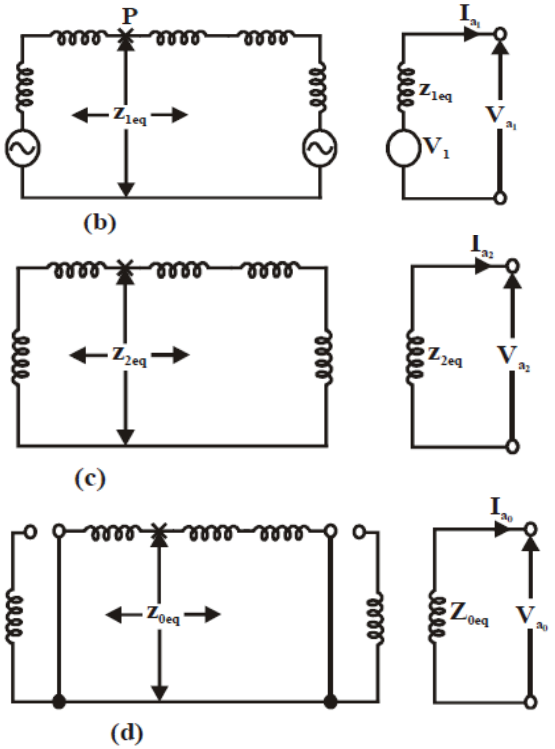

Fig: (b),(c) and (d) Thevenin's equivlent of positive, negative and zero sequence networks.

3.6.20 PHASE SHIFT Δ - Y TRANSFOMERS

The small letters used refer to the star side and capital letters to the delta side of the transformer. The winding e'e on star side corresponds to the E'E on the delta side.

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The primed letters indicate the beginning of the winding and unprimed the finish of the winding. Fig (c) and (d) give the voltage vector diagram for positive sequence of the connections in (a) and (b) respectively. Vector diagram V_{a1} and V_{CB1} are in phase, in (d), V_{a1} and V_{BC1}

$$V_{A1} = jV_{CB1} = jV_{a1}$$

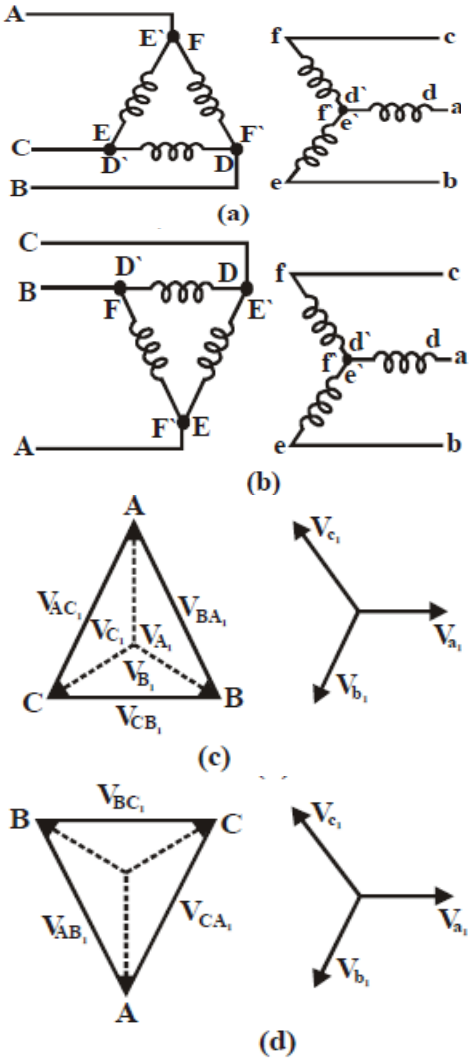
$$V_{A1} = -jV_{BC1} = -jV_{a1}$$

The line to neutral voltage V_{A1} on the delta side leads the line to neutral voltage on star side in figure (a) by 90° whereas in figure (b) it lags by 90°.

Figure (e) and (f) which are the negative-sequence voltage vector diagram of figures (a) and (b) respectively,

$$V_{A2} = -jV_{CB2} = -jV_{a2}$$

$$V_{A2} = jV_{CB2} = jV_{a2}$$



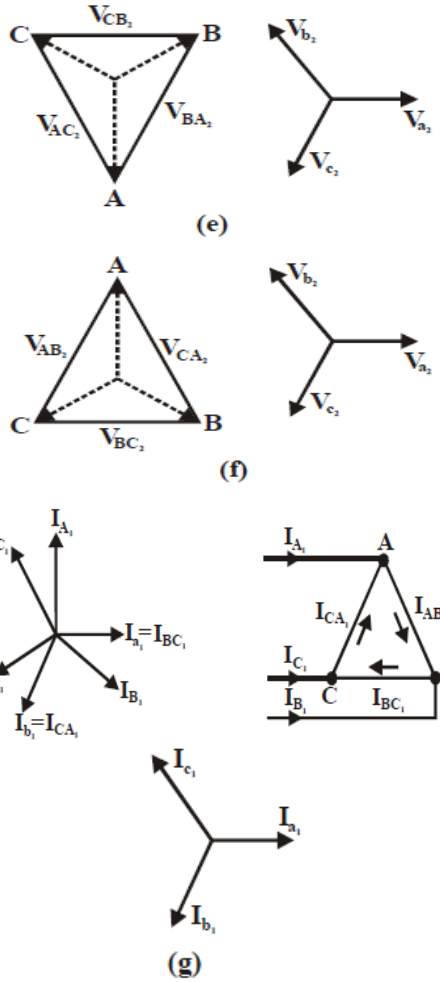


Fig. Phase shift in Δ-Y transformer.

The phase shift in the negative sequence voltages is in the direction opposite to the shift in phase of the positive sequence voltage for the same connection diagram.

The positive sequence line-to-neutral voltages and line currents are shifted 90° in phase in the same direction in passing through a Y-Δ or Δ-Y transformer whereas the corresponding negative sequence quantities are shifted 90° in the direction opposite to the positive sequence shift.

3.6.21 CALCULATION OF 3-PHASE SHORT-CIRCUIT CURRENTS

The impedance of the alternator grows from the instant of short circuit to the steady state condition. Which impedance should be considered for evaluating the short-circuit currents, depends upon

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whether subtrasient, transient or steady state short circuit current is required.

The p.u. impedance of equipment = $\frac{IZ}{V}$

Where Z is the impedance of the equipment in ohms and I and V are the rated current and voltage respectively.

Now

$I_{SC} = V / Z$

$I_{p.u.} = \frac{IZ}{V} = \frac{I}{I_{SC}} = \frac{IV}{I_{SC}V}$

If VI is the base or full load volt-amperes and VI_{sc} the short-circuit volt-amperes, then

$$Z_{p.u.} = \frac{\text{Base or full load volt} - \text{amperes}}{\text{Short} - \text{circuit volt} - \text{amperes}}$$

$$\text{S.C.MVA} = \frac{\text{Base or full load MVA}}{Z_{p.u.}}$$

3.6.22 SELECTION OF CIRCUIT BREAKERS

Two of the circuit breaker ratings which require the computation of SC current are: rated momentary current and rated symmetrical interrupting current. Symmetrical SC current is obtained by using subtransient reactances for synchronous machines. Momentary current (rms) is then calculated by multiplying the symmetrical momentary current by a factor of 1.6 to account for the presence of DC off-set current.

The current that a circuit breaker can interrupt is inversely proportional to the operating voltage over a certain range, i.e.,

Amperes at operating voltage = $\times \frac{\text{rated voltage}}{\text{operating voltage}}$

Rated interrupting MVA (three-phase) capacity

$= \sqrt{3} \,|\, V(\text{line}) \,|_{\text{rated}} \times |\, I(\text{line}) \,|_{\text{rated int errupting current}}$

V(line) is in kV and I(line) is in kA

Three-phase SC MVA to be interrupted, where

SC (MVA) (3-phase) = $\sqrt{3} \times$ prefault line voltage in kV $\times$ SC current in kA.

If voltage and current are in per unit values on a three-phase basis

$\text{SC MVA}(3-\text{phase}) = |\, V \,|_{\text{prefault}} \times |\, I \,|_{SC} \times (\text{MVA})_{\text{Base}}$

Rated MVA interrupting capacity of a circuit breaker is to be more than (or equal to) the SC MVA required to be interrupted.

A three-phase fault though rare is generally the one which gives the highest SC MVA and a circuit breaker must be capable of interrupting it.

3.6.23 SYMMETRICAL COMPONENTS

Typical relative frequencies of occurrence of different kinds of faults in a power system (in order of decreasing severity) are:

Three-phase (3L) faults5%

Double line-to-grounded (LLG) faults 10%

Double line (LL) faults 15%

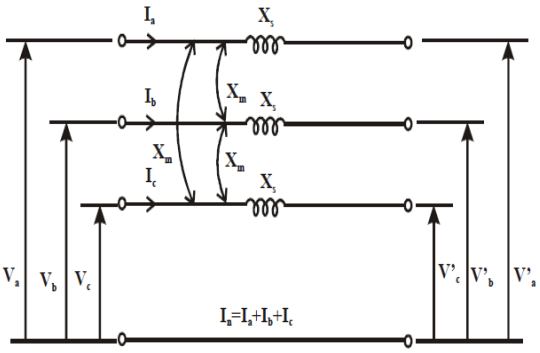
Single line-to-ground (LG) faults 70%

3.6.24 POWER INVARIANCE

The symmetrical component trans-formation is power invariant, which means that the sum of powers of the three symmetrical components equals the three-phase power.

A star/delta transformer is so labeled that the positive sequence quantities on the HV side lead their corresponding positive sequence quantities on the LV side by 30°. The reverse is the case for negative sequence quantities wherein HV quantities log the corresponding LV quantities by 30°

X_s = self reactance of each line



X_m = mutual reactance of any line pair.

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$Z_1 = j(X_s - X_m) = \text{positive sequence impedance}$

$Z_2 = j(X_s - X_m) = \text{negative sequence impedance}$

$Z_0 = j(X_s + 2X_m) = \text{zero sequence impedance}$

Fully transposed transmission has
i) Equal positive and negative sequence impedances
ii) Zero sequence impedance much larger than the positive (or negative) sequence impedance (it is approximately 2.5 times).

3.6.25 SEQUENCE IMPEDANCES AND SEQUENCE NETWORK OF POWER SYSTEM

Power system elements –transmission lines, transformers and synchronous machines –have a three-phase symmetry because of which when currents of a particular sequence are passed through these elements, voltage drops of the same sequence appear, i.e., the elements posses only self-impedance to sequences currents.

3.6.26 POSITIVE SEQUENCE IMPEDANCE AND NETWORK

Since a synchronous machine is designed with symmetrical windings, it induces emfs of positive sequence only, i.e. no negative or zero sequence voltages are induced in it.
$Z_1 = jX_d''$ (if 1 cycle transient is of interest)
$= jX_d'$ (if 3-4 cycle transient is of interest)
$= jX_d$ (if steady state value is of interest)
If the machine short circuit takes place from unloaded conditions, the terminal voltage constitutes the positive sequence voltage; on the other hand, if the short circuit occurs from loaded conditions, the voltage behind appropriate reactance (subtransient, transient or synchronous) constitutes the positive sequence voltage.

$$Z_2 = j\frac{X_q'' + X_d''}{2}; |Z_2| < |Z_1|$$

$$(Z_{0g} < Z_2 < Z_1)$$

3.6.27 ORDER OF VALUES OF SEQUENCE IMPEDANCE OF A SYNCHRONOUS GENERATOR

Z_1 = 12% (subtransient)
Z_1 = 20% (transient)
Z_1 = 110 (synchronous)
Z_2 = 12%
Z_0 = 5%

3.6.28 UNSYMMETRICAL FAULT ANALYSIS

A three-phase (3L) fault being the most severe must be used to calculate the rupturing capacity of circuit breakers, a low frequency of occurrence, situations when an LG can greater fault current than a three-phase fault (when the fault location is close to large generating units).
An important observation, when the generator neutral is solidly grounded, LG fault is more severe than a 3L fault.
For a fault on a line sufficiently away from generator, 3L fault will be more severe than an LG fault.

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4 POWER SYSTEM STABILITY

4.1 INTRODUCTION

A single-phase load red from a source

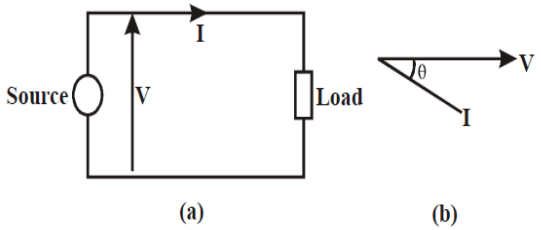

Fig. Complex power flow in a single-phase load

When θ is positive, the current lags behind voltage.

Complex power flow in the direction of current indicated is given by

$S = VI^*$

$= |V||I| \angle\theta$

$= |V||I|\cos\theta + j|V||I|\sin\theta = P + jQ$

$\text{or } |S| = (P^2 + Q^2)^{1/2}$

Here

S = complex power (VA, kVA, MVA)

|S| = apparent power (VA, kVA, MVA); it signifies rating of equipments (generators, transformers)

P=|V| |I | cos θ = real (active) power (watts, kW, MW)

Q = |V| |I| sin θ = reactive power

= voltamperes reactive (VAR)

= Kilovoltamperes reactive (kVAR)

= Megavoltamperes reactive (MVAR)

Q, the reactive power, is positive for lagging current (lagging power load) and negative for leading current (leading power factor loa.

$\theta = \tan^{-1}\dfrac{Q}{P} = \text{positive for lagging current}$

=negative for leading current

In a series RL load

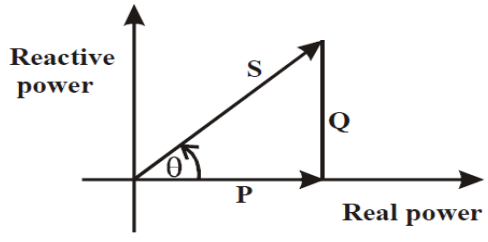

Fig. Phasor representation of complex power

$V = I(R + jX_L)$

$S = VI^* = I^2R + jI^2X_L$

$P = I^2R = \text{active power absorbed by load}$

$Q = I^2X_L = \text{reactive power absorbed by load}$

In case of a series RC load

$P = I^2R$

$Q = -I^2X_C = (\text{reactive power absorbed is negative})$

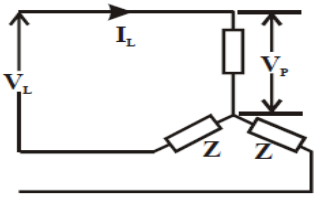

Fig. Complex power fed to three-phase load

The three-phase complex power fed into load is given by

$S = 3V_PI_L^* = 3|V_P| \angle\delta_P I_L^* = \sqrt{3}|V_L| \angle\delta_P I_L^*$

If

$I_L = |I_L| \angle(\delta_p - \theta)$

Then

$S = \sqrt{3}|V_L||I_L| \angle\theta$

$= \sqrt{3}|V_L|||I_L|\cos\theta + j\sqrt{3}|V_L||I_L|\sin\theta = P + jQ$

Here

$|S| = \sqrt{3}|V_L||I_L|$

$P = \sqrt{3}|V_L||I_L|\cos\theta$

$Q = \sqrt{3}|V_L||I_L|\sin\theta$

Where

$\theta = \text{power factor angle}$

$S = \dfrac{|V_L|^2}{Z^*}$

4.2 SYNCHRONOUS MACHINE

The synchronous machine is the most important element of a power system. It converts mechanical power into electrical form and feeds it into the power network or, in the case of a motor, it draws electrical power from the network and converts it into the mechanical form. The machine

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excitation which is controllable determines the flow of VARs into or out of the machine.
The rotor winding is so arranged on rotor periphery that field excitation produces nearly sinusoidally distributed flux/pole (ϕ_f) in the air gap. As the rotor rotates, three-phase emfs are produced in stator winding. Since the machine is a balanced one and balanced loading will be considered, it can be modeled on per phase basis for the reference phase a.
The frequency of induced emf is given by

$$f = \frac{NP}{120} Hz$$

N=rotor speed (synchronous speed) in rpm
P = Number of poles
On no load As balanced steady load, φ_a armature reaction flux, is therefore stationary with respect to field flux φ_f. φ_a is in phase with phase a current I_a which causes it.
The superposition principle is applicable so that the resultant air gap flux is given by the phasor sum

$$\varphi_r = \varphi_f + \varphi_a$$

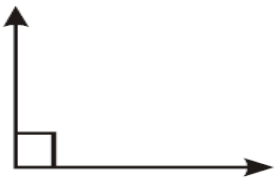

Fig. Phasor relationship between ϕt and E_t

ϕ_r induces the armature emf which equals the terminal voltage V_t.

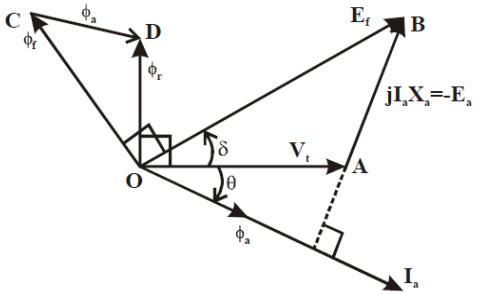

Fig. Phasor diagram of synchronous generator

δ = angle by which E_f leads V_t called load angle or turque angle , δ mainly determines the power delivered by the generator and the magnitude of E_f (i.e. excitation) determines the VARs delivered by it.
$AB = jI_aX_a$
X_a is the constant of proportionality
$V_t = E_f - jI_aX_a$

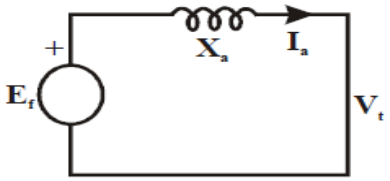

Fig. Circuit model of round rotor synchronous generator (resistance and leakage reactance neglected)

E_f = voltage induced by field flux ϕ_f alone
= no load emf
X_a inductive reactance which accounts for the effect of armature reaction
The effect of armature leakage reactance and resistance
$(X_a + X_1) = X_s$ is called the synchronous reactance of the machine.

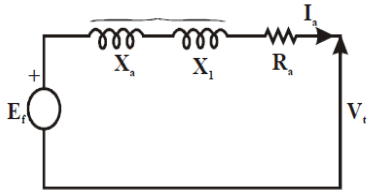

Fig. Circuit model of round rotor synchronous generator

Armature resistance R_a is invariably neglected in power system studies. The field induced emf E_f leads the terminal voltage by the torque (load) angle δ. This, in fact, is the condition for active power to flow out of the generator. The magnitude of power delivered depends upon sin δ.

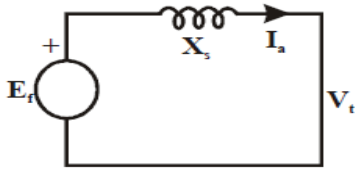

Fig. Simplified circuit model of round rotor synchronous generator

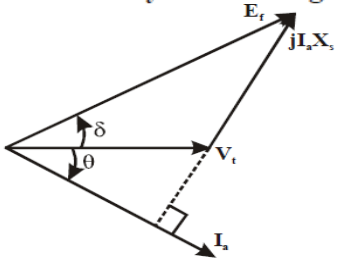

Fig. Phasor diagram of synchronous generator

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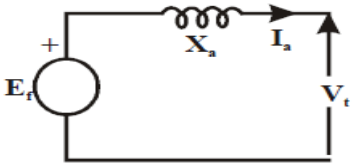

Fig. Motoring operation of synchronous machine

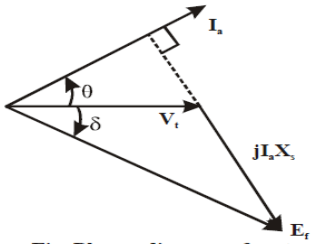

Fig. Phasor diagram of motoring operation

$$E_f = V_t - jI_aX_s$$

V_t now leads E_f by δ. This in fact is the condition for power to flow into motor terminals.

The flow of reactive power and terminal voltage of a synchronous machine is mainly controlled by means of its excitation.

As infinite bus means a large system whose voltage and frequency remain constant independent of the power exchange between the synchronous machine and the bus, and independent of the excitation of the synchronous machine.

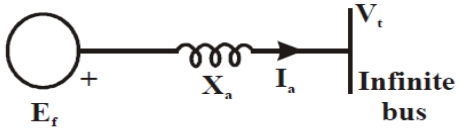

Fig. Synchronous machine connected to infinite bus

As the machine excitation is varied, armature current I_a and its angle θ, i.e. power factor, change in such a manner as to keep

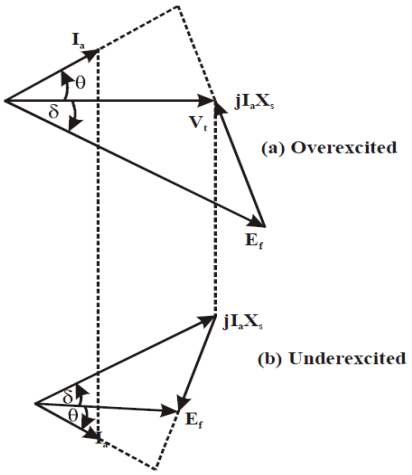

Fig. Phasor diagrams of synchronous motor drawing constant power as excitation is varied

$$|V_t||I_a|\cos\theta = \text{cons tan t} = \text{active power output}$$

Since $|V_t|$ is fixed, the projection $|I_a|\cos\theta$ of the phasor I_a on V_t remains constant, while the excitation is varied. Unity power factor case.

$$|E_f|\cos\delta = |V_t|$$

Normal excitation overexcited, $|E_f|\cos\delta > |V_t|$, I_a lags behind V_t, the generator feeds positive reactive power into the bus, underexcited case $|E_{fc}|\cos\delta\ |V_t|$, I_a leads V_t so that the generator feeds negative reactive power into the bus.

In overexcited case, I_a leads V_t , i.e. the motor draws negative reactive power (or supplies positive reactive power); while in the underexcited case I_a lags V_t, i.e. the motor draws positive reactive power (or supplies negative reactive power).

The general conclusion that a synchronous machine (generating or motoring), supplies positive reactive power, overexcited, underexcited machine, feeds negative reactive.

The power delivered by a synchronous generator to an infinite bus.

$$P = \frac{|E_f||V_t|}{X_a}\sin\delta$$

4.2.1 POWER ANGLE CURVE

The maximum power that can be delivered occurs at δ =90°

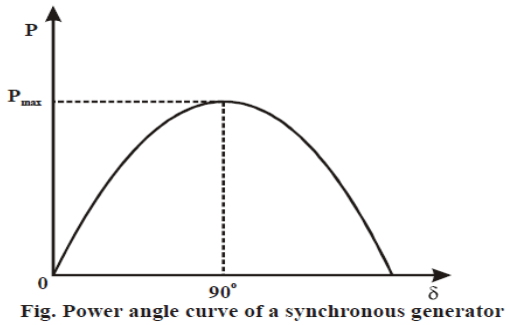

Fig. Power angle curve of a synchronous generator

For P > P_{max} or for δ >90° the generator falls out of step

Power factor and Power control

$$|E_f|\sin\delta = |I_a|X_s\cos\theta$$

$$= \frac{PX_s}{|V_t|} = \text{cons tan t}$$

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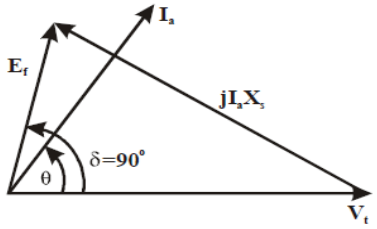

Fig. Case of limiting excitation of generator delivering constant power to infinite bus bar

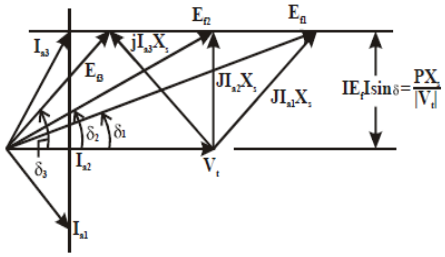

Fig. Effect of varying excitation of generator delivering constant Power to infinite bus bar

The direction of phasor I_a is always 90° lagging jI_nX_a limiting excitation with δ -90°. For excitation lower than this value the generator becomes unstable.

Representation of Loads

An industrial load consists mainly of large three phase induction motors with sufficient load constancy.

It is essential to know the variation of real and reactive power with variation of voltage.

Induction motors 55-75%

4.3 POWER SYSTEM SYNCHRONOUS STABILITY

4.3.1 INTRODUCTION

Normally, a transmission loss of about 15% is permissible. Synchronous machines, If attempts are made to transfer power more than certain value known as steady state stability limit, the machines may gall out of step and supply to customers may be affected.

The magnitude of power that can be transmitted from a source to asynchronous loads such as heaters, lamps and induction motors depends upon the range of voltage that is available from the source which may be tolerated by the load and the current carrying ability of the various components of the network.

If a synchronous motor is connected to a synchronous generator, loss of synchronism results in stalling of synchronous motor and if two generators are connected, loss of synchronism will result in wild fluctuation of current and voltage within the transmission network.

Two forms of instability in power systems, the stalling of asynchronous loads (voltage stability or load stability), loss of synchronism between synchronous machines, synchronous stability in two regimes

i) Steady state stability

ii) Transient state stability

The steady state stability is the stability of the system under conditions of gradual or relatively slow change in load.

The transient state stability refers to the maximum flow of power possible through a point without losing the stability with sudden and large changes in the network conditions such as brought about by faults, by sudden large increment of loads.

iii) Dynamic stability, when synchronous machines are operated alongwith fast acting voltage regulator, the stability limits of the system are higher than when rather slow acting regulators are used. Dynamic stability also corresponds to slow changes in load as in the case of steady state stability but the main difference between the two is that dynamic stability is made possible by the action of fast acting voltage regulators which are capable of changing the flux at a faster rate than that caused by the system in falling out of step whereas in steady state stability.

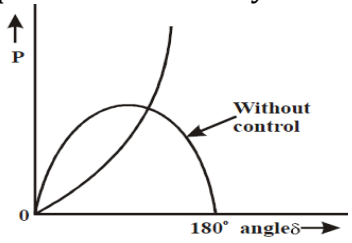

Fig. Power angle curves with and without excitation control

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Regular acts slowly, However, during disturbance and under emergency conditions, the power system can be operated for realizing additional transfer of power by operating it in the dynamic stability zone.

4.3.2 POWER RECEIVED

$V_1 = V_2,$

For P_{2max} to be maximum

$$\frac{dP_{2max}}{dx} = 0$$

$$x = \sqrt{3}r$$

The maximum power can be transferred from end 1 to end 2 when the reactance of the line is $\sqrt{3}$ times it resistance.

The power can be transferred only if reactance in present. In case reactance is zero power cannot be transmitted.

For a lossless line r = 0 and the transmitted power

$$P_m = \frac{V_1 V_2}{x}$$

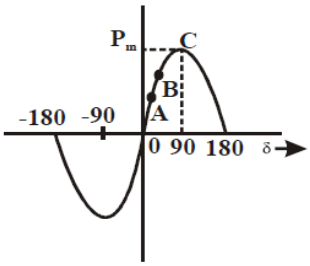

Fig. Power angle curve

The torque angle δ is positive for generator action and negative for motor action. In case of generator action and negative for motor action. In case of generator action the rotor advances in the direction of rotation whereas for motor action, the rotor retards or falls back opposite to the direction of rotation. The maximum value of power transmitted can be varied by varying V_1, V_2 and x the circuit reactance. The system is stable if and only if for an increase in rotor angle δ the transmitted power also increases, i.e., the $dP/d\delta$ should be positive. It can be seen from that the range where $dP/d\delta$ is positive lies between 90 and -90°. When the tie-line impedance is purely capacitive (negative reactance) the range of angle for delivering power to the system is from 180° to 270° instead of from 0 to 90°.

The gradual addition of load on the motor shaft is possible till the point C is reached on the power angle curve where $P = P_{max}$ and any further addition of load will result in increase in angle δ but reduction in input power to the motor and, therefore, the motor will decelerate further and it will pull out of step and will probably stall unless it has damper winding which may keep it running as an induction motor. P_m is known as the steady state stability limit of the system which means that it is the maximum power that can be transmitted and synchronism will be lost if an attempt is made to transmit power more than this limit.

The steady state stability limit can be increased by (i) increasing the excitation of the motor or generator or both so that the internal e.m.fs. are increased, and (ii) reducing the reactance. This is done by either running parallel lines or by using the series capacitors.

4.3.3 THE SWING EQUATION

Under normal operations, the relative position of the rotor axis and the stator magnetic field axis is fixed. The angle between the two is known as the load angle or torque angle denoted by δ and depends upon the loading of the machine. Larger the loading, larger is the value of the torque angle δ. If some load is added or removed from the shaft of the synchronous machine, the rotor will decelerate or accelerate respectively with respect to the synchronously rotating stator field and a relative motion begins. It is said that the rotor is swinging with respect to the stator field.

Swing equation. T_s shaft torque and T_e the electromagnetic torque and if these are assumed positive for a generator, the net torque causing acceleration is

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$T_a = T_s - T_e$

Terms of Power

$P_a = P_s - P_e$

P_a is accelerating power

$P_a = T_a\omega$

$P_a = T_a\omega = I\alpha\omega = M\alpha$

$\omega = \frac{2\pi n_s}{60}$

n_s is the synchronous speed of the machine in r.p.m. and α is the acceleration radians/sec^2.

I is the moment of inertia in kg-m^2.

$M = I\omega$

M is in joule-sec/mechanical radian

M is angular momentum

$M\frac{d^2\delta}{dt^2} = P_a = P_s - P_e$

The swing equation, The angle δ is the difference between the internal angle of the machine and the angle of the synchronously rotating reference axis. If it is a two machine system two swing equations are required, one for each machine.

M is the inertia constant of the machine. The inertia constant is truly constant because it is the angular momentum at synchronous speed.

$H = \frac{\text{stored energy in megajoules}}{\text{rotating in MVA}}$

H is also sometimes called as inertia constant. Let G be the rating of the machine in MVA and *f* the frequency of the system.

$G \times H$ = Stored energy in megajoules

$= \frac{1}{2}M\omega = \frac{1}{2}M.2\pi f$

$M = \frac{GH}{\pi f}$ Megajoule $-$ sec ond / radian

$= \frac{GH}{180f}$ Megajoule-second/elect. Degree

M depends upon the size of the machine as well as on its type whereas H does not vary widely with size and has a characteristic value or set of values for each class of machines.

$M\frac{d^2\delta}{dt^2} = P_s - \frac{V_1V_2}{x}\sin\delta$

$= P_s - P_m \sin\delta$

For a multi-machine system solution of several swing equations is required. Normally the point by point method is used for the solution.

The solution of swing equation gives the relation between rotor angle as a function of time and this relation is plotted in terms of curves. If the curves show that the angle between two machine rotors increases without limit, the system is unstable. If the angles initially increase and then start reducing stable.

For a two machine system under the assumption of constant input, no damping and constant voltage behind transient reactance, the machines either fall out of step in the first swing or never. Under this condition the two machines are said to be running at standstill with respect to each other. There is a graphical method of determining whether the two machines are running at standstill with respect to each other or not. This method is known as Equal Area Criterion for stability. The use of this method eliminates partially or wholly the calculation of swing curves which thus saves a considerable amount of work. The method is not applicable to a multi-machine system directly.

4.3.4 STEADY STATE STABILITY

The study of steady state stability of power system involves the study of dynamics of the system when the rate of application of load is quite slow as compared with the natural frequency of oscillation of the system.

Initial operating point on the power angle curve as (P_0, δ_0).

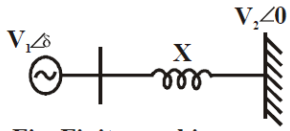

Fig. Finite machine connected to an infinite bus

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The load is changed (increased) by ΔP, as a result of which the load angle changes by $\Delta\delta$ and the swing equation.

$$M\frac{d^2\Delta\delta}{dt^2} = P_i - P_e$$

$$= P_i - (P_0 + \Delta P) = -\Delta P$$

$$= -\left(\frac{\partial P}{\partial \delta}\right)\Big|_{\delta 0} .\Delta\delta$$

$$\frac{d}{dt} = p,$$

$$Mp^2\Delta\delta + \frac{\partial P}{\partial\delta}\Big|_{\delta_0} \Delta\delta = 0$$

$$\left(Mp^2 + \frac{\partial P}{\partial\delta}\Big|_{\delta_0}\right)\Delta\delta = 0$$

The two roots

$$p = \pm\left(\frac{(-\partial P/\partial\delta)\delta_0}{M}\right)^{\frac{1}{2}}$$

When $\frac{\partial P}{\partial\delta}$ is positive $\delta < \frac{\pi}{2}$, the two roots are pure imaginary and conjugate, the rotor motion is oscillatory and undamped around δ_0, when $\frac{\partial P}{\partial\delta}$ is negative $(\delta > 90^o)$, both the roots are real, one positive and the other negative respectively and hence the system is unstable. When $\frac{\partial P}{\partial\delta}$ =0, $\delta = 90^o$ the system is critically stable. The frequency of oscillation of the system is given by the roots of the characteristic equation.

The steady state stability of the system when system series resistance and shunt capacitance are included.

$$M\frac{d^2\delta}{dt^2} = P_a = P_s - P_e$$

$$\frac{d\delta}{dt}\sqrt{\frac{2}{M}\int_{\delta_o}^{\delta}(P_s - P_e)d\delta + c}$$

δ_o is the initial torque angle before any disturbance occurs and at this time dδ /dt=0. The angle δ will stop changing and the machine will again be operating at synchronous speed after a disturbance when dδ /dt=0

$$\int_{\delta_0}^{\delta}(P_s - P_e)d\delta = 0 = \int_{\delta_0}^{\delta} P_a d\delta$$

This means that the area under the curve P_a should be zero which is possible only when P_a is both accelerating and decelerating powers, i.e., for a part of the graph $P_s > P_e$ and for the other $P_e > P_s$. For a generator action $P_s > P_e$ for positive area A_1 and $P_e > P_s$ for negative area A_2 for stable operation. Hence the name equal area criterion. The area A_1 represents the kinetic energy stored by the rotor during acceleration and the area A_2 represents the kinetic energy given up by the rotor to the system and when it is all given up, the machine has returned to its original speed.

The operation of a synchronous motor using equal area criterion when when sudden increase in mechanical load on that motor occurs.

$$f_n = \left\{\left(\frac{\partial P_e}{\partial\delta}\right)\delta_o / M\right\}^{\frac{1}{2}}$$

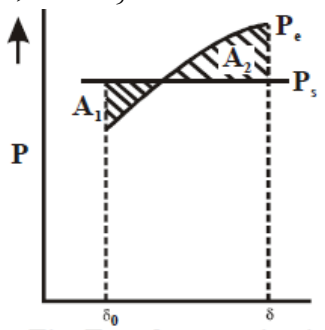

Fig. Equal area criterion

To the change in torque-angle whenever a disturbance occurs

1. There is no change in torque angle when the speed of the rotor is the synchronous speed.
2. The angle increases in case of a motor if $P_s > P_e$ i.e., the mechanical output is more than the electrical input and the speed goes down.
3. Motor is δ_0, mechanical output P_0.

The speed is minimum at b. When the speed equals the synchronous speed beyond point b, say at point c, the rotor angle stops increasing.

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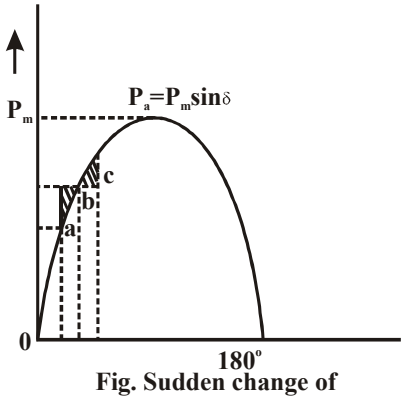

Fig. Sudden change of load-euqal areacriterion

The point b where this time the speed is maximum and is more than the synchronous speed.

The machine will settle at b after the oscillations are damped out.

$\omega = \omega_n$

Find out the maximum value of the P_s such that the system is critically stable i.e., any attempt to increase P_s beyond this value the system becomes unstable.

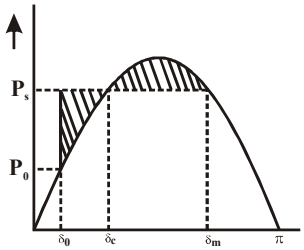

Fig. Equal area criterion

$\delta_m = (\pi - \delta_c)$

δ_c is known as critical torque angle

4.3.5 TWO FINITE MACHINES

A system having two machines can be replaced by an equivalent system having one machine connected to an infinite bus.

Let δ_1, M_1, P_{a1}

One machine and δ_1, M_1, P_{a1} , other machine.

$$\frac{d^2\delta_1}{dt^2} = \frac{P_{a1}}{M_1} = \frac{P_{s1} - P_{e1}}{M_1}$$

$$\frac{d^2\delta_2}{dt^2} = \frac{P_{a2}}{M_2} = \frac{P_{s2} - P_{e2}}{M_2}$$

$\delta = \delta_1 - \delta_2$

$$\frac{d^2\delta}{dt^2} = \frac{d^2\delta_1}{dt^2} - \frac{d^2\delta_2}{dt^2}$$

$$\frac{d^2\delta}{dt^2} = \frac{P_{s1} - P_{e1}}{M_1} - \frac{P_{s2} - P_{e2}}{M_2}$$

Multiplying both the sides by $\frac{M_1M_2}{M_1 + M_2}$

$$\frac{M_1M_2}{M_1 + M_2}\frac{d^2\delta}{dt^2} = \frac{M_1M_2}{M_1 + M_2}\left[\frac{P_{s1} - P_{e1}}{M_1} - \frac{P_{s2} - P_{e2}}{M_2}\right]$$

$$= \frac{1}{M_1 + M_2}[(M_2P_{s1} - M_1P_{s2}) - (M_2P_{e1} - M_1P_{e2})]$$

$$= \frac{M_2P_{s1} - M_1P_{s2}}{M_1 + M_2} - \frac{M_2P_{e1} - M_1P_{e2}}{M_1 + M_2}$$

$$\text{as } M\frac{d^2\delta}{dt^2} = P_s - P_e$$

$$M = \frac{M_1M_2}{M_1 + M_2}$$

$$P_s = \frac{M_2P_{s1} - M_1P_{s2}}{M_1 + M_2}$$

$$P_e = \frac{M_2P_{e1} - M_1P_{e2}}{M_1 + M_2}$$

The inertia constant of the equivalent machine is a function of the inertia constant of the two actual machines and the law of combination is the equivalent machine is smaller

Noted that law of combination of inertia constants swing together is different from not swing together

$$M_1\frac{d^2\delta}{dt^2} = P_{a1}$$

$$M_2\frac{d^2\delta}{dt^2} = P_{a2}$$

$$(M_1 + M_2)\frac{d^2\delta}{dt^2} = P_{a1} + P_{a2} = P_a$$

$$M = (M_1 + M_2)$$

Higher moment of inertia method of improving the transient stability is uneconomical and is normally not used. The methods normally used.

(i) Higher system voltage

(ii) Use of parallel lines to reduce the series reactance

(iii) Use of high speed circuit breakers and auto-reclosing breakers.

An increase in system voltage results in higher value of power P_m that can be

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transferred between nodes. Since shaft power $P_s = P_m \sin\delta_0$ with higher value of P_m, δ_0 *is reduced*, the difference between the critical clearing angle and the initial angle δ_0 is increased. Increasing P_m allows the machine to rotate through large angle before it reaches the critical clearing angle which results in greater critical clearing time and the probability of maintaining stability.

Reducing the series reactance by using series capacitor is normally economical for lines of length more than 320 kms. For lines of length less than 320 kms, the objective is achieved by running parallel lines.

The effect of reducing the series reactance is to increase P_m which, therefore, increases the transient stability limit of a system.

The faster the fault is removed from the system and the better is the tendency of the system to restore to normal operating conditions.

4.4 POWER SYSTEM STABILITY

4.4.1 INTRODUCTION

The stability of an interconnected power system is its ability to return to normal or stable operation after having been subjected to some form of disturbance. Conversely, instability means a condition denoting loss of synchronism or falling out of step.

Accordingly power system stability problems are classified into three basic types*-steady state, dynamic and transient.

Steady state stability is basically concerned with the determination of the upper limit of machine loadings before losing synchronism, provided the loading is increased gradually.

The system is said to be dynamically stable if the oscillations do not acquire more than certain amplitude and die out quickly (i.e. , the system is well-damped). In a dynamically die out quickly (i.e., the system is well-damped). In a dynamically unstable system, the oscillation amplitude is large and these persist for a lont time (i.e., the system is underdamped). 5-10 s upto 30 s.

For a large disturbances, changes in angular differences may be so large as to cause the machines to fall out of step. Transient instability 1s

The transient stability limit is almost always lower than the steady state limit, Thus a multimachine system can often be to an equivalent few machine system. If synchronism is lost, the machines of each group stay together although they go out of step with other groups.

4.4.2 DYNAMICS OF A SYNCHRONOUS MACHINE

$$\omega_s = \left(\frac{P}{2}\right)\omega_{sm} = \text{rotor speed in rad (elect) / s}$$

Moment of inertia in MJ-s/elec rad

$$GH = \text{K.E.} = \frac{1}{2}M\omega_s \ \text{MJ}$$

H = Inertia constant in MJ/MVA or MW-s/MVA

$$\frac{GH}{\pi f}\ \text{MJ} - \text{s / elect rad}$$

$$\frac{GH}{180f}\ \text{MJ} - \text{s / elect degree}$$

M is also called the inertia constant.

$$M(\text{pu}) = \frac{H}{\pi f}\ \text{s}^2 / \text{elect rad}$$

$$= \frac{H}{180f}\ \text{s}^2 / \text{elect degree}$$

4.4.3 THE SWING EQUATION

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e \ \text{Nm}$$

$\theta_m = \text{angle in rad (mech)}$

T_m = turbine torque in Nm

$\delta = \theta_e - \omega_s t$; rotor angular displacement from synchronously rotating reference frame (called torque angle / power angle)

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \ \text{MW}$$

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$$\frac{GH}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \text{ MW}$$

$$M(pu)\frac{d^2\delta}{dt^2} = P_m - P_e \text{ in pu of machine rating as base}$$

$$M(pu) = \frac{H}{\pi f}$$

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \text{ pu}$$

Swing equation and it describes the rotor dynamics for a synchronous machine (generating/motoring).

4.4.4 MULTIMACHINE SYSTEM

$$H_{system} = H_{mach}\left(\frac{G_{mach}}{G_{system}}\right)$$

4.4.5 MACHINES SWINGING COHERENTLY

The machine rotors swing together

$$\delta_1 = \delta_2 = \delta$$

$$H_{eq} = H_1 + H_2$$

$$H_{eq} = H_{1mach}\, G_{1mach} / G_{system} + H_{2mach} G_{2mach} / G_{system}$$

$$P_e = P_{max} \sin\delta$$

$$P_{max} = \frac{|E_1'||E_2'|}{X}$$

X = transfer reactance between nodes (i.e., between E_1' and E_2')

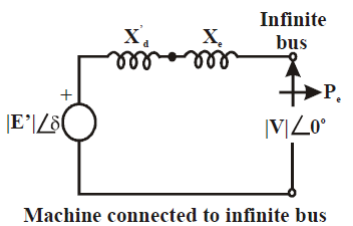
4.5 SIMPLE SYSTEMS

4.5.1 MACHINE CONNECTED TO INFINITE BUS

$$X_{transfer} = X_d' + X_e$$

$$P_e = \frac{|E'||V|}{X_{transfer}}\sin\delta = P_{max}\sin\delta$$

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m - P_e \text{ pu}$$



Machine connected to infinite bus

4.5.2 TWO MACHINE SYSTEM

$$H_{eq} = \frac{H_1 H_2}{H_1 + H_2}$$

$$P_e = \frac{|E_1'||E_2'|}{X_{d1}' + X_e + X_{d2}'}\sin\delta$$

4.5.3 TRANSIENT STABILITY

No generalized criteria are available* for determining system stability with large disturbances (called transient stability). Numerical solution of the swing equation of such disturbances giving a plot of δ v. t called the swing curve. If δ starts to decrease after reaching a maximum value, it is normally assumed that the system is stable and the oscillation of δ around the equilibrium point will decay and finally die out.

4.5.4 EQUAL AREA CRITERION

In a system where one machine is swinging with respect to an infinite bus, it is possible to study transient stability by means of a simple criterion.

If the system is unstable δ continues to increase indefinitely with time and the machine loses synchronism. On the other hand, if the system is stable, δ (t) performs oscillations (nonsinusoidal) whose amplitude decreases in actual practice because of damping terms.

A stability the system is stable if at some time $c\frac{d\delta}{dt} = 0$

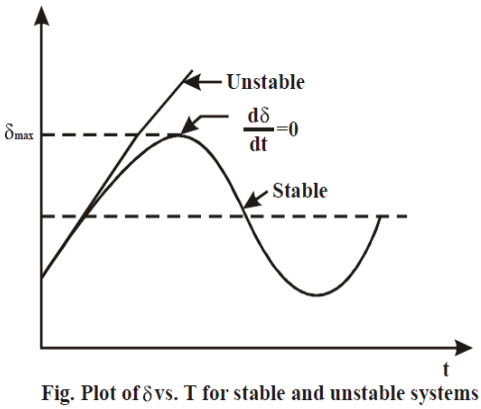


Fig. Plot of δ vs. T for stable and unstable systems

Is unstable, if

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$$\frac{d\delta}{dt} > 0$$

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

$$\left(\frac{d\delta}{dt}\right)^2 = \frac{2}{M}\int_{\delta_0}^{\delta} P_a\, d\delta$$

$$\frac{d\delta}{dt} = \left(\frac{2}{M}\int_{\delta_0}^{\delta} P_a d\delta\right)^{1/2}$$

where δ_0 is the initial rotor angle before if begins to swing due to disturbance. the condition for stability

$$\left(\frac{2}{M}\int_{\delta_0}^{\delta} P_a\, d\delta\right)^{1/2} = 0$$

$$\int_{\delta_0}^{\delta} P_a\, d\delta = 0$$

The system is stable if the area under P_a (accelerating power) – δ curve reduces to zero at some value of δ. In other words, the positive (accelerating) area under P_a –δ curve must equal the negative (decelerating) area and hence the name 'equal area' criterion of stability.

Several types of disturbances that may occur in a single machine infinite bus bar system.

4.5.5 SUDDEN CHANGE IN MECHANICAL

The electrical power transmitted

$$P_e = \frac{|E'||V|}{X'_d + X_e}\sin\delta = P_{max}\sin\delta$$

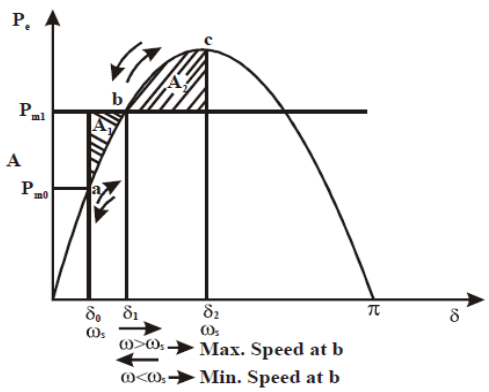

Fig. Pe=δdiagram for sudden increase in mechanical input to generator of above fig.

Let the mechanical input to the rotor be suddenly increased to P_{m1}(by opening the steam valve). The accelerating power $P_a = P_{m1} - P_e$ causes the rotor speed to increase ($\omega > \omega_s$) and so does the rotor angle. At angle δ_1, $P_a = P_{m1} - P_a(= P_{max}\ \text{Sin}\ \delta_1) = 0$ (state point at b) but the rotor angle continues to increase as $\omega > \omega_s$. P_a now becomes negative (decelerating), the rotor speed begins to reduce but the angle continues to increase till at angle δ_2, $\omega = \omega_s$ once again (state point at c). At c, the decelerating area A_2 equals the accelerating area A_1 (areas are shaded), i.e., $\int_{\delta_0}^{\delta_2} P_a\, d\delta = 0$.

Since the rotor is decelerating, the speed reduces below ω_s and the rotor angle begins to reduce. The state point now traverses the P_e-δ curve in the opposite direction as indicated by arrows in Fig, It is easily seen that the system oscillates about the new steady state point b ($\delta = \delta_1$) with angle excursion upto δ_0 and δ_2 on the two sides. These oscillations are similar to the simple harmonic motion of an inertia-spring system except that these are not sinusoidal.

The system settles to the new steady state where.

$P_{m1} = P_e = P_{max}\sin\delta_1$

areas A_1 and A_2 are given by

$$A_1 = \int_{\delta_0}^{\delta_1}(P_{m1} - P_e)\, d\delta$$

$$A_2 = \int_{\delta_1}^{\delta_2}(P_e - P_{m1})\, d\delta$$

For the system to be stable, it should be possible to find angle δ_2 such that $A_1 = A_2$. As P_{m1} is increased, a limiting condition is finally reached when A_1 equals the area above the P_{m1} line as shown in fig. Under this condition, δ_2 acquires the maximum value such that

$$\delta_2 = \delta_{max} = \pi - \sin^{-1}\frac{P_{m1}}{P_{max}}$$

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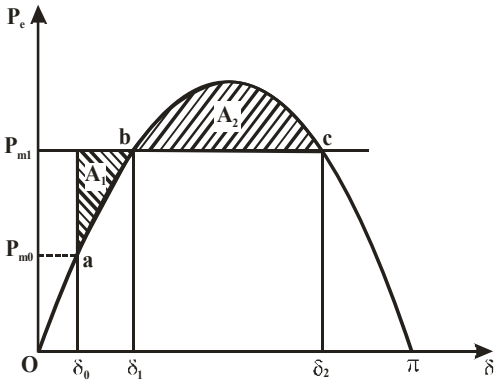


Fig. Limiting case of transient stability with mechanical input suddenly increased

Any further increase in P_{m1} means that the area available for A_2 is less than A_1, so that the excess kinetic energy causes δ to increase beyond point c and the decelerating power changes over to accelerating power, with the system consequently becoming unstable. It has thus been shown by use of the equal area criterion that there is an upper limit to sudden increase in mechanical input ($P_{m1} - P_{m0}$), for the system in question to remain stable.

The system will remain stable even though the rotor may oscillate beyond $\delta = 90^0$, so long as the equal area criterion is met. The condition of $\delta = 90^0$ is meant for use in steady state stability only and does not apply to the transient stability case.

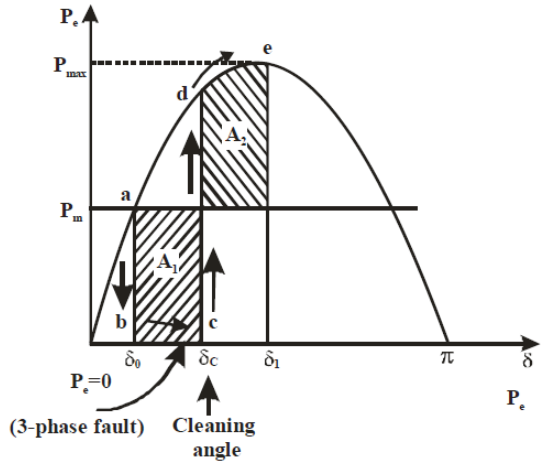
4.5.6 EFFECT OF CLEARING TIME ON STABILITY

Operating with mechanical input P_m at a steady angle of δ_0 ($P_m = P_a$) as shown by the point α on the $P_e - \delta$ diagram of fig.

If a 3-phase fault occurs at the point P of the outgoing radial line, the electrical output of the generator instantly reduces to zero, i.e., $P_e = 0$ and the state point drops to b. The acceleration area A_1 begins to increase and so does the rotor angle while the state point moves along bc. At time t_c corresponding to angle δ_c the faulted line is cleared by the opening of the line circuit breaker.

The values of t_c and δ_c are respectively known as clearing time and clearing angle.

The system once again becomes healthy and transmits $P_e = P_{max} \sin \delta$, i.e., the state point shifts to d on the original $P_e - \delta$ curve. The rotor now decelerates and the decelerating area A_2 begins while the state point moves along de.



If an angle δ_1 can be found such that $A_2 = A_1$, the system is found to be stable. The system finally settles down to the steady operating point a in an oscillatory manner because of inherent damping.

The value of clearing time corresponding to a clearing angle can be established only by numerical integration except in this simple case. The equal area criterion therefore gives only qualitative answer to system stability as the time when the breaker should be opened is hard to establish.

As the clearing of the faulty line is delayed, A_1 increases and so does δ_1 to find $A_2 = A_1$ till $\delta_1 = \delta_{max}$ as shown in fig. For a clearing time (or angle) larger than this value, the system would be unstable as $A_2 < A_1$. The maximum allowable value of the clearing time and angle for the system to remain stable are known respectively as critical clearing time and angle.

Simple case ($P_e = 0$ during fault)

$\delta_{max} = \pi - \delta_0$

$P_m = P_{max} \sin \delta_0$

$$A_1 = \int_{\delta_0}^{\delta_{cr}} (P_m - 0)\, d\delta = P_m(\delta_{cr} - \delta_0)$$

$$A_2 = \int_{\delta_{cr}}^{\delta_{max}} (P_{max} \sin\delta - P_m)\, d\delta$$

$= P_{max} (\cos \delta_{cr} - \cos \delta_{max}) - P_m (\delta_{max} - \delta_{cr})$

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For the system to be stable, $A_2 = A_1$,

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

δ_{cr} = critical clearing angle.

Substituting Eqs.

$\delta_{cr} = \cos^{-1}[(\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0]$

During the period the fault is persisting, the swing

equation is

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H}P_m; \quad P_e = 0$$

Integrating twice,

$$\delta = \frac{\pi f}{2H}P_m t^2 + \delta_0$$

$$\delta_{cr} = \frac{\pi f}{2H}P_m t_{cr}^2 + \delta_0$$

t_{cr} = critical clearing time

δ_{cr} = critical clearing angle

$$t_{cr} = \left(\frac{2H(\delta_{cr} - \delta_0)}{\pi f P_m}\right)^{1/2}$$

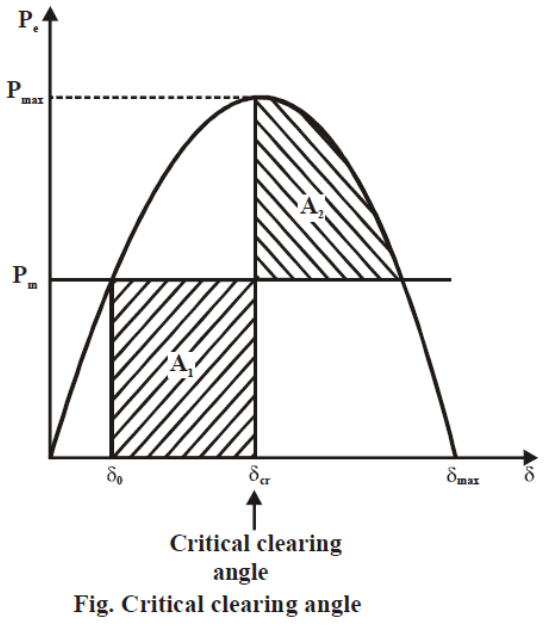

Fig. Critical clearing angle

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5 LOAD FLOWS / ECONOMIC LOAD DISPATCH / LOAD FREQUENCY CONTROL

5.1 INTRODUCTION

For a system n buses and bus 1 designated as slack bus, For an n bus system having 1 slack bus and g voltage controlled (PV) bus, the total number of equations is (2n – 2 – g).

Let y_{ik} (i = k) be the total admittance connected between the ith and kth buses and y_{i0} be the admittance between ith bus and the ground.

$$Y_{ii} = \frac{I_i}{V_i}(\text{all } V = 0 \text{ except } V_i)$$

$$= \text{Short circuit driving point admittance or self} - \text{admittance at the ith bus}$$

$$Y_{ik}(i \neq k) = -y_{ik} = \text{Negative of the total admittance connected between ith and kth bus.}$$

$(Y_{ik}(i \neq k) = 0$ if there is no transmission line between ith and kth bus)

$$Y_{ii} = y_{i0} + y_{il} + y_{i2} + \ldots\ldots\ldots$$

$$+ y_{i,i-1} + y_{i,i+1} + \ldots\ldots\ldots + y_{in}$$

$$= \text{Sum of the admittances directly connected to ith bus}$$

$I_{BUS} = Y_{BUS} V_{BUS}$

$$Y_{BUS} = \begin{bmatrix} Y_{11} & Y_{12} & . & . & . & Y_{1n} \\ Y_{21} & Y_{22} & . & . & . & Y_{2n} \\ . & . & & . & & . \\ . & . & & . & & . \\ . & . & & . & & . \\ Y_{n1} & Y_{n2} & . & . & . & Y_{nn} \end{bmatrix}_{n \times n}$$

It follows that,

1) The diagonal element of Y_{BUS} is given by Eq. and is the self-admittance. The off-diagonal element of Y_{BUS} transfer admittance.
2) Y_{BUS} is n × n matrix where n is the number of buses.
3) Y_{BUS} is a symmetric matrix ($Y_{ik} = Y_{ki}$ (k ≠ i))

The Y_{BUS} of a large network is very sparse, i.e. it has a large number of zero elements.

$V_{BUS} = Z_{BUS} I_{BUS}$

Z_{BUS} (Bus Impedance Matrix) = Y_{BUS}^{-1}

$$Z_{BUS} = \begin{bmatrix} Z_{11} & Z_{12} & . & . & . & Z_{1n} \\ Z_{21} & Z_{22} & . & . & . & Z_{2n} \\ . & . & & . & & . \\ . & . & & . & & . \\ . & . & & . & & . \\ Z_{n1} & Z_{n2} & . & . & . & Z_{nn} \end{bmatrix}_{n \times n \text{ for n bus system}}$$

1) Symmetric Y_{BUS} yields symmetric Z_{BUS}
2) Z_{BUS} is a full-matrix, i.e. zero elements in Y_{BUS} become non-zero elements in the corresponding Z_{BUS}

+Y_{BUS} is often used in solving load flow problems. It has gained widespread application owing to its simplicity in data preparation, and the ease with which it can be formed and modified for network changes. One of its greatest advantages is its sparsity, as it heavily reduces computer memory and time requirements.

Addition of an element of admittance y between buses i and j affects four entries in Y_{BUS}, viz, Y_{ii}, Y_{ij}, Y_{ji}, Y_{jj}, as follows:

$$Y_{ii\,new} = Y_{ii\,old} + y$$

$$Y_{ij\,new} = Y_{ij\,old} - y$$

$$Y_{ji\,new} = Y_{ji\,old} - y$$

$$Y_{jj\,new} = Y_{jj\,old} + y$$

Addition of an element of admittance y from bus i to ground will only affect.

Y_{ii}, i.e.

$$Y_{ii\,new} = Y_{ii\,old} + y$$

Example

Figure 6.7 shows the one-line diagram of a simple four-bus system. Table gives the lines impedances identified by the buses on which these terminate. The shunt

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admittance at all the buses is assumed to be negligible.

a) Find Y_{BUS}, assuming that the line shown dotted is not connected.
b) What modifications need to be carried out in Y_{BUS} if the line shown dotted is connected? Solution (a) from Table first and Table second is obtained from which Y_{BUS} for the system can be written as

Line, bus to bus	R, pu	X, pu
1-2	0.05	0.15
1-3	0.10	0.30
2-3	0.15	0.45
2-4	0.10	0.30
3-4	0.05	0.15

Line	G, pu	B, pu
1-2	2.000	-6.0
1-3	1.000	-3.0
2-3	0.666	-2.0
2-4	1.000	-3.0
3-4	2.000	-0.6

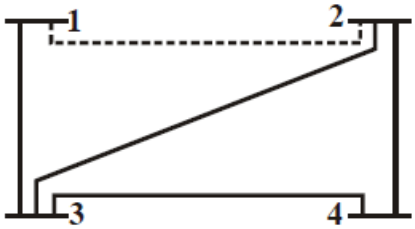

Fig. Sample system for Example

$$Y_{BUS} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{211} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix}$$

$$Y_{BUS} \begin{bmatrix} y_{13} & 0 & -y_{13} & 0 \\ 0 & (y_{23}+y_{24}) & -y_{23} & -y_{24} \\ -y_{23} & -y_{23} & (y_{31}+y_{32}+y_{34}) & -y_{34} \\ 0 & -y_{24} & -y_{34} & (y_{43}+y_{42}) \end{bmatrix}$$

$$Y_{BUS} = \begin{bmatrix} 1-j3 & 0 & -1+j3 & 0 \\ 0 & 1.666-j5 & -0.666+j2 & -1+j3 \\ -1+j3 & -0.666+j2 & 3.666-j11 & -2+j6 \\ 0 & -1+j3 & -2+j6 & 3-j9 \end{bmatrix}$$

a) The following elements of Y_{BUS} of part
b) are modified when a line is added between buses 1 and 2

$$Y_{11new} = Y_{11old} + (2-j6) = 3-j9$$

$$Y_{12new} = Y_{12old} - (2-j6) = -2-j6 = Y_{21new}$$

$$Y_{22new} = Y_{22old} + (2-j6) = 3.666-j11$$

Modified Y_{BUS} is written as

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

The Gauss-Siedel (GS) method is an interative algorithm for solving a set of non-linear algebraic equations.

If $|x_i^k - x_i^{k-1}| < \varepsilon$ (a very small number), for all i values, then the solution is said to converge. The iterative process is repeated till the solution converges within prescribed accuracy.

To solve a load flow problem by GS method, two cases depending on the type of buses present. In the first case we assume all the buses other than the slack bus are PQ buses. In the second case, we assume the presence of both PQ and PV buses, other than the slack bus. Later on we also include the presence of voltage controlled bus, whose voltage is controlled by a regulating transformer.

Case I: The slack bus is numbered one, and the remaining (n – 1) buses are PQ buses (i = 2, ……,n). With slack bus voltage assumed, the remaining (n -1) bus voltages are found through iterative process as follows:

Iterations are repeated till no bus voltage magnitude changes by more than a prescribed value.

Gauss Iterative Method. It converges much slower and may sometimes fail to do so.

Acceleration of Convergence in the GS method can sometimes be speeded up by the use of the acceleration factor. For the ith bus, the accelerated value of voltage at the (r + 1)st iteration is given by

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$$V_i^{(r+1)}(\text{accelerated}) = V_i^{(r)} + \alpha(V_i^{(r+1)} - V_i^{(r)})$$

Where α is a real number called the acceleration factor. A suitable value of α for any system can be obtained by trial load flow studies. A generally recommended value is α = 1.6. A wrong choice of α may indeed slow down convergence or even cause the method to diverge.

Physical limitations of Q generation require that Q demand at any bus must be in the range Q_{min} to Q_{max}. If at any stage during iteration, Q at any bus goes outside these limits, it is fixed at Q_{min} or Q_{max} as the case may be, and the bus voltage specification is dropped, i.e. the bus is now treated like a PQ bus.

5.2 NEWTON-RAPHSON METHOD

A powerful method of solving non-linear algebraic equations. It works faster, and is sure to converge in most, the practical method of load flow solution of large power networks. Its only drawback is the large requirement of computer memory, which can be overcome through a compact storage scheme. Convergence can be considerably speeded up by performing the first iteration through the GS method, and using the values so obtained for solving the NR iterations.

The Jacobian is as sparse as the Y_{BUS} matrix.

5.3 LOAD FLOWS

5.3.1 INTRODUCTION

Load flow solution is a solution of the network under steady state condition subject to certain inequality constraints under which the system operates. These constraints can be in theform of load nodal voltages, reactive power generation of the generators,

The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels (transmission lines). Load flow solution is essential for designing a new power system and for planning extension of the existing one for increased load demand. Load flow solution also gives the initial conditions of the system, Load flow solution worked out both ways

(i) Balanced

(ii) Unbalanced conditions

The following treatment under balanced conditions only. A load flow solution of the power system requires mainly the following steps:

(i) Formulation or the network equations

(ii)Suitable mathematical technique for solution of the equations.

Assume here that loads and hence generation are fixed at a particular value over a suitable period of time.

In a power system each bus or node is associated with four quantities, real and reactive powers, bus voltage magnitude and its phase angle. In a load flow solution two out of the four quantities are specified and the remaining two are require to be obtained through the solution of the equations. Depending upon which quantities have been specified.

Classified in three categories

1. Load bus: The real and reactive components or power are specified.
2. Generator bus or voltage controlled bus: The voltage magnitude corresponding to the generation voltage and real power P_G corresponding to its ratings are specified.
3. Slack, swing or reference bus: $\sum_{i=1}^{n} P_i$ = real power loss P_L where P_i is the power injection at the buses, positive for generator buses and is negative for load buses. The losses remain unknown until the load flow solution is complete. It is for this reason that generally one of the generator buses is made to take the additional real and reactive power to supply transmission losses.

Why slack or swing bus, the voltage magnitude V and phase angle δ are specified.

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Bus type	Quantities specified	Quantities to be obtained
Load bus	P, Q	| V |, δ
Generator bus	P, | V |	Q, δ
Slack bus	| V |, δ	P, Q

The load flow equations can be formulated using either the loop or bus frame of reference. The nodal admittance formulation, using the nodal voltages as the independent variables is the most economic.

Nodal Admittance Matrix

The load flow equations, using nodal admittance formulation for a three-bus system

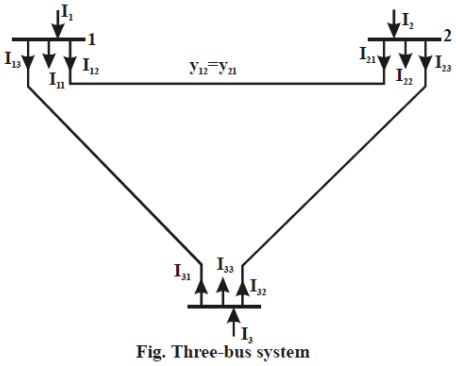

Fig. Three-bus system

$$I_1 = I_{11} + I_{12} + I_{13}$$
$$= V_1 y_{11} + (V_1 - V_2) y_{12} + (V_1 - V_3) y_{13}$$
$$= V_1 y_{11} + V_1 y_{12} - V_2 y_{12} + V_1 y_{13} - V_3 y_{13}$$
$$= V_1 (y_{11} + y_{12} + y_{13}) - V_2 y_{12} - V_3 y_{13}$$
$$= V_1 Y_{11} + V_2 Y_{12} + V_3 Y_{13}$$
$$Y_{11} = y_{11} + y_{12} + y_{13}$$
$$Y_{12} = -y_{12}$$
$$Y_{13} = -y_{13}$$
$$I_2 = V_1 Y_{21} + V_2 Y_{22} + V_3 Y_{23}$$
$$I_3 = V_1 Y_{31} + V_2 Y_{32} + V_3 Y_{33}$$

In a matrix form

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{331} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

$$I_p = \sum_{q=1}^{3} Y_{pq} V_q, p = 1 \text{ to } 3$$

$$I_p = \sum_{q=1}^{n} Y_{pq} V_q, p = 1, 2, \ldots\ldots, n$$

The nodal admittance matrix is a sparse matrix (a few number of elements are non-zero) for an actual power system.

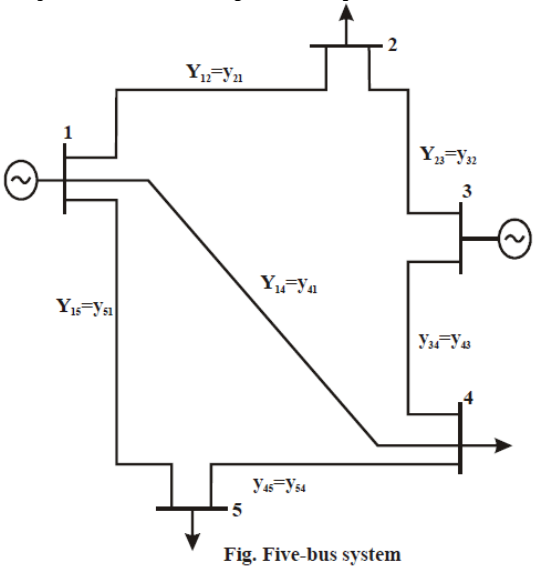

Fig. Five-bus system

$$I_p = \sum_{q=1}^{3} Y_{pq} V_q, p = 1 \text{ to } 3$$

$$Y_{pq} = \begin{bmatrix} Y_{11} & Y_{12} & 0 & Y_{14} & Y_{15} \\ Y_{21} & Y_{22} & Y_{23} & 0 & 0 \\ 0 & Y_{32} & Y_{33} & Y_{34} & 0 \\ Y_{41} & 0 & Y_{43} & Y_{44} & Y_{45} \\ Y_{51} & 0 & 0 & Y_{54} & Y_{55} \end{bmatrix}$$

In a large system of 100 nodes, these non-zero elements may be as small as 2% of the total elements. The computer memory requirements very low. It need store only a very few non-zero elements, the nodal admittance being a symmetric matrix along the leading diagonal, the computer need store the upper triangular nodal admittance matrix only.

The admittance matrix may be assembled as follows

(i) The diagonal element of each node is the sum of the admittances connected to it

(ii) The off-diagonal element is the negated admittance between the nodes.

The sum of the elements in each column of the admittance matrix summates to zero which means that nodal admittance matrix

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is a singular matrix and hence the rows of the matrix are linearly dependent.
Necessity of the slack or reference summates bus based on power balance in the system. Based on admittance matrix approach, it can be said mathematically that one of the buses should be taken as slack, otherwise the nodal matrix is singular and cannot be handled. By taking one of the buses as reference, corresponding row and column are deleted from the nodal admittance matrix and hence the reduced matrix becomes non-singular, which can be handled very easily.

5.3.2 SHUNT BRANCHES

Shunt admittances, are added to the diagonal elements corresponding to the nodes at which they are connected. The off-diagonal elements are unaffected. The addition of shunt element. Either strengthen or weaken the Y matrix diagonal depending on whether the add to or subtract. Shunt inductances strengthen shunt capacitances weaken it.

$$V_p = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{V^*_p} - \sum_{\substack{q=1 \\ q\neq p}}^{n} Y_{pq} V_q\right], p = 1, 2, ..., n$$

I_p has been substituted by the real and reactive powers because normally in a power system these quantities are specified.

5.4 ITERATIVE METHODS

Bus voltages are the variables load flow equations are nonlinear and solved by an iterative method.
The iterative methods are
(i) Gauss's method
(ii) Gauss-Seidel method
Refer above Fig. two generators at buses 1 and 3 and three load buses 2, 4 and 5. Assuming bus 1 as the slack bus,
All the other buses except bus No. 1 are load buses i.e., buses where P and Q are specified. The number of nonlinear equations is (n – 1) where n is the total number of buses in the system.

5.4.1 GAUSS METHOD

Except the slack bus 1. Assume a suitable value of convergence criterion $\varepsilon, e.g.,$ if the absolute value of the maximum change in voltage between any two consecutive iterations is less than a prespecified tolerance ε, the convergence is achieved and the iterative procedure is terminated.
After Q at the voltage controlled bus has been calculated, it should be checked whether this value violates the reactive power generation at the bus i.e., whether it is less than the minimum reactive power generation permissible (because of stability problem) or it is more than the maximum reactive power generation permissible (because of rotor heating). If it violates, the voltage controlled bus is made to act as a load bus for that iteration only and the reactive power to be substituted in the expression for that iteration will correspond to the limit it has violated, i.e., if it is less than Q_{min}, the value to be substituted will be Q_{min}. If the calculated value of Q lies within the limits, this value of Q will be substituted in the expression.
It may be noted that a wrong selection of α may result in slower converagence and sometimes even result in divergence from the solution.

Example
The following is the system data for a load flow solution:
The line admittances
Bus code
1-2
1-3
2-3
2-4
3-4
Admittance
2 – j8.0
1 – j4.0

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0.666-j2.664
1-j4.0
2-j8.0

The schedule of active and reactive powers:

Bus code	P	Q	V	Remarks
1	-	-	1.06	Slack
2	0.5	0.2	1+j0.0	PQ
3	0.4	0.3	1+j0.0	PQ
4	0.3	0.1	1+j0.0	PQ

Determine the voltages at the end of first iteration using Gauss-Seidel method. Take α = 1.6.

Solution:

The admittance matrix will be as given below:

$$Y_{pq} = \begin{bmatrix} 3-j12.0 & -2+j8.0 & -1+j4.0 & 0.0 \\ -2+j8.0 & 3.666-j14.664 & -0.666+j2.664 & -1+j4.0 \\ -1+j4.0 & -0.666+j2.664 & 3.666-j14.664 & -2+j8.0 \\ 0.0 & -1+j4.0 & -2+j8.0 & 3-j12.0 \end{bmatrix}$$

The powers for load buses are to be taken as negative and that for generator buses as positive.

For an n-bus system, the number of unknowns are 2(n -1) because the voltage at the slack bus is known and is kept fixed both in magnitude and phase.

To solve the problem for 2(n -1) variables we need to solve 2(n -1) set of equations.

It is to be noted that the initial solution for the equations should not far from the actual solution.

Otherwise, there are chances of the solution diverging rather than converging and it may not be possible to achieve a solution whatever be the computer time utilized.

B = J.C

Here J is the first derivative matrix known asthe Jacobian matrix.

When referred to a power system problem (assuming there is only one generator bus which istaken as slack bus and all other buses are load buses), the above set of linearized equations become

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_3 \\ \vdots \\ \Delta Q_n \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial e_2} & \frac{\partial P_2}{\partial e_3} & \cdots & \frac{\partial P_2}{\partial e_n} & \frac{\partial P_2}{\partial f_2} & \frac{\partial P_2}{\partial f_3} & \cdots & \frac{\partial P_2}{\partial f_n} \\ \frac{\partial P_3}{\partial e_2} & \frac{\partial P_3}{\partial e_3} & \cdots & \frac{\partial P_3}{\partial e_n} & \frac{\partial P_3}{\partial f_2} & \frac{\partial P_3}{\partial f_3} & \cdots & \frac{\partial P_3}{\partial f_n} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial P_n}{\partial e_2} & \frac{\partial P_n}{\partial e_3} & \cdots & \frac{\partial P_n}{\partial e_n} & \frac{\partial P_n}{\partial f_2} & \frac{\partial P_n}{\partial f_3} & \cdots & \frac{\partial P_n}{\partial f_n} \\ \frac{\partial Q_2}{\partial e_2} & \frac{\partial Q_2}{\partial e_3} & \cdots & \frac{\partial Q_2}{\partial e_n} & \frac{\partial Q_2}{\partial f_2} & \frac{\partial Q_2}{\partial f_3} & \cdots & \frac{\partial Q_2}{\partial f_n} \\ \frac{\partial Q_3}{\partial e_2} & \frac{\partial Q_3}{\partial e_3} & \cdots & \frac{\partial Q_3}{\partial e_n} & \frac{\partial Q_3}{\partial f_2} & \frac{\partial Q_3}{\partial f_3} & \cdots & \frac{\partial Q_3}{\partial f_n} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \frac{\partial Q_n}{\partial e_2} & \frac{\partial Q_n}{\partial e_3} & \cdots & \frac{\partial Q_n}{\partial e_n} & \frac{\partial Q_n}{\partial f_2} & \frac{\partial Q_n}{\partial f_3} & \cdots & \frac{\partial Q_n}{\partial f_n} \end{bmatrix} \begin{bmatrix} \Delta e_2 \\ \Delta e_3 \\ \vdots \\ \Delta e_n \\ \Delta f_2 \\ \Delta f_3 \\ \vdots \\ \Delta f_n \end{bmatrix}$$

$2(n-1)\times 1 \qquad 2(n-1)\times 2(n-1) \qquad 2(n-1)\times 1$

In short form

$$\begin{bmatrix} \Delta P \\ -- \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & \vdots & J_2 \\ --- & \vdots & --- \\ J_3 & \vdots & J_4 \end{bmatrix} \begin{bmatrix} \Delta e \\ -- \\ \Delta f \end{bmatrix}$$

$$\begin{bmatrix} \Delta P \\ -- \\ \Delta Q \\ -- \\ |\Delta V_p|^2 \end{bmatrix} = \begin{bmatrix} J_1 & \vdots & J_2 \\ --- & \vdots & --- \\ J_1 & \vdots & J_4 \\ --- & \vdots & --- \\ J_1 & \vdots & J_6 \end{bmatrix} \begin{bmatrix} \Delta e \\ -- \\ \Delta f \end{bmatrix}$$

Example

The load flow data for the sample power system are given below. The voltage magnitude at bus 2 is to be maintained at 1.04 p.u. The maximum and minimum reactive power limits of the generator at bus 2 are 0.35 and 0.0 p.u. respectively. Determine the set of load flow equations at the end of first iteration by using Newton-Raphson method.

Impedance for sample system:

Bus code	Impedance	Line Charging admittance
1-2	0.08 + j0.24	0.0
1-3	0.02 + j0.06	0.0
2-3	0.06 + j0.18	0.0

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Schedule of generation and loads:

Bus code	Assumed Voltages	Generation		Load	
		MW	MVAR	MW	MVAR
1	1.06 +	0	0	0	0
2	j0.0	0.2	0.0	0.0	0.0
3	1.0 + j0.0	0	0	0	0.25
	1.0 + j0.0				

Solution

$$y_{12} = \frac{1}{Z_{12}} = \frac{(0.08 - j0.24)}{(0.08 + j0.24)(0.08 - j0.24)}$$

$$= 1.25 - j3.75$$

Similarly $y_{13} = 5 - j15$ and $y_{23} = 1.667 - j5.0$ and the nodal admittance matrix

$$Y = \begin{bmatrix} 6.25 - j18.75 & -1.25 + j3.75 & -5 + j15 \\ -1.25 + j3.75 & 2.916 - j8.75 & -1.666 + j5.0 \\ -5 + j15 & -1.666 + j5.0 & 6.666 - j20 \end{bmatrix}$$

5.4.2 COMPARSION OF SOLUTION METHODS

Gauss-Seidel is undoubtedly superior to Gauss method, the comparison is restricted only between G-S method and Newton-Raphson method and that too when Y bus matrix is used for problem formulation.

Polar coordinates are preferred for solution based on N-R method and rectangular coordinates for the G-S method.

The time taken to perform one iteration of the computation is relatively smaller in case of G-S method as compared to N-R method but the number of iterations required by G-S method for a particular system are greater as compared to N-R method and they increase with the increase in the size of the system. In case of N-R method the number of iterations is more or less independent of the size of the system and vary between 3 to 5 iterations. The convergence characteristics of N-R method are not affected by the selection of a slack bus.

G-S method very seriously affected, the main advantage of G-S method as compared to N-R method is its ease in programming and most efficient use of core memory. For large power N-R method.

5.5 ECONOMIC LOAD DISPATCH

5.5.1 INTRODUCTION

The economic load dispatch problem involves the solution of two different problems. The first of these is the Unit Commitment or predispatch problem wherein it is required to select optimally out of the available generating sources to operate, to meet the expected load and provide a specified margin of operating reserve over a specified period of time. The second aspect of economic dispatch is the no-line economic dispatch wherein it is required to distribute the load among the generating units actually paralleled with the system in such manner as to minimize the total cost of supplying the minute-to-minute requirement of the system.

It is very essential to reduce the running charges of the electric energy i.e., reduce the fuel consumption for meeting a particular load demand.

For a particular load demand the generation at all the generator buses are fixed except at one generator bus known as slack, reference or swing bus where we allow the generation to take value within certain limits. In case of economic load dispatch the generations are not fixed but they are allowed to take values again within certain limits so as to meet a particular load demand with minimum fuel consumption. This means economic load dispatch problem is really the solution of a large number of load flow problems and choosing the one which is optimal in the sense that it needs minimum cost of generation.

5.5.2 SYSTEM CONSTRAINTS

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kVA loading

$$P_p^2 + Q_p^2 \le C_p^2$$

The maximum active power generation limited again by thermal consideration and minimum generation is limited by the flame instability of a boiler.

The generator powers P_P cannot be outside the range stated by the inequality, i.e.

$$P_{p\min} \le P_p \le P_{p\max}$$

Maximum reactive power is limited because of overheating of the rotor and minimum is limited because of the stability limit of the machine

$$Q_{p\min} \le Q_p \le Q_{p\max}$$

$$|V_{p\min}| \le |V_P| \le |V_{p\max}|$$

$$\delta_{p\min} \le \delta_P \le \delta_p \max$$

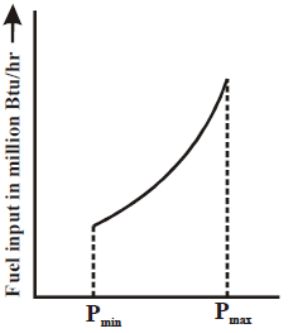

Fig. Input-output curve

The normal operating angle of transmission line lies between 30° to 45° for transient stability reasons; therefore a higher limit is imposed on angle δ. A lower limit of δ assures proper utilization of transmission facility.

The fixed costs like salaries and capital costs are neglected from the cost criteria only the thermal plants, only with the cost of fuel input to different generating stations.

These transmission line losses are calculated by making use of the B-coefficients. From the heat rate curve another characteristic known as incremental fuel curve can be obtained. Incremental fuel rate is defined as

$$\text{Incremental fuel rate} = \frac{\Delta \text{input}}{\Delta \text{output}}$$

Now as the incremental quantities tend to zero, incremental fuel rate tends to

F is the fuel input in million Btu per hr and P is the power output in MW. The units associated with incremental fuel rate are, therefore, million Btu per MWhr and the incremental fuel cost is expressed in terms of Rs. Per MWhr which is obtained by multiplying the incremental fuel rate by the fuel cost in Rs. Per Btu.

Incremental production cost consists of the incremental fuel cost plus the incremental cost of labour, supplies, maintenance and water. The incremental cost of production equal to the incremental cost fuel. The incremental efficiency is defined as the reciprocal of incremental fuel rate or incremental production cost and is given as

$$\text{Incremental efficiency} = \frac{(\text{output})}{(\text{input})} = \frac{dP}{dF}$$

5.5.3 MERIT ORDER SCHEDULING

To economic scheduling of power plants, it assumes that the incremental cost of all the generators is constant over the full range. The economical way of meeting a load will be to load the machines in order of highest incremental efficiency.

ECONOMIC DISPATHC NEGLECTING LOSSES

The economic dispatch problem is defined as

$$\text{Min } F_T = \sum_{n=1}^{n} F_n$$

$$\text{Subject to } P_D = \sum_{n=1}^{n} P_n$$

Where F_T is total fuel input to the system, F_n the fuel input to nth unit, P_D the total load demand and P_n the generation of nth unit.

By making use of Lagrangian multiplier the auxiliary function

$$F = F_T + \lambda(P_D - \sum_{n=1}^{n} P_n)$$

λ is the Lagrangian multiplier

$$\frac{\partial F}{\partial P_n} = \frac{\partial F_T}{\partial P_n} + \lambda(0-1) = 0$$

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$$= \frac{\partial F_T}{\partial P_n} - \lambda = 0$$

Since $F_T = F_1 + F_2 + \ldots\ldots + F_n$,

$$\therefore \quad \frac{\partial F_T}{\partial P_n} = \frac{\partial F_n}{\partial P_n} = \lambda$$

The condition for optimum operation is

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2} = \ldots\ldots = \frac{dF_n}{dP_n} = \lambda$$

$\frac{dF_n}{dP_n}$ = incremental production cost of plant n in Rs. Per MWhr.

The incremental production cost of a given plant over a limited range is represented by

$$\frac{dF_1}{dP_1} = F_{nn} P_n + f_n$$

Where F_{nn} = Slope of incremental production cost curve

f_n = Intercept of incremental production cost curve

The machines be so loaded that the incremental cost of production of each machine is same

In case of an urban area where the load density is very high, the transmission loss could be neglected.

If the energy to be transported is over relatively larger distances with low load density, the transmission losses in some cases may amount to 20 to 30% of the total load.

5.5.4 OPTIMUM LOAD DISPATCH INCLUDING TRANSMISSION LOSSES

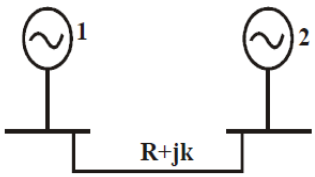

Fig. Two identical generators connected through a transmission link

Two identical generators i.e., generators with identical incremental production cost. If generator 2 has a local load, according to equal incremental production criterion, the total load must be shared equally by both the generators, i.e., each generator should supply half of the total load. The common sense tells us that it is more economical to let generator 2 supply most of the local load because generator 1has to supply in addition to the load, the transmission losses also. Therefore, the criterion of sharing load by equal incremental production cost does not hold good under such situation and a strategy must be evolved which takes into account the transmission losses also.

The optimal load dispatch problem including transmission losses is definedas

$$\text{Min } F_T = \sum_{n=1}^{n} F_n$$

$$\text{Subject to } P_D + P_L - \sum_{n=1}^{n} P_n = 0$$

P_L is the total system loss which is assumed to be a function of generation and the other term have their usual significance.

Use of the Lagrangian multiplier λ, the auxiliary function is given by

$$F = F_T + \lambda(P_D + P_L - \sum P_n)$$

The partial differential of this expression when equated to zero gives the condition for optimal load dispatch, i.e.

$$\frac{\partial F}{\partial P_n} = \frac{\partial F_T}{\partial P_n} + \lambda\left(\frac{\partial P_L}{\partial P_n} - 1\right) = 0$$

$$\frac{dF_n}{dP_n} + \frac{\partial P_L}{\partial P_n} = \lambda$$

As the incremental cost of received power in Rs. Per MWhr.

A set of n equations with (n + 1) usnknows. Here n generations are unknown and λ is also unknown. These equations are known as coordination equations because they coordinate the incremental transmission losses with the incremental cost of production.

The loss formula equation

$$P_L = \sum_m \sum_n P_m B_{mn} P_n$$

Where P_m and P_n are the source loadings, B_{mn} the transmission loss coefficients.

The calculation of $\frac{\partial P_L}{\partial P_n}$

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$$\frac{\partial P_L}{\partial P_n} = 2\sum_m B_{mn} P_m$$

Also

$$\frac{dF_n}{dP_n} = F_{nn} P_n + f_n$$

$\therefore$ The coordiantion equations can be rewritten as

$$F_{nn} P_n + f_n + \lambda \sum 2B_{mn} P_m = \lambda$$

Collecting all coefficients of P_n, we obtain

$$P_n (F_{nn} + 2\lambda B_{nn}) = -\lambda \left(\sum_{m \neq n} 2B_{mn} P_m\right) - f_n + \lambda$$

Solving for P_n we obtain

$$P_n = \frac{1 - \frac{f_n}{\lambda} \sum_{m \neq n} 2B_{mn} P_m}{\frac{F_{nn}}{\lambda} + 2B_{nn}}$$

Penalty factor method: From the coordination equation

$$\frac{dF_n}{dP_n} + \lambda \frac{\partial P_L}{\partial P_n} = \lambda$$

$$\frac{dF_n}{dP_n} + \lambda \left(1 - \frac{\partial P_L}{\partial P_n}\right)$$

$$\frac{dF_n}{dP_n} \cdot \frac{1}{1 - \frac{\partial P_L}{\partial P_n}} = \lambda$$

$$\frac{dF_n}{dP_n} . L_n = \lambda$$

Where L_n is the penalty factor of plant n and is given by

$$L_n = \frac{1}{1 - \frac{\partial P_L}{\partial P_n}}$$

$$\approx \left(1 + \frac{\partial P_L}{\partial P_n}\right) \text{approximate penalty factor}$$

$$= L_n$$

When transmission losses are included and coordinated, the following points must be kept in mind for economic load dispatch solution.

1. Whereas the incremental cost of production of a plant is always positive, the incremental transmission losses can be both positive or negative.
2. The individual generators will operate at different incremental costs of production.
3. The generation with highest positive incremental transmission loss will operate at the lowest incremental cost of production.

The B_{mn} coefficients are the loss coefficients and for an n generator system the coefficient is an n × n symmetric matrix

$$B_{mn} = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2n} \\ \vdots & & & \\ B_{n1} & B_{n2} & \cdots & B_{nn} \end{bmatrix}$$

The diagonal elements are all positive and strong as compared with the off diagonal elements which mostly are negative and are relatively weaker.

Two simplifying assumptions for deriving the loss coefficients

(i) The ratio X/R for all the transmission lines is the same

(ii) The phase angle of all the load currents is the same

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GATE QUESTIONS

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1 PERFORMANCE OF TRANSMISSION LINES, LINE PARAMETERS & CORONA

Q.1 The conductors of a 10km long. Single phase, two wire line are separated by a distance of 1.5m. The diameter of each conductor is 1cm. if the conductor are of copper,the inductance of the circuit is

a)50.0mH b)45.3mH
c)23.8mH d)19.6mH

[GATE-2001]

Q.2 Consider a long, two –wire line composed of solid conductors. The radius of both conductors is 0.25 cm and the distance between their centers is / meters. If this distance is doubled, then the inductance per unit length

a)Doubles
b) Halves
c) Increase but does not double
d) Decrease but does not halve

[GATE-2002]

Q.3 Bundle conductors are mainly used in high voltage overhead transmission lines to

a) Reduce transmission line losses
b) Increases mechanical strength of the line
c) Reduce corona
d) Reduce sag

[GATE-2003]

Q.4 The ABCD parameters of a 3-phase overhead transmission line are $A = D = 0.9\angle 0 B = 200\angle 90°\Omega$ and $C = 0.95 \times 10^{3}\angle 90°$ S. At no-load condition a shut inductive reactor is connected at the receiving end of the line to limit the receiving –end voltage to be equal to the sending –end voltage. The ohmic value of the reactor is

a)$\infty\ \Omega$ b)2000Ω
c) 105.26Ω d) 1052.6Ω

[GATE-2003]

Q.5 A surge of 20kV magnitude travels along a lossless cable towards its junction with two identical lossless overheads transmission lines. The inductance and the capacitance of the cable are 0.4mH and 0.5μF per km. The inductance and capacitance of the overhead transmission lines are 1.5 mH and 0.015 μF per km. The magnitude of the voltage at the junction due to surge is

a)36.72kV b)18.36kV
c)6.07kV d)33.93kV

[GATE-2003]

Q.6 The generalized circuit constants of a 3-phase, 220 kV rated voltage, medium length transmission line are

$A=D=0.936+j0.016=0.936\angle 0.98°$

$B=33.5+j138=142.0\angle 76.4°\Omega$

$C = (-5.18 + j914) \times 10^{-6}\mho$

If the load at the receiving end is 50 MW at 220 kV with a power factor of 0.9 lagging then magnitude of line to line sending end voltage should be

a)133.23kV b)220.00kV
c)230.78kV d)246. 30kV

[GATE-2004]

Q.7 The parameters of transposed overhead transmission line are given as: Self reactance $X_s = 0.4\Omega/km$ and Mutual reactance $X_m = 0.1\Omega/km$

The positive sequence reactance X_1 and zero sequence reactance X_0 respectively, in Ω/km are

a) 0.3,0.2 b)0.5,02
c)0.5,0.6 d)0.3,0.6

[GATE-2005]

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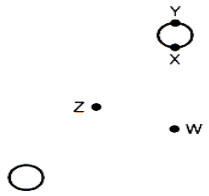
Q.8 The concept of an electrically short, medium and long lie is primarily based on the
a) Nominal voltage of the line
b) Physical length of the line
c) Wavelength of the line
d) Power transmitted over the line
[GATE-2006]

Q.9 The A,B,C,D constant of a 220kv line are: A=D=0.94∠10°
, B = 130 ∠730 C = 0.001 ∠900 If the sending end voltage of the line for a given load delivered at nominal voltage is 240 kV the % voltage regulation of the line is
a) 5 b)9
c)16 d)21
[GATE-2006]

Q.10 A single phase transmission line and a telephone line are both symmetrically strung one below the other, in horizontal configurations on a common tower . The shortest and longest distances between the phase and telephone conductors are 2.5 m and 3m respectively .The voltage (volt/ km) induced in the telephone circuit , due to 50Hz current of 100 amps in the power circuits
a)4.81 b) 3.56
c)2.29 d)1.27
[GATE-2006]

Q.11 Consider a bundled conductor of an overhead line consisting of three identical sub conductors placed at the corners of an equilateral triangle as shown in the figure. If we neglect the charges on the other phase conductors and ground, and assume that spacing between sub-conductors is much larger than their radius, the maximum electric fields intensity is experienced at



a)Point X b) Point Y
c)Point Z d) Point W
[GATE-2007]

Q.12 The total reactance and total susceptance of a lossless overhead EHV line, operating at 50Hz, are given by 0.045 pu and 1.2 pu respectively. If the velocity of wave propagation is 3×10^5 km/s, then the approximate length of the line is
a)122km b)172km
c) 222km d) 272km
[GATE-2007]

Q.13 An extra high voltage transmission line of length 300 km can be approximate by a lossless line having propagation constant $\beta =$ 0.00127 radians per km. then the percentage ratio of line length to wavelength will be given by
a) 24.24% b) 12.12%
c) 19.05% d) 6.06%
[GATE-2008]

Q.14 A lossless transmission line having Surge impedance Loading (SIL) of 2280 MW is provided with a uniformly distributed series capacitive compensation of 30% Then, SIL of the compensated transmission line will be
a)1835 MW b)2280 MW
c)2725MW d)3257 MW
[GATE-2008]

Q.15 For a fixed value of complex power flow in a transmission line having a sending end voltage V the real power loss will be proportional to
a) V b) V^2

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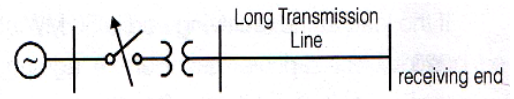
c) $\frac{1}{V^2}$ d) $\frac{1}{V}$

[GATE-2009]

Q.16 A 50 Hz synchronous generator is initially connected to a long lossless transmission line which is open circuited at the receiving end. With the field voltage held constant, the generator is disconnected from the transmission line. Which is open circuited at receiving end. With the field voltage held constant the generator is disconnected from the transmission line. Which of the following may be said about the steady state terminal voltage and field current of the generator?



a) The magnitude of terminal voltage decreases, and the field current does not change.
b) The magnitude of terminal voltage increases, and the field current does not change.
c) The magnitude of terminal voltage increases and the field current increases
d) The magnitude of terminal voltage does not change and the field current decreases

[GATE-2010]

Q.17 The horizontally placed conductors of a single phase line operating at 50 Hz are having outside diameter of 1.6 cm, and the spacing between centers of the conductors is 6 m. The permittivity of free space is 8.854×10^{-12}F/m. The capacitance to ground per kilometer of each line is

(A) 4.2×10^{-9} F (B) 8.4×10^{-9} F

(C) 4.2×10^{-12} F (D) 8.4×10^{-12} F

[GATE-2014]

Q.18 In a long transmission line with r, l, g and c are the resistance, inductance,shunt conductance and capacitance per unit length, respectively, the condition for distortionless transmission is

(A) $rc = lg$ (B) $r = \sqrt{l/c}$

(C) $rg = lc$ (D) $g = \sqrt{c/l}$

[GATE-2014]

Q.19 For a fully transposed transmission line

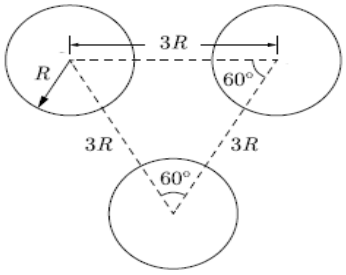
(A) positive, negative and zero sequence impedances are equal
(B) positive and negative sequence impedances are equal
(C) zero and positive sequence impedances are equal
(D) negative and zero sequence impedances are equal

[GATE-2014]

Q.20 For a 400 km long transmission line, the series impedance is $(0.0 + j0.5)\ \Omega/\text{km}$ and the shunt admittance is $(0.0 + j5.0)$ μmho/km. The magnitude of the series impedance $(\text{in } \Omega)$ of the equivalent π circuit of the transmission line is ___.

[GATE-2014]

Q.21 A composite conductor consists of three conductors of radius R each. The conductors are arranged as shown below. The geometric mean radius (GMR) (in cm) of the composite conductor is kR. The value of k is_____



[GATE-2015]

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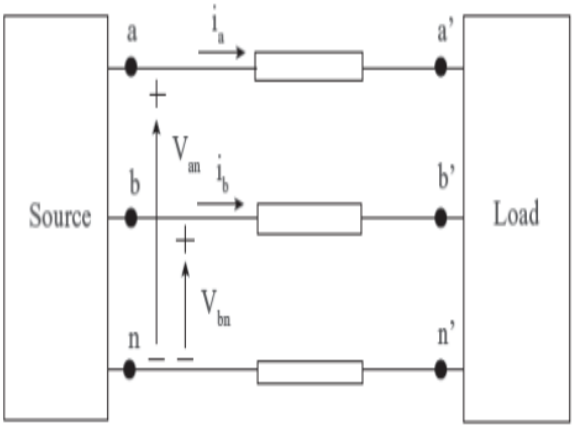
Q.22 At no load condition, a 3 - phase, 50Hz, lossless power transmission line has sending - end and receiving - end voltages of 400KV and 420KV respectively.Assuming the velocity of travelling wave to be the velocity of light, the length of the line, in km, is _____.

[GATE-2016]

Q.23 A source is supplying a load through a 2 – phase, 3 – wire transmission system as shown in figure below. The instantaneous voltage and current in phase – a are V_{an} = 220 sin(100 π t)V and i_a = 10 sin(100 π t)A, respectively. Similarly for phase – b, the instantaneous voltage and current are V_{bn}= 220 cos(100 π t)V and ib = 10 cos(100 π t)A, respectively



The total instantaneous power flowing from the source to the load is

(A) 2200 W

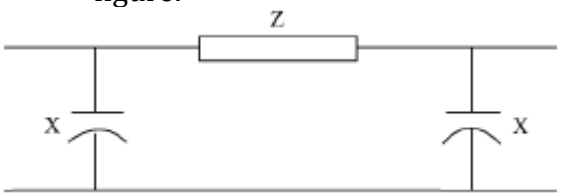
(B) 2200 $\sin^2$(100 π t) W

(C) 4400 W

(D) 2200 sin (100 π t) cos(100 πt)W

[GATE-2017]

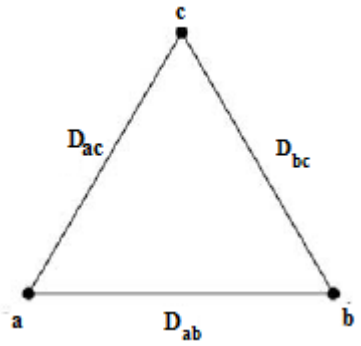
Q.24 The nominal π – circuit of a transmission line is shown in the figure.



Impedance Z = 100∠80° Ω and reactance X = 3300Ω. The magnitude of the characteristic impedance of the transmission line, in Ω, is _____. (Given the answer up to one decimal place)

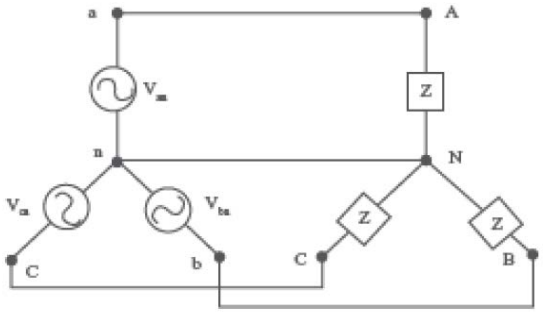
[GATE-2017]

Q.25 Consider an overhead transmission line with 3 – phase, 50 Hz balanced system with conductors located at the vertices of an equilateral triangle of length D_{ab} = D_{bc} = D_{ca} = 1m as shown in figure below. The resistances of the conductors are neglected. The geometric mean radius (GMR) of each conductor is 0.01 m.Neglecting the effect of ground, the magnitude of positive sequence reactance is Ω/km (rounded off to three decimal places) is _____.



[GATE-2017]

Q.26 For the balanced Y – Y connected 3 – phase circuit shown in the figure below,the line – line voltage is 208 V rms and the total power absorbed by the load is 432 What a power factor of 0.6 leading.



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(a) $33\angle -53.1°\Omega$
(b) $60\angle 53.1°\Omega$
(c) $60\angle -53.1°\Omega$
(d) $180\angle -53.1°\Omega$

[GATE-2017]

Q.27 Consider a lossy transmission line with V_1 and V_2 as the sending and receiving end voltages, respectively. Z and X are the series impedance and reactance of the line, respectively. The steady-state stability limit for the transmission line will be

(A) Greater than $\left|\frac{V_1 V_2}{X}\right|$

(B) less than $\left|\frac{V_1 V_2}{X}\right|$

(C) equal to $\frac{V_1 V_2}{X}$

(D) equal to $\frac{V_1 V_2}{Z}$

[GATE-2018]

Q.28 The series impedance matrix of a short three-phase transmission line in phase coordinates is $\begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix}$ If the positive sequence impedance is $(1+j10)\ \Omega$ and the zero sequence is $(4+j31)\ \Omega$, then the imaginary part of $Z_m\,(\text{in } \Omega)$ is is _____ (up to 2 decimal places).

[GATE-2018]

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(c)	(c)	(c)	(b)	(d)	(c)	(d)	(b)	(c)	(c)	(b)	(c)	(d)	(c)
15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
(c)	(a)	(b)	(a)	(b)	(187)	(1.913)	294.59	(a)	406.2	0.289	(c)	(b)	7

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EXPLANATIONS

Q.1 **(c)**

$$L_{ab}=0.4\ln\left(\frac{d}{r'}\right)\text{mH/km}$$

$$=0.4\ln\left(\frac{150}{0.7788\times\frac{1}{2}}\right)\text{mH/km}$$

$=2.3815\text{mH/km}$

For 10kmlong line

$L_{ab}=23.815\text{mH}/\text{km}$

Q.2 **(c)**

$$L\propto\ln\left(\frac{d}{r'}\right)$$

$\ln(2d)>\ln d$

Q.3 **(c)**

- By bonding of conductors the self GMD of the conductors is increased.
- Corona loss $\propto(V-V_o)^2$

  V_o is approximately directly proportional to the size of the conductor, hence larger the size of the conductor larger will be the critical disruptive voltage and smaller will be the factor $(V-V_o)^2$ and hence, smaller will be the corona loss.

Q.4 **(b)**

At no-load condition

Active power at receiving end $=P_R=0$

Reactive power at receiving end $=Q_R$

=reactive power absorbed by the reactor to make $|V_S|=|V_R|$

$A=D=0.9\angle0°$

$|A|=0.9$and $\alpha=0°$

$B=200\angle90°\Omega$

$|B|=200$ and $\beta=90°$

$$S_R=\frac{|V_S||V_R|}{|B|}\angle(\beta-\delta)-\left|\frac{A}{B}\right||V_R|^2\angle(\beta-\alpha)$$

The above equation is expressed in real and imaginary parts, we can write the real and imaginary parts, we can write the real and reactive powers at the receiving –end as

$$P_R=\frac{|V_S||V_R|}{|B|}\cos(\beta-\delta)-\left|\frac{A}{B}\right||V_R|^2\cos(\beta-\alpha)$$

...(i)

$$Q_R=\frac{|V_S||V_R|}{|B|}\sin\sin c(\beta-\delta)-\left|\frac{A}{B}\right||V_R|^2\sin(\beta-\alpha)$$

...(ii)

Since,$P_R=0$, equation (i) becomes

$$0=\frac{|V_R|^2}{200}\cos(90°-\delta)-\frac{0.9}{200}|V_R|^2\cos(90°-0)0$$

$$=\frac{|V_R|^2}{200}\sin\delta$$

$\delta=0°$

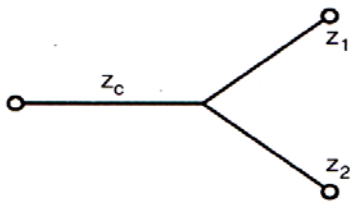
Equation (ii) becomes

$$Q_R=\frac{|V_R|^2}{200}\sin(90°-0)-\frac{0.9}{200}|V_R|^2\sin(90°-0)$$

$$Q_R=\frac{0.1}{200}|V_R|^2 \quad ....(iii)$$

Reactive power absorbed by rector of reactance x

Q.5 **(d)**



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Where $z_1=z_2$

Parameter of cable

Inductance $=L_C=0.4\text{mH/km}$ and

Capacitance $=C_C=0.5\mu\text{F/km}$

Surface impedance of the cable $=Z_C$

$$=\sqrt{\frac{L_C}{C_C}}=\sqrt{\frac{0.4\times10^{-3}}{0.5\times10^{-6}}}$$

$=28.28\Omega$

Parameters of OH

Transmission lines

Inductance $=L_1=1.5\text{mH/km}$ and

Capacitance $=C_1=0.015\mu\text{F/km}$

Surge impedance of the lines

$$=z_1=z_2=\sqrt{\frac{L_1}{C_1}}=\sqrt{\frac{1.5\times10^{-3}}{0.015\times10^{-6}}}$$

$=316.22\Omega$

E=20kV

Junctionvotage$=E_j$

$$=\frac{2E\times\frac{1}{Z_C}}{\frac{1}{Z_C}+\frac{1}{Z_1}+\frac{1}{Z_2}}$$

$$=\frac{2\times20\times\frac{1}{28.28}}{\frac{1}{28.28}+\frac{2}{316.22}}$$

=33.93kV

Q.6 **(c)**

$A=0.936\angle0.98°$

And

$B=142\angle76.4°\Omega$

$$=\frac{220}{\sqrt{3}}\text{kV}=127\angle0°\text{kV}$$

$$l_R=\frac{50\times10^6}{\sqrt{3}\times220\times10^3\times0.9}$$

=145.8A

$l_R=0.1458\angle-25.84°\text{kA}$

(powerfactor = 0.9lagging)

$V_s(\text{phasevoltage})=AV_R+Bl_R$

$V_s=(0.936\angle0.98)\times(127\angle0)+(142\angle76.4)$

$\times(0.1458\angle-25.84)$

$=133.23\angle7.77\text{kV}$

line to line sending end votage

$=|V_s|_{l\text{-}l}=\sqrt{3}\times133.23\text{kV}$

$=230.78\text{kV}$

Q.7 **(d)**

For transmission line

Positive sequence impedance,

$X_1=X_s-X_m$

$=0.4-0.1$

$=0.3\Omega/km$

Zero sequence impedance,

$X_0=X_s+2X_m$

$=0.4+0.2$

$=0.6\Omega/\text{km}$

Q.8 **(b)**

L=length of line

If $L\le80\text{km}$

The line is short line

If $80\text{km}<L\le250\text{km}$

The line is medium line

If $L>250\text{km}$

The line is long line

Q.9 **(c)**

Sending end voltage $=V_s=240\text{kV}$

Full –load receiving end voltage $=(V_R)_{FL}=220\text{kV}$

$$V_{s(\text{perphase})}=\frac{240}{\sqrt{3}}\text{kV}$$

As we know,

$V_{s(\text{perphase})}=AV_{R(\text{perphase})}+Bl_R$

At no-load,

$l_R=0$

No-load receiving end voltage (per phase)

$=(V_R)_{NIL(\text{perphase})}$

$$=\frac{V_{s(\text{perphase})}}{A}$$

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$$=\frac{240}{\sqrt{3}\times 0.94}=\frac{255.32}{\sqrt{3}}\text{kV}$$

No - load receing ingend votage (lineto line)

$=\left(V_R\right)_{NL}=255.32\text{kV}$

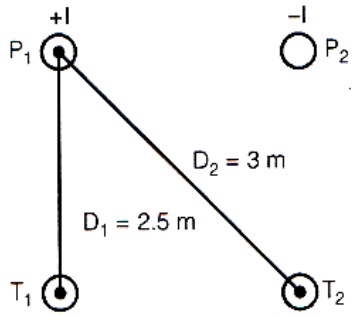
% voltage regulation

$$=\frac{\left(V_R\right)_{NL}-\left(V_R\right)_{FL}}{\left(V_R\right)_{FL}}\times 100$$

$$=\frac{255.32-220}{220}\times 100$$

$\approx 16\%$

Q.10 (c)



Where, P_1 and P_2 from power line and T_1 and T_2 form telephone line current in power circuit =I=100A

Mutual inductance between power line and telephone line

$$=M_{PT}=4\times 10^{-7}\ln\left(\frac{D_2}{D_1}\right)\text{H/m}$$

$$\Rightarrow M_{PT}=4\times 10^{-7}\ln\left(\frac{3}{2.5}\right)$$

$=0.73\times 10^{-7}\text{H/m}$

Voltage incuded in the telephone line

$=\left|V_T\right|=\omega M_{PT}|$

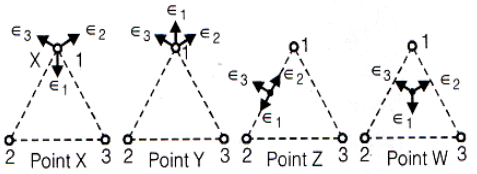
$=2\pi\times 50\times 0.73\times 10^{-7}\times 100$

$\Rightarrow\left|V_T\right|=2.29\times 10^{-3}\text{H/m}$

$=2.29\text{H/km}$

Q.11 (b)

Electric field intensity at various points are shown as follows.



It is clear from the above diagrams that minimum cancellation of vector occurs at the point Y. Hence maximum electric field intensity

Q.12 (c)

Reactance $=X\left(\text{inp.u}\right)=0.045\text{p.u.}$

Suspectance $=Y\left(\text{inp.u}\right)=1.2\text{p.u.}$

Let base impedance $=Z_B$

$X\left(\text{in}\Omega\right)=0.045Z_B$

$$Y\left(\text{in}J\right)=\frac{1.2}{Z_B}\text{J}$$

Assuming impedance of line = LH/km

$X=\omega lL$

Capacitance of line =CF/km

$Y=\omega lC$

Where l=length of the line

$$L=\frac{X}{\omega l}=\frac{0.045Z_B}{\omega l}\text{and}$$

$$C=\frac{Y}{\omega l}=\frac{1.2}{\omega l Z_B}$$

Velocity of propagation is given by

$$v_c=\frac{1}{\sqrt{LC}}$$

$$v_c=\frac{1}{\sqrt{\left(\frac{0.045Z_B}{\omega l}\right)\left(\frac{1.2}{\omega l Z_B}\right)}}$$

$$=\frac{\omega l}{\sqrt{0.45\times 1.2}}$$

$$3\times 10^5=\frac{2\times\pi\times 50l}{\sqrt{0.45\times 1.2}}$$

$\Rightarrow l\approx 222\text{km}$

Q.13 (d)

Wave length=λ, propagation constant =β

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$$\lambda=\frac{2\pi}{\beta}=\frac{2\pi}{0.00127}=4947.39\text{km}$$

$$\text{Ratio}=\frac{\text{line length}}{\text{wave length}}$$

$$=\frac{300\text{km}}{4947.39\text{km}}=0.0606$$

% ratio =6.06%

Q.14 (c)

Surge impedance loading =SIL=2280MW

Z_c = Surge impedance

Surge impedance loading $=\text{SIL}=\frac{V^2}{Z_c}$

as voltage is constant

$$\text{SIL}\propto\frac{1}{Z_c}$$

Suppose C_{sc} is the series capacitance per unit length for series compensation. Therefore, series reactance will be,

$$j\omega L-\frac{1}{j\omega C_{se}}=j\omega L\left(1-\frac{1}{\omega^2 LC_{se}}\right)$$

$$=j\omega L\left(1-\frac{X_{cse}}{X_L}\right)$$

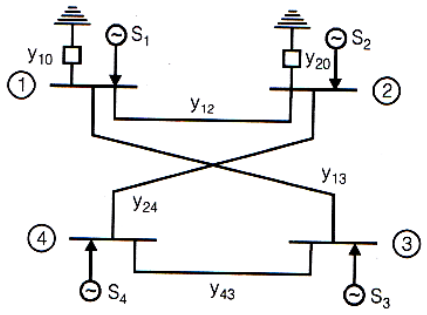
$$=j\omega L\left(1-\gamma_{se}\right)$$

Where γ_{se} is known as degree of series compensation

Therefore, $Z_{C_2}=\sqrt{\frac{j\omega L\left(1-\gamma_{se}\right)}{j\omega C}}$

$$\text{SIL}_2=\text{SIL}_1\times\frac{Z_{C_1}}{Z_{C_2}}=\frac{\text{SIL}_1}{\sqrt{1-\gamma_{se}}}$$

$$\text{SIL}_2=\frac{2280}{\sqrt{1-0.3}}=2725.12\text{MW}$$



Q.15 (c)

S=Complex power

S is defined as S=VI

$$I=\frac{S}{V}$$

If R is the resistance of transmission line

$$\text{Real power loss}=I^2R=\left(\frac{S}{V}\right)^2R$$

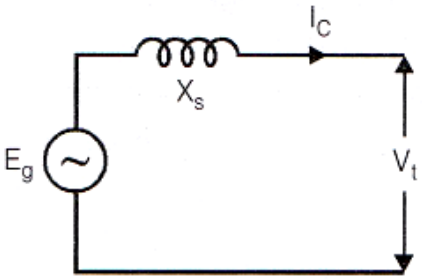
$$=\frac{S^2R}{V^2}$$

Since ,S an R are fixed

$$\text{Real power loss}\ \alpha\frac{1}{V^2}$$

Q.16 (a)

- As field voltage is held constant, so field current does not change.
- When the generator is connected with open–circuit transmission line, line draws charging current



Therefore V_t is higher than Eg i.e., $V_t>E_g$ But when the generator is disconnected from the line, no charging current is delivered by the generator i.e $I_C=0$., In this $V_t=E_g$ So, terminal voltage decreases.

Q.17 (b)

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Correct option is (B).

$$C = \frac{2\pi\varepsilon_0}{\text{In}\left(\frac{d_2}{d_1}\right)}$$

d_2 = distance b/w two sphere, d_1 = radius of first sphere.

$$= \frac{2 \times \pi \times 8.85 \times 10^{-12}}{\text{In}\left(\frac{600}{0.8}\right)}$$

$$C = 8.39 \times 10^{-12} \text{ F/m}$$

$$C = 8.39 \times 10^{-12} \times 10^{-3} F$$

$$C_{eq} \approx 8.4 \times 10^{-9} \text{F}$$

Q.18 For a transmission line to be distortionless, the required condition is

$$\frac{R}{L} = \frac{G}{C}$$

where G = shunt conductance (in siemens/meter)

C = capacitance (in Farad/meter)

R = Resistance (in ohm/meter)

L = inductance (in henries per meter)

So, for the given parameters of long transmission line, the required condition for distortionless transmission becomes

$$\frac{r}{l} = \frac{g}{C}$$

$$or \quad rc = \lg$$

Q.19 (b)

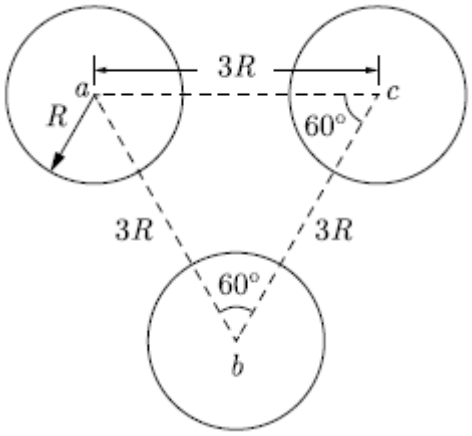
Correct option is (B).

A fully transposed transmission line is completely symmetrically and therefore the phase impedance offered by it is independent of phase sequence of a balanced set of current. In other word impedance offered by it to positive and negative sequence currents are equal.

Q.20 (187)

Q.21 (1.913)

We have to obtain the GMR of composite conductor. Given conductor arrangement is redrawn below.



From the figure, we have

$$GMR = \sqrt[3]{r_a \text{ x } r_{ab} x r_{ac}}$$

$$= \sqrt[3]{r' \text{ x } r_{ab} x r_{ac}}$$

$$= \sqrt[3]{7788 x R x 3R x 3R}$$

$$GMR = 1.913R$$

$$Hence, k = 1.913$$

Q.22 (294.59)

sol:

$$\cosh vL = A = \left.\frac{V_s}{V_R}\right|_{\text{no load}}$$

$$1 + \frac{YZ}{2} = \frac{400}{420}$$

$$1 + \frac{(j\omega c)(j\omega c)}{2} = \frac{400}{420}$$

$$1 - \frac{\omega^2 LC}{2} = \frac{400}{420}$$

$$\frac{20}{420} = \frac{\omega^2 LC}{2}$$

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$$\frac{1}{21}=\frac{\omega^2 l^2}{2U^2}$$

$$v^2=\frac{21}{2}\omega^2 l^2$$

$$v=\omega l\sqrt{\frac{21}{2}}$$

$$l=\frac{3\times10^8}{314\times\sqrt{\frac{21}{2}}}=294.847\ \text{Km}$$

Ans : 294.847

Q.23 (a)

$$P_{instantaneous}=R_e\{V_{an}I_b^{*}\}$$

$$=2200W$$

Q.24 (409)

$$Z_c=\sqrt{Z_{oc}.Z_{sc}}$$

$$=\sqrt{A/C.B/D}\ (A=DQ\ \textit{practical}\ \text{transmission line is symmetrical as well as reciprocal})$$

$$Z_c=\sqrt{\frac{B}{C}}$$

For nominal π model B=Z=100∠80°

$$C=Y\left[1+\frac{ZY}{4}\right]$$

$$Y/2=1/X$$

$$Y=\frac{2}{X}=\frac{1}{1650}mho$$

$$C=\frac{j}{1650}\left[1+\frac{100\angle180°}{4}\left[\frac{j}{1650}\right]\right]\ [Q\ Y=j\omega C]$$

$$Z_c^2=167498.715\angle10.153$$

$$Z_c=409ohm$$

Q.25 (0.289)

$$L/ph=2x10^{-7}\ln\left(\frac{GMD}{self\ GMD}\right)H/m$$

$$L/ph=2x10^{-7}\ln\left(\frac{1}{0.01}\right)H/m$$

$$L/ph=9.21034x10^{-7}$$

$$X_L=2\pi fL$$

$$=2\pi x50x9.21034x10^{-7}$$

$$X_L=0.289\Omega/km$$

Q.26 (C)

$$P=\sqrt{3}V_L.I_L\cos\phi$$

$$432=\sqrt{3}\ x208\ xI_L\ x0.6$$

$$I_L=1.9985\angle53.13°$$

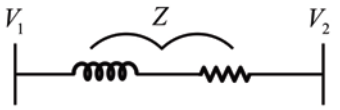
$$Z=\frac{V_{load(ph)}}{I_L}=\frac{208/\sqrt{3}}{1.9985\angle53.13°}$$

$$Z=60\angle-53.1°\Omega$$

Q.27 (b)

Given : A lossy transmission line

Case I : Power with impedance (Z)



$$P=\frac{V_1V_2}{|z|}\cos(\theta-\delta)-\frac{V_2^2}{|z|}\cos\theta$$

Where, θ = Impedance angle and

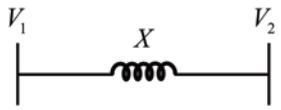
δ = Load angle

To get maximum power, δ = θ

Hence,

$$P_{max}=\frac{V_1V_2}{|z|}-\frac{V_2^2}{|z|}\cos\theta$$

Case II : Power with reactance,



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$$P' = \frac{V_1 V_2}{X} \sin\delta$$

To get maximum power, $\delta = 90^0$

Hence, $P'_{max} > P_{max}$

Hence, the maximum power with resistance is less than the maximum power without resistance.

$$P_r = \left\{ \frac{|V_s||V_r|}{|B|} \cos(\beta - \delta) - \frac{|A|}{|B|} |V_r|^2 \cos(\beta - \alpha) \right\} MW \rightarrow (1)$$

If Resistance of the transmission line = 0

$\beta = 90°$

$$P_r = \frac{|V_s||V_r|}{X} \sin\delta,$$

$$P_{rmax} = \frac{|V_s||V_r|}{X} \rightarrow (2)$$

(1) is always less than (2).

Hence, the correct option is (B).

Q.28 (7)

Sol. The positive sequence impedance

$$(Z_1) = Z_s - Z_m = 1 + j10$$

The zero second sequence impedance

$$(Z_0) = Z_s + 2Z_m = 4 + j31$$

From equation (i) and (ii),

$$Z_0 - Z_1 = 3Z_m = 3 + j21$$

$$Z_m = 1 + j7$$

Hence. imaginary part of Z_m is 7.

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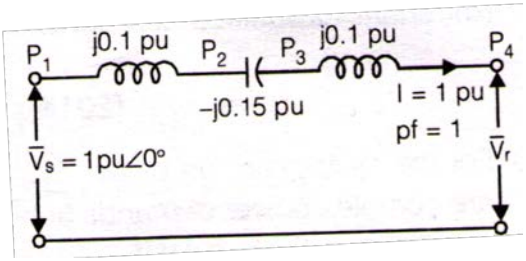
2 COMPENSATION TECHNIQUE & VOLTAGE PROFILE CONTROL

Q.1 A lossless radial transmission line with surge impedance loading
a) Taking negative VAR at sending end and zero VAR at receiving end
b) Takes positive VAR at sending end and zero VAR at receiving end.
c) Has flat voltage profile and unity power factor all points along it
d) Has sending end voltage higher than receiving end voltage and unity power factor at sending end.

[GATE-2001]

Q.2 Consider the model shown in figure of a transmission line with a series capacitor at its mid-point .The maximum voltage on the line is at the location



a) P_1 b) P_2
c) P_3 d) P_4

[GATE-2001]

Q.3 A 3-phase 11-kV generator feeds power to a constant power unity power factor load of 100MW through a 3- phase transmission lien .The line –to –line voltage at the terminals of the machine is maintained constant at 11kV. The per unit positive sequence impedance of the line based on 100MVA and 11kV .The power unit positive sequence impedance of the line based on 100MVA and 11kV is j 0.2 The line to line voltage at the load terminals is measured to be less than 1kV .The total reactive power to be injected at the terminals of the load to increase the line –to-line voltage at the load terminal to 11kV is
a) 100MVAR b) 10.1MVAR
c) -100MVAR d) -10.1MVAR

[GATE-2003]

Q.4 A balanced delta connected load of $(8+j6)\Omega$ per phase is connected to a 400V, 50Hz, 3-phase supply lines. If the input power factor is to be improved to 0.9 by connectiong a bank of star connected capacitors the required kVAR of the bank is
a) 42.7 b) 10.2
c) 28.8 d) 38.4

[GATE-2003]

Q.5 At an industrial sub-station with a 4 MW load, a capacitor of 2 MVAR is installed to maintain the load power factor at 0.97 lagging. if the capacitor goes out of service , the load power factor becomes
a) 0.85 b) 1.00
c) 0.80lag d) 0.90lag

[GATE-2005]

Q.6 A 400V, 50Hz, three phase balanced source supplies power to a star connected load whose rating is $12\sqrt{3}$KVA,0.8pf(lag). The rating (in KVAR) of the delta connected (capacitive) reactive power bank necessary to bring the pf to unity is
a) 28.78 b) 21.60
c) 16.60 d) 12.47

[GATE-2006]

Q.7 The figure below shows a three phase self commutated voltage

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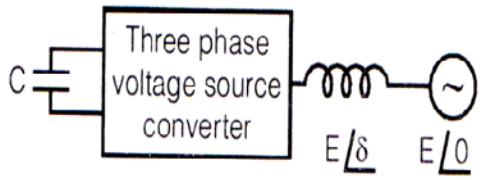
source converter connected to a power system. The converter's dc bus capacitor is marked as c in the figure. The circuit in initially operating in steady state with $\delta = 0$ and the capacitor dc voltage is equal to V_{dc0} You may neglect all losses and harmonics. What action should be taken to increase the capacitor dc voltage slowly to a new steady state value?



a) Make δ positive and maintain it at a positive value
b) Make δ positive and return it to its original
c) Make δ negative and maintain it at a negative value
d) Make δ negative and return it to its original value

[GATE-2007]

Q.8 A 230 V (Phase), 50Hz three, -phase 4-wire, system has a sequence ABC A unity power factor load of 4 kW is connected between phase A and neutral N. it is desired to achieve zero neutral current through the use of a pure inductor and impure capacitor in the other two phases. The Value of inductor and capacitor is

a) 72.95 mH in phase C and139.02μF in phase B
b) 72.95 mH in phase B and139.02μF in phase C
c) 42.12 mH in phase C and 240.79 μF in phase B
d) 42.12 mH in phase B 240.79 μF in phase C

[GATE-2007]

Q.9 Match the items in List-I (To with the items in List-II (Use) and select the correct answer using the codes given below the lists.

List-I
A. improve power factor
B. reduce the current ripples
C. increase the power flow in line
D. reduce the Ferranti effect

List –II
1.shunt reactor
2.shunt capacitor
3.series capacitor
4.series reactor

	A	B	C	D
a)	2	3	4	1
b)	2	4	3	1
c)	4	3	1	2
d)	4	1	3	2

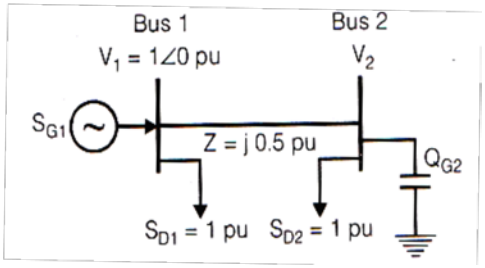
[GATE-2009]

Q.10 For enhancing the power transmission in a long EHV transmission line, the most preferred method is to connect a

a) series inductive compensator in the line
b) shunt inductive compensator at the receiving end
c) Series capacitive compensator in the line
d) shunt capacitive compensator at the sending end

[GATE-2011]

Q.11 For the system shown below S_{D1} and S_{D2} are complex power demands at bus 1 and bus 2 respectively. If $|V_2|$=1pu, the VAR rating of the capacitor (Q_{G2}) connected at bus 2 is



a) 0.2pu
b) 0.268pu
c) 0.312pu
d) 0.4pu

[GATE-2012]

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Q.12 Shunt reactors are sometimes used in high voltage transmission systems to
(A) limit the short circuit current through the line
(B) compensate for the series reactance of the line under heavily loaded condition
(C) limit over-voltages at the load side under lightly loaded condition.
(D) compensate for the voltage drop in the line under heavily loaded condition.

[GATE-2014]

Q.13 The complex power consumed by a constant-voltage load is given by $\left(P_1 + jQ_1\right)$, where,

$1\text{ kW} \le P_1 \le 1.5\text{ kW}$ and

$0.5\text{ kVAR} \le Q_1 \le \text{kVAR}$

A compensating shunt capacitor is chosen such that $|Q| \le 0.25\text{ kVAR}$, where Q is the net reactive power consumed by the capacitor load combination. The reactive power (in kVAR) supplied by the capacitor is ___.

[GATE-2014]

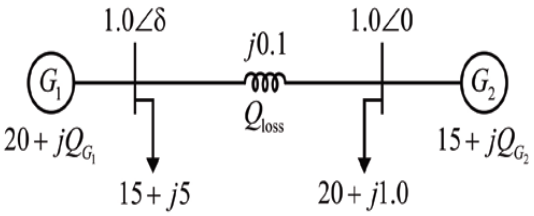
Q.14 The inductance and capacitance of a 400kV, three-phases 50HZ lossless transmission line are 1.6mH/km/phase and 10nF/km/phase respectively. The sending end voltage is maintained at 400kV. To maintain a voltage of 400kV at the receiving end, when the line is delivering 300MW load, the shunt compensation required is
(A) Capacitive (B) Inductive
(C) Resistive (D) Zero

[GATE-2016]

Q.15 A load is supplied by a 230 V, 50 Hz source. The active power P and the reactive power Q consumed by the load are such that 1 kW ≤ P ≤ 2 kW and 1kVAR ≤ Q ≤2kVAR. A capacitor connected across the load for power factor correction generates 1 kVAR reactive power. Theworst case power factor after power factor correction is
(A) 0.447 lag
(B) 0.707 lag
(C) 0.894 lag
(D) 1

[GATE-2017]

Q.16 Consider the two bus power system network with given loads as shown in the figure. All the values shown in the figure are in per unit. The reactive power supplied by generator G_1 and G_2 are Q_{G1} and Q_{G2} respectively. The per unit values of Q_{G1}, Q_{G2} and line reactive power loss (Q_{loss}) respectively ares



(A) 5.00, 12.68, 2.68
(B)6.34, 10.00, 1.34
(C) 6.34, 11.34, 2.68
(D) 5.00, 11.34, 1.34

[GATE-2018]

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EXPLANATIONS

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
(c)	(c)	(b)	(c)	(d)	(d)	(d)	(b)	(b)	(c)	(c)	(c)	0.75	(b)	(b)	(c)

Q.1 **(c)**

Q.2 **(c)**

V_{p_2} =pu-1pu×j0.1pu

V_{p_3} =pu+1pu×j0.05pu

V_{p_4} =1pu-1pu×j0.05pu

$\Rightarrow P_3$ is maximum

Q.3 **(b)**

$|V_s|=|V_R|=11kV$

p.u impedance of the line = j0.2p.u.

Impedance of the line = p.u. impedance × base impedance

$$x = j\,0.2\times\frac{11^2}{100} = j\,0.242\Omega$$

Active power at receiving end $=P_R$

$= 100MW$

$$P_R=\frac{|V_s||V_R|}{x}\sin\delta \Rightarrow 100=\frac{11\times11}{0.242}\sin\delta$$

Reactive power at receiving end

$$Q_R=\frac{|V_s||V_R|}{x}\cos\delta-\frac{|V_R|^2}{x}$$

$$=\frac{11\times11}{0.242}\cos11.54-\frac{11^2}{0.242}$$

$= -10.1$ MVAR

Since power factor = 1

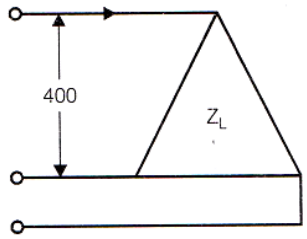
Load reactive power should be zero

Therefore, reactive power to be injected at terminals $=-Q_R$

$=-(-10.1)=10.1MVAR$

Q.4 **(b)**

- When load is connected to $3-\Phi$ supply



Load impedance $=Z_L=8+j6\Omega$

As, load is delta connected phase to neutral voltage (V_p)

=Line to line volatge$(V_{l\text{-}l})$

$V_p=V_{l\text{-}l}=400\angle0°V$

Phase current $= I_p$

$$=\frac{V_p}{Z_L}=\frac{400\angle0°}{8+j6}$$

$$=40\angle0-36.87°A$$

Load complex power

$=S_L=3V_pI_p^*-3\times400\angle0°\times(40\angle36.87)^*$

$S_L=38.4+j28.8kVA$

$P_L+jQ_L=38.4+j28.8$

$\Rightarrow P_L=38.4kW$

And $Q_L=28.8kVAR$

- When capacitors banks are connected, power factor changes to 0.9 Assuming required kVAR of the bank $=Q_{cap}$

$\cos\theta = 0.9$

$\Rightarrow \theta = 25.842°$

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$$\tan\theta=\frac{Q}{P_L}=\frac{Q_L-Q_{cap}}{P_L}$$

$$\tan 25.842°=\frac{28.8-Q_{cap}}{38.4}$$

$$Q_{cap}\approx 10.2\text{kVAR}$$

Q.5 (c)

Active power demand of the load $=P_L=4\text{MW}$

Let reactive power demand of the load $=Q_L$

Reactive power supplied by the capacitor $=Q_C=2\text{MVAR}$ initial load power factor

$=\cos\theta_1=0.97$

$\theta_1=\cos^{-1}(0.97)=14.07°$

$$\tan\theta_1=\frac{Q_L-Q_C}{P_L}$$

$$0.25=\frac{Q_L-2}{4}$$

$\Rightarrow Q_L=3$

When the capacitor goes out of service

$$\tan\theta_2=\frac{Q_L}{P_L}=\frac{3}{4}=0.75$$

$\theta_2=36.87°$

$\cos\theta_2=0.8\text{lag}$

Q.6 (d)

Rating of the load $12\sqrt{3}\text{KVA},0.8\text{pf(lag)}$ at 0.8 pf lag

Active power demand of the load $=P_L$

$12\sqrt{3}\times 0.8=16.63\text{kW}$

$\cos\theta=0.8$

$\Rightarrow \sin\theta=0.6$

Reactive power demand of the load $=Q_L$

$=12\sqrt{3}\sin\theta$

$=12\sqrt{3}\times 0.6$

$\Rightarrow Q_L=12.47\text{kVAR}$

For unity pf, the total reactive power is zero Assuming kVAR rating of capacitor bank $=Q_c$

$Q_L+Q_C=0$

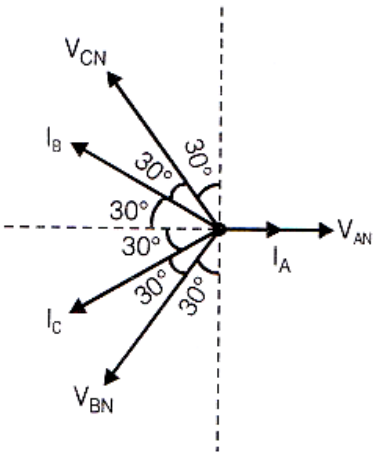
$Q_C=-Q_L=-12.47$ kVAR

So, capacitor banks supplies 12.47 kVAR reactive power of the load.

Q.7 (d)

- To increase the capacitor dc voltage, energy has to be supplied by the generator to capacitor through converter .
- Power flow from higher angle to lower angle. As angle of induced emf of generator is 0. So δ should be made negative to make the power flow in required direction.

Q.8 (b)



Taking V_{AN} as the reference

$V_{AN}=230\angle 0°\text{V}$

$V_{BN}=230\angle -120°\text{V}$

$V_{CN}=230\angle 120°\text{V}$

$$I_A=\frac{p}{V_{AN}\cos\Phi}$$

$$=\frac{4\times 10^3}{230\times 1}$$

$=17.4\angle 0°$

- If an pure inductor is present in phase B, then I_B lags V_{BN} by 90°

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- If a pure capacitor is present in phase C, then I_C leads V_{CN} by 90°

  If current through natural is to be zero $I_B \sin 30° = I_C \sin 30°$

  $I_A = I_B \cos 30° + I_C \cos 30°$

  $= 2I \cos 30° = \sqrt{3}\, I$

  $|I_B| = |I_C| = |I| = \frac{|I_A|}{\sqrt{3}}$

  $= \frac{17.04}{\sqrt{3}} = 10.05 A$

Q.9 (b)

- Shunt capacitor are used to provide part of the reactive VAR's required by the load to keep the voltage within desirable limits and to improve factor.
- Series reactor reduces current ripple.
- Shunt reactor are used across capacitive loads or lightly loaded lines to absorb some of the leading VARs to control the voltage across the load to within certain desirable limit.
- Series capacitor compensation reduces the series impedance of the line. Power flow in line $\propto \frac{1}{X_L}$, power flow in line increases, as X_L decreases.

Q.10 (c)

Series capacitance compensation reduces reactance of the line. Power flow in line

$$\alpha \frac{1}{\text{reactance of the line}}$$

As reactance of line decreases, power flow in the line C_a increases

Q.11 (c)

Q.12 (C)

Correct option is (C).
Shunt reactors are used in high voltage transmission system to limit over voltages at the load side under lightly loaded condition.

Q.13 (0.75kVAR)

Correct answer is 0.75kVAR.
Given the constant voltage load,

$$P_1 + jQ_1$$

where $1 \text{ kW} < P1 < 1.5 \text{ kW}$

and $0.5 \text{ kVAR} \le Q1 \le 1 \text{ kVAR}$

Now, the shunt capacitor is chosen such that reactive power across capacitor load
is

$|Q| \le 0.25 \text{ kVAR}$

Since, we have $Q1 = 1$ kVAR,
therefore, capacitor will supply
$Q_C = .75$ kVAR
i.e. capacitor must supply .75 kVAR.

Q.14 (b)

Given
C = 10nF/Km/Ph
L = 1.6mH/Km/Ph

$\therefore$ Surge impedenace $\left(Z_s\right) = \sqrt{\frac{L}{C}}$

$= \sqrt{\frac{1.6 \times 10^{-3}}{10 \times 10^{-9}}} = 400\ \Omega$

Load impedance $\left(Z_L\right) = \frac{\left(400 \times 10^3\right)}{300 \times 10^6}$

$= 533.33\ \Omega$

As load impedance is more than surge impedance, the receiving end voltage will
rise more than sending end voltage.

$\therefore V_R\ V_s \Rightarrow V_R > 400\,KV$

$\therefore$ We need an inductive compensation to
reduce the voltage to 400KV.

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Q.15 (b)

$$\cos\phi = \frac{P}{\sqrt{P^2+Q^2}} \text{ lag (Before correction)}$$

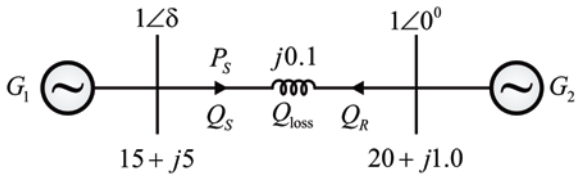
Least power factor is experienced
With P = 1 kW and Q = 2 KVAR

$$\cos\phi = \frac{1}{\sqrt{1+4}} = 0.4472 lag$$

With capacitor

$$\cos\phi(new) = \frac{1}{\sqrt{1+1}} = 0.707 lag$$

Q.16 (c)



At G_2 load demand is 20 pu, G_2 supplies only 15. Remaining supplied by G_1 through transmission line.

$$P_s \left|\frac{V_s V_R}{X_L}\right| \sin\delta$$

$$5 = \frac{1\times 1}{0.1}\sin\delta$$

$$\delta = 30^0$$

$$Q_s = \frac{V_s^2}{X_L} - \frac{V_s V_R}{X_L}\cos\delta$$

$$Q_s = \frac{1^2}{0.1} - \frac{1\times 1}{0.1}\cos 30^0 = 1.34 \text{ p.u.}$$

$$Q_R = \left|\frac{V_s V_R}{X_L}\right| \cos\delta - \left|\frac{V_R^2}{X_L}\right|$$

$$Q_R = \left|\frac{1\times 1}{0.1}\right| \cos 30^0 - \frac{1^2}{0.1} = -1.34 \text{ p.u.}$$

$$Q_{loss} = 1.34 - (-1.34) = 2.68 \text{ p.u.}$$

At G_1 : $Q_{G1} = Q_{load} + Q_s$

$$Q_{G1} = 5 + 1.34 = 6.34 \text{ p.u.}$$

At G_2 : $Q_{G2} = Q_{load}(-Q_R)$

$$Q_{G2} = 10 - (-1.34) = 11.34 \text{ p.u.}$$

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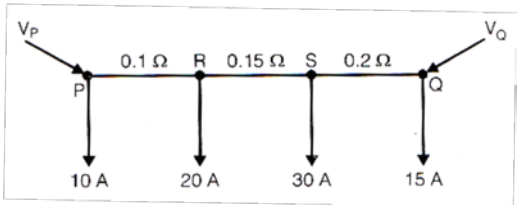
3 DISTRIBUTION SYSTEMS, CABLES & INSULATORS

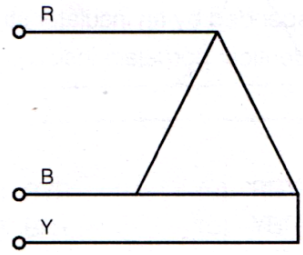
Q.1 A dc distribution system is shown in figure with load currents as marked. The two ends of the feeder are fed by voltage sources such that $V_p \sim V_Q = 3V$ .The value of the voltage V_p for a minimum voltage of 220V at any point along the feeder is



a) 225.89V b) 222.89V
c) 220.0V d) 228.58V
[GATE-2003]

Q.2 The rated voltage of a 3- phase power system is given as
a) rms phase voltage
b) peak phase voltage
c) rms line to line voltage
d) peak line to line voltage
[GATE-2004]

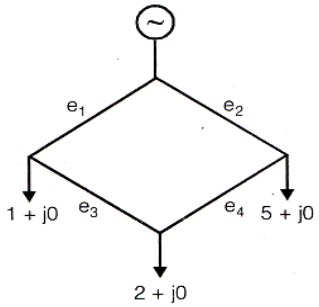
Q.3 The phase sequence of the 3-phase system shown in figurer is



a)RYB b)RBY
c)BRY d)YBR
[GATE-2004]

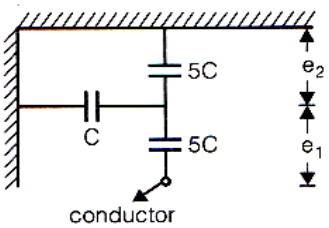
Q.4 A 110kV, single core coaxial, XLPE insulated power cable delivering power at 50 Hz , has a capacitance of 125nF/km. if the dielectric loss tangent of XLPE is 2×10^{-4} then dielectric power loss in this cable in W/km is
a) 5.0 b) 31.7
c) 37.8 d) 189.0
[GATE-2004]

Q.5 Single line diagram of a 4- bus single source distribution system is shown below. Branches e_1, e_2, e_3 and e_4 have equal impedances. The load current values indicated in the figure are in per unit.



Distribution Company's policy requires radial system operation with minimum loss. This can be achieved by opening of the branch
a)e_1 b) e_2
c)e_3 d)e_4
[GATE-2008]

Q.6 Consider a three –phase, 50Hz, 11kV distribution system. Each of the conductors is suspended by an insulator string having two identical porcelain insulators. The self capacitance of the insulators is 5 times the shunt capacitance between the link and the ground, as shown in the figures. The voltage across the two insulators are



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a) e_1=3.74kV,e_2=2.61kV

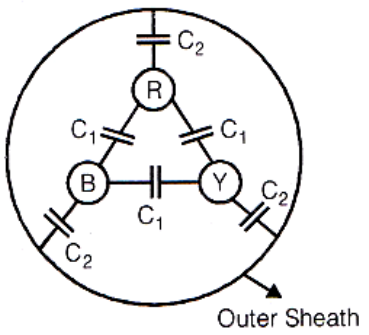
b) e_1=3.46kV,e_2=2.89kV

c) e_1=6.0kV,e_2=4.23kV

d) e_1=5.5kV,e_2=5.5kV

[GATE-2010]

Q.7 Consider a three- core, three-phase, 50Hz, 11kV cable whose conductors are denoted as R, Y and B in the figure. The inter-phase capacitance (C_1) between each pair of conductors is 0.2μF and the capacitance between each line conductor and the sheath is 0.4μF .The per-phase charging current is



a) 2.0A b) 2.4A

c) 2.7A d) 3.5A

[GATE-2010]

Q.8 The undesirable property of an electrical insulating material is

(A) high dielectric strength

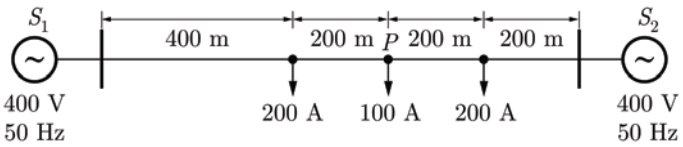
(B) high relative permittivity

(C) high thermal conductivity

(D) high insulation resistivity

[GATE-2014]

Q.9 A distribution feeder of 1 km length having resistance, but negligible reactance, is fed from both the ends by 400 V, 50 Hz balanced sources. Both voltage sources S_1 and S_2 are in phase. The feeder supplies concentrated loads of unity power factor as shown in the figure.



The contributions of S_1 and S_2 in 100 A current supplied at location P respectively,are

(A) 75 A and 25 A

(B) 50 A and 50 A

(C) 25 A and 75 A

(D) 0 A and 100 A

[GATE-2014]

Q.10 A three-phase cable is supplying 800 kW and 600 kVAr to an inductive load. It is intended to supply an additional resistive load of 100 kW through the same cable without increasing the heat dissipation in the cable, by providing a three-phase bank of capacitors connected in star across the load. Given the line voltage is 3.3 kV, 50 Hz, the capacitance per phase of the bank, expressed in microfarads, is _____.

[GATE-2016]

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10
(a)	(c)	(b)	(b)	(d)	(b)	(a)	(b)	(d)	48.23

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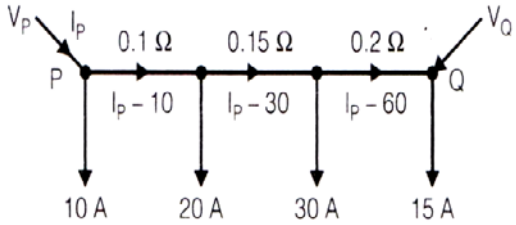
EXPLANATIONS

Q.1 (a)

Let current injected at point $P=l_p$



$$V_p - V_Q = 0.1(l_p - 10)$$
$$+0.15(l_p - 30) + 0.2(l_p - 60)$$
$$\Rightarrow 3 = 0.45 l_p - 17.5$$
$$\Rightarrow l_p = 45.55\text{A}$$

Direction of current will be in opposite section SQ. So, point will have minimum voltage $V_s = 220\text{V}$

$$V_p = V_S + 0.1(l_p - 10) + 0.15(l_p - 30)$$
$$= 220 + 01 \times (45.55 - 10)$$
$$+0.15(45.55 - 30)$$
$$\approx 225.89\text{V}$$

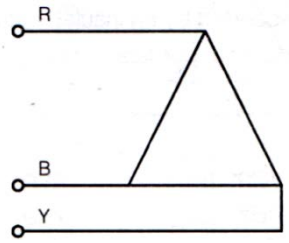
Q.2 (c)

Note:

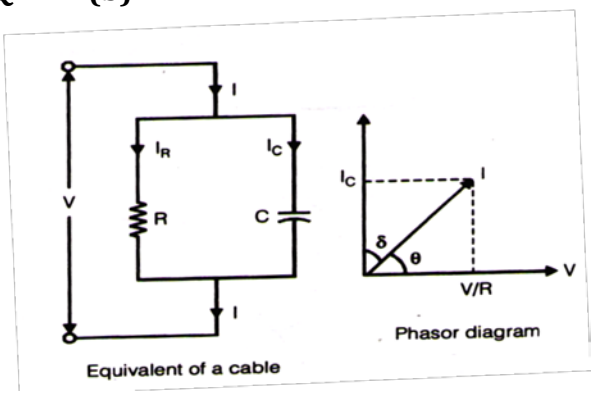
- Generators are specified in $3-\Phi$ MVA, line to line voltage and per- phase reactance (equivalent star.)
- Transformer are specified in $3-\Phi$ MVA, line to line transformation ratio and per phase (equivalent star) impedance on one side
  Load is specified in $3-\Phi$ MW, line to lie voltage and power factor.

Q.3 (b)

- The phase sequence of the given figure is RBY.
- RYB, BRY and YBR represent the same phase sequence of the figure(given below).



Q.4 (b)



$$V(\text{Phasevoltage}) = \frac{110}{\sqrt{3}}\text{kV}$$

$C = 125\text{nF/km}$

$\tan\delta = 2\times10^{-4}$

Dielectric power is in cable

$= P = V^2\omega C\tan\delta$

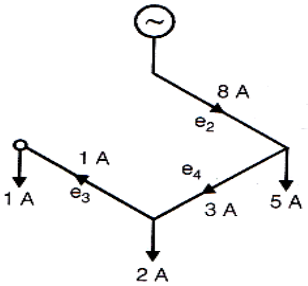
$$P = \left(\frac{110\times10^3}{\sqrt{43}}\right)^2 \times 2\times\pi\times50\times125\times10^{-9}\times2\times10^{-4}$$

$$\approx 31.7\text{W/km}$$

Q.5 (d)

Assuming impedance of each branch

R (i) if e_1 is opened



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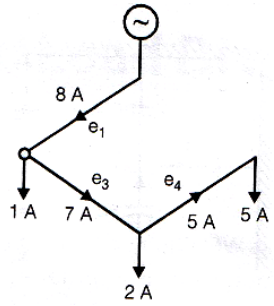
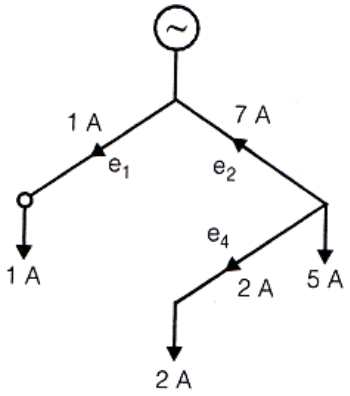
Total losses $=8^2R+3^2R+l^2$

$R=74R$ (ii) if e_2 is opened

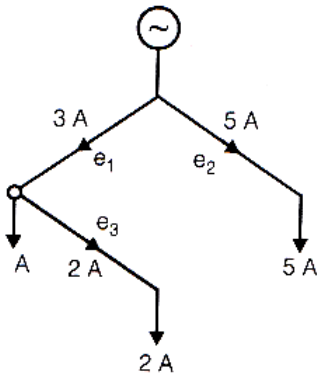


Total losses $=8^2R+7^2R+5^2R=138R$ (iii) if e_3 is opened



Total losses

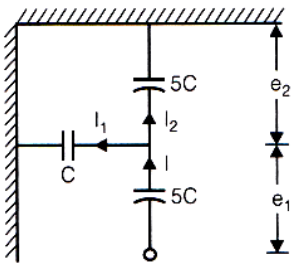
$=1^2R+7^2R+2^2R=54R$ (iv) if e_4 is opened



Total losses $=5^2R+3^2R+l^2R=38R$

Operation with minimum loss can be achieved by opening line e_4 .

Q.6 (b)



Line to line voltage $=V_{l\text{-}l}=11kV$

V_p = Phase to ground voltage

$$=\frac{V_{l\text{-}l}}{\sqrt{3}}$$

$$\Rightarrow V_p=\frac{11}{\sqrt{3}}kV$$

$$e_1+e_2=\frac{11}{\sqrt{3}}kV=6.35kV \quad ...(i)$$

$l=l_1+l_2$

$(j\omega 5C)\times e_1=(j\omega C)\times e_2+(j\omega 5C)\times C_2$

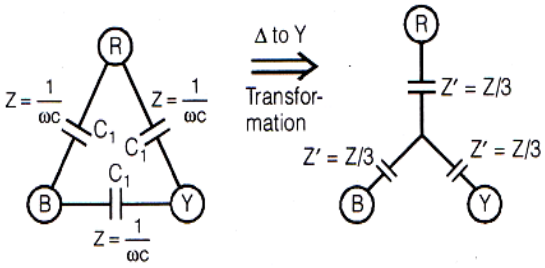
$5e_1=6e_2$ .....(ii)

Solving equation (i) and (ii) ,we get

$e_1=3.46kV$

And $e_2=2.89kV$

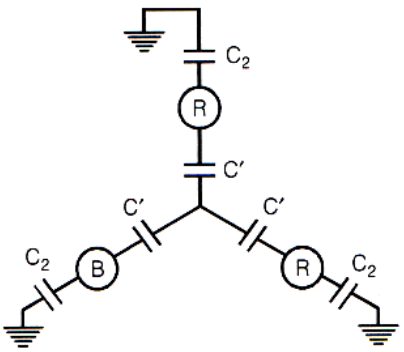
Q.7 (a)



$Z^{'}=Z/3$

$$\Rightarrow \frac{1}{\omega C^{'}}=\frac{1}{3\omega C}$$

$C'=3C$



Equivalent capacitance (C_{eq}) between a phase and ground

$C_{eq}=C^{'}+C_2=3C_1+C_2$

$C_{eq}=3\times 0.2+0.4=1\mu F$

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Per phase voltage $= V_p = \frac{11}{\sqrt{3}} kV$

Per phase charging current =l

$= j\omega C_{eq} V_p$

$|l_C| = \omega C_{eq} V_p$

$= 2\pi \times 50 \times 1 \times 10^{-6} \times \frac{11}{\sqrt{3}} \times 10^3$

$\approx 2A$

Q.8 (b)

Correct option is (B).

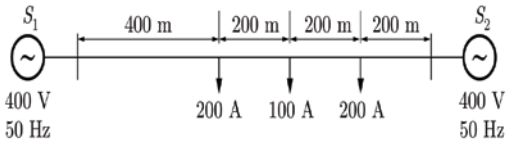
Undesirable property of electrical insulating material is its high relative

Permittivity.

Q.9 (d)

Correct option is (D).

We have the distribution feeder as



Let current *I* be supplied by source (s_1), and *r* be the resistance per unit length.

Applying KVL, we get

So, we redraw the current in distribution system as

$\{400 - (r \times 400)\ I - (200r)(I - 200)$

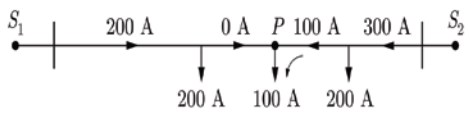
$-(200r)(I - 300) - (200r)(I - 500)\}$

= 400

or $400Ir + 200Ir - 40000r + 200Ir$

$- 60000r + 200Ir - 100000r = 0$

So, we redraw the current in distribution system as



Thus, the contribution of source (s_1) in 100 A load at *P* is 0 A, and the contribution

of s_2 in 100 A load at *P* is 100 A.

Q.10 (48.23)

P = 800 kW Q = 600KVAR

V_L = 3.3 kV

For the given load,

$\tan\theta = \frac{Q}{P} = 0.75$

$\Rightarrow \cos\phi = 0.8 lag$

Now, current flowing through cable is

$P = \sqrt{3} V_L I_L \cos\phi$

$I_L = \frac{800 \times 10^3}{\sqrt{3} \times 3.3 \times 10^3 \times 0.8} = 174.95\ A$

Now, new load of 100 kW is added if the

heating in cable should be same as before,

the current should not alter I_L = 174.95A,

But P = 900 kW

$P = \sqrt{3} V_L I_L \cos\phi = 900 \times 10^3$

$\cos\phi = \frac{900 \times 10^3}{\sqrt{3} \times 3.3 \times 10^3 \times 174.95} = 0.90$

The new Pf requirement is 0.9 lag

$\Rightarrow \sin\phi = 0.435$

The new reactive power from supply should be

$Q_3 = \sqrt{3} \times 3.3 \times 10^3 \times 174.95 \times 0.435$

= 434.98 kVAR

But load requires 600 kVAR

So, the capacitor bank must supply

Q_C = 600 – 434.98 = 165 kVAR

Each phase $\frac{165}{3} = 55 kVAR$

$\frac{Vph^2}{X_c} = 55 kVAR \Rightarrow VAR \Rightarrow X_C = 65.99$

$\Rightarrow C = 48.23 \mu F$

Ans : 48.23

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4 ECONOMIC POWER GENERATION & LOAD DISPATCH

Q.1 A power system has two generators with the following cost curves

Generator

1: $C_1(P_{G1}) = 0.006P_{G1}^2 + 8P_{G1} + 350$

Thousnd ruypees/Hours

Generator

2: $C_2(P_{G1}) = 0.006P_{G1}^2 + 7P_{G2} + 400$

Thousnd ruypees/Hours

the generator limits are

$100MW \le P_{G1} \le 650MW$

$50MW \le P_{G2} \le 500MW$

A load demand of 600 MW is supplied by the generators in an optimal manner neglecting losses in the transmission network, determine the optimal generation of each generators.

[GATE-2001]

Q.2 Consider a power system with three identical generators. The transmission losses are negligible. On generator (G1) has a speed over nor which maintains its speed constant at threaded value , while the other generator (G2 and g3) have governors with a drop of 55 .If the load of the system is increased. Then in steady state

a) Generation of G2 and G3 is increased equally while generation of G1 is unchanged.
b) Generation of G1 alone is increased while generation of G2 and G3 is unchanged
c) Generation of G1 ,G2 andG3 is increased equally .
d) Generation of G1, G2, and G3 is increased in the ratio 0.5:0.25:0.25

[GATE-2002]

Q.3 Incremental fuel costs (in some appropriate unit) for a power plant consisting of three generating units are

$lC_1 = 20 + 0.3P_1, lC_2 = 30 + 0.4P_2, lC_3 = 30$

Where P_1 is the power in MWE generated by unit I, for i=1, 2 and 3. Assume that all the three units are operating al the time. Minimum and maximum loads on each unit are 50 MW and 300 MW respectively. If the plant is operating on economic load dispatch to supply the total power dead of 700MW, the power generated by each unit is

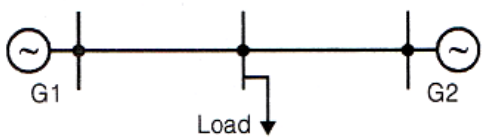
a) $P_1 = 242.86MW; P_2 = 157.14MW; and P_3 = 300MW$
b) $P_1 = 157.14MW; P_2 = 242.86MW; and P_3 = 300MW$
c) $P_1 = 300.0MW; P_2 = 300.0MW; and P_3 = 100MW$
d) $P_1 = 233.3MW; P_2 = 233.3MW; and P_3 = 233.4MW$

[GATE-2003]

Q.4 A load center is at an equidistant from the two thermal generating stations G_1 and G_2 as shown in the figure . The fuel cost characteristics of the generating station are given by

$F_1 = a + bP_1 + cP_1^2 Rs/hour$

$F_2 = a + bP_2 + 2cP_2^2 Rs/hour$



Where P_1 and P_2 are the generation in MW of G_1 and G_2 respectively .For most economic generation to meet 300MW of load , P_1 and P_2 respectively For most economic

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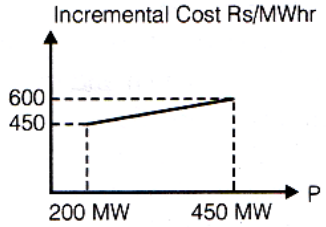
generation to meet 300MW of load , P_1 and P_2 respectively are

a)150,150 b)100,200

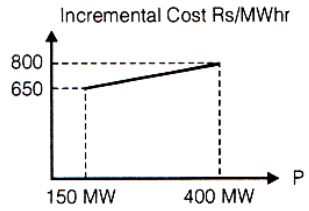
c)200,100 d)175,125

[GATE-2005]

Q.5 The incremental cost curves in Rs/ MWhr for two generators supplying a common load of 700MW are shown in the figures. The maximum and minimum generation limits are also indicated. The optimum generation schedule is:



GENERATOR A



GENERATOR B

a) Generator A: 400MW Generator B:300MW
b) Generator A: 350MW Generator B: 350MW
c) Generator A: 450MW Generator B: 250MW
d) Generator A: 425MW Generator B: 275MW

[GATE-2007]

Q.6 A lossless power system has to serve a load of 250 MW. Three are two generators (G1 and G2) in the system with cost curve C_1 and C_2 respectively defined a follows:

$C_1(P_{G1}) = P_{G1} + 0.055 \times P_{G1}^2$

$C_2(P_{G2}) = 3P_{G2} + 0.03 \times P_{G2}^2$

Where P_{G1} and P_{G2} are the MW injections from generators G1 and g2 respectively. Thus , the minimum cost dispatch will be

a) $P_{G1} = 250MW; P_{G2} = 0MW$
b) $P_{G1} = 150MW; P_{G2} = 100MW$
c) $P_{G1} = 100MW; P_{G2} = 150MW$
d) $P_{G1} = 0MW; P_{G2} = 250MW$

[GATE-2008]

Q.7 Three generators are feeding a load of 100MW. The details of the generators are

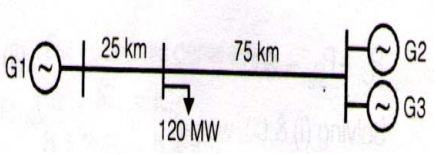
	Rating (MW)	Efficiency (%)	Regulation (p.u) on 100MVA base
Generator-1	100	20	0.02
Generator-2	100	30	0.04
Generator-3	100	40	0.03

In the event of increased load power demand, which of the following will happen?

a) All the generators wil share equal power.
b) Generator -3 will share more power compared to Generator-1
c) Generator -1 will share more power compared to Generator -2
d) Generator -2 will share more power compared to Generator -3

[GATE-2009]

Q.8 A load center of 102 MW derives power from two power stations connected by 220kV transmission lines of 25km and 75km as shown in the figure below. The three generators G1, G2 and G3 are of 100MW capacity each and have identical fuel cost characteristics .The minimum loss generation schedule for supplying the 120 MW load is



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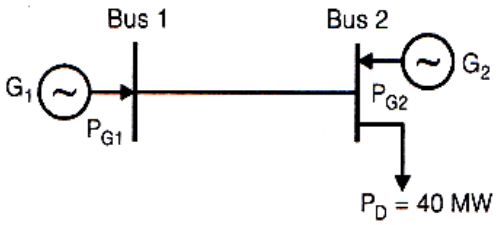
a) P1=80 MW+ losses
P2=20MW
P3=20MW
b) P1=60 MW
P2=30MW+losses
P3=30MW
c) P1=40 MW
P2=40MW
P3=40MW+losses
d) P1=30 MW+ losses
P2=45MW
P3=45MW

[GATE-2011]

Q.9 The figure shows a two –generator system supplying a load of $P_D = 40MW$ connected at bus 2.



The fuel cost of generators G_1 and G_2 are:

$C_1(P_{G1})$=10,000Rs/MWh and

$C_2(P_{G2})$=12,500Rs/MWh

And the loss is $P_{loss(pu)} = 0.5P_{G1(pu)}^2$ where the loss coefficient is specified in pu on a 100MVA base. The most economic power generation schedule in MW is

a) $P_{G1}=20, P_{G2}=22$ b) $P_{G1}=22, P_{G2}=20$

c) $P_{G1}=20, P_{G2}=20$ d) $P_{G1}=0, P_{G2}=40$

[GATE-2012]

Q.10 The fuel cost functions of two power plants are

$$\text{Plant } P_1 : C_1 = 0.05P_{g1}^2 \; AP_{g1} + B$$

$$\text{Plant } P_2 : C_2 = 0.10P_{g2}^2 \; 3AP_{g2} + 2B$$

where, P_{g1} and P_{g2} are the generated powers of two plants, and A and B are the constants. If the two plants optimally share 1000 MW load at incremental fuel cost of100Rs/MWh , the ratio of load shared by plants P_1 and P_2 is

(a) 1 : 4 (b) 2 : 3
(c) 3 : 2 (d) 4 : 1

[GATE-2014]

Q.11 Consider the economic dispatch problem for a power plant having two generatingunits. The fuel costs in Rs/MWh along with the generation limits for the two units are given below:

$C_1(P_1) = 0.01P_1^2 + 30P_1 + 10$;
$100 MW < P_1 < 150 MW$
$C_2(P_2) = 0.05P_2^2 + 10P_2 + 10$;
$100 MW < P_2 < 180 MW$

The incremental cost (in Rs/MWh) of the power plant when it supplies 200 MW is _____

[GATE-2015]

Q.12 The incremental costs (in Rupees/MWh) of operating two generating units are functions of their respective powers P_1 and P_2 in MW, and are given by

$$\frac{dC_1}{dP_1} = 0.02P_1 + 50; \frac{dC_2}{dP_2} = 0.24P_2 + 40$$

Where,

$20MW \le P_1 \le 150MW$ and

$20MW \le P_2 \le 150MW$

For a certain load demand, P1 and P2 have been chosen such that

$$\frac{dC_1}{dP_1} = 76Rs/MWh; \frac{dC_2}{dP_2} = 68.8Rs/MWh$$

If the generations are rescheduled to minimize the total cost, that P2 is___

[GATE-2015]

Q.13 Two generating units rated 300 MW and 400 MW have governor speed regulation of 6% and 4% respectively from no load to full load, Both the generating units are operating in parallel to share a load of 600 MW . Assuming free governor action, the load shared by the larger unit is ____ MW.

[GATE-2017]

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ANSWER KEY

1	2	3	4	5	6	7	8	9	10	11	12	13
*	(b)	(a)	(c)	(c)	(c)	(c)	(a)	(a)	(d)	*	136.6	400

EXPLANATIONS

Q.1

$$\frac{dC_1}{dP_{G1}} = 0.012P_{G1} + 8$$

$$\frac{dC_2}{dP_{G2}} = 0.012P_{G2} + 7$$

For economic generation,

$$\frac{dC_1}{dP_{G1}} = \frac{dC_2}{dP_{G2}}$$

$$0.012P_{G1} + 8 = 0.012P_{G2} + 7$$

$$P_{G2} - P_{G1} = 83.33 \quad \text{...(i)}$$

$$P_{G1} - P_{G2} = 600 \quad \text{...(ii)}$$

Solving (i) & (ii) we get

$$P_{G1} = 258.335MW$$

$$P_{G2} = 341.665MW$$

Both the limits are in the respective specified ranges

Q.2 **(b)**

Q.3 **(a)**

When P_1 is minimum

i.e. $P_1 = 50MW$

$$IC_1 = 20 + 0.3 \times 50 = 35$$

When P_2 is minimum

i.e. $P_2 = 50MW$

$$IC_2 = 30 + 0.4 \times 50 = 50$$

For minimum value of P_1 and P_2

IC_1 and $IC_2 > IC_3$

Therefore

$P_3 = 300MW$ [Maximum load is assigned to unit 3]

Remaining power is to shared by unit 1 and 2

so,

$p_1 + p_2 = 700 - 300 = 400$ ..(1)

For optimal operation

$$IC_1 = IC_2$$

$$20 + 0.3P_1 = 30 + 0.4P_2$$

$$0.3P_1 - 0.4P_2 = 10$$

Solving equation (i) and (ii) we get

$$P_1 = 242.86MW$$

And

$$P_2 = 157.14MW$$

Q.4 **(c)**

Fuel–cost curve of generating station 1

$$F_1 = a + bP_1 + cP_1^2 Rs/hour$$

Fuel–cost curve of generating station 2

$$F_2 = a + bP_2 + 2cP_2^2 Rs/hour$$

The slope of the fuel –cost curve i.e. $\frac{dF_i}{dP_i}$ is called the incremental fuel-cost (IC) and is expressed in Rs/MWh.

$$IC_1 = \frac{dF_1}{dP_1} = b + 2cP_1$$

$$IC_2 = \frac{dF_2}{dP_2} = b + 4cP_2$$

For economic generation

$$IC_1 = IC_2$$

$$b + 2cP_1 = b + 4cP_2$$

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$P_1 = 2P_2$ ....(i)

To meet 300MW of load

$P_1 + P_2 = 300$ ...(ii)

Solving equaton (i)adn (ii)

$P_1 = 200MW$ and

$P_2 = 100MW$

Q.5 (c)

Maximum incremental cost in Rs/ Mw hr for generator A

$= 600(at 450MW)$

Minimum incremental cost in Rs/ Mw hr for generator B

$= 650(at 150MW)$

A maximum value of incremental cost of A is less than minimum value of B,

∴ Generator 'A' will operate at its maximum (o/p) 450MW and B at (70-450)=250 MW

Q.6 (c)

$C_1(P_{G1}) = P_{G1} + 0.055 \times P_{G1}^2$

$\frac{dC_1}{P_{G1}} = 1 + 0.11P_{G1}$

$C_2(P_{G2}) = P_{G2} + 0.03 \times P_{G2}^2$

$\frac{dC_2}{P_{G2}} = 3 + 0.06P_{G2}$

For minimum cost analysis

$\frac{dC_1}{P_{G1}} = \frac{dC_2}{P_{G2}}$

$1 + 0.11P_{G1} = 3 + 0.06P_{G2}$ ... (i)

$P_{G1} + P_{G2} = 250MW$ ....(ii)

Solving equation (i) and (i)

We get , $P_{G1} = 100MW$

And $P_{G2} = 150MW$

Q.7 (c)

Let x_1, x_2, x_3 are reactance of generator -1 generator -2 and generator-3 respectively. Neglecting armature resistance of all the three generators

$VR_1 = 0.02p.u$

$VR_2 = 0.04p.u$ and

$VR_3 = 0.03p.u$

$VR_1 < VR_3 < VR_2$

Since, voltage regulation (VR)

$\propto$ reactanceof generator.

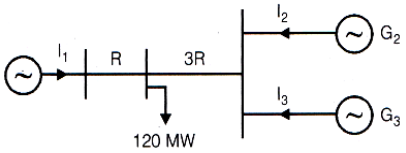
$x_1 < x_3 < x_2$

Power shared by a generator

$\propto \frac{1}{\text{reactance of generator}}$

Power Shared by Generator 1> Generator 2>Generator3

Q.8 (a)



Let load center is connected at point x if r is resistance /km of line

Resistance of section between 1 and x $R_1 = r \times 25 = R$

Resistance of section between 1 and x $R_2 = r \times 75 = R$

Current (I) fed by generator ∝ power produced by the generator.

$I_1 \propto P_1, I_2 \propto P_2$ and $I_3 \propto P_3$

Transmission losses $= P_L$

$= I_1^2R + I_2^2 3R + I_3^2 3R$

$P_L \propto \left(P_1^2 + 3P_2^2 + 3P_3^2\right)$

$P_L = \left[P_1^2 + 3P_2^2 + 3P_3^2\right]$

Option (a)

$P_1 = 80MW$

$P_2 = 20MW$

$P_3 = 20MW$

$P_L = K\left[80^2 + 3 \times 20^2 + 3 \times 20^2\right]$

$= 8800K\ MW$

Option (b)

$P_1 = 60MW$

$P_2 = 30MW$

$P_3 = 30MW$

$P_L = K\left[60^2 + 3 \times 30^2 + 3 \times 30^2\right]$

$= 9000K\ MW$

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Option (c)

$P_1 = 40MW$

$P_2 = 40MW$

$P_3 = 40MW$

$P_L = K\left[40^2 + 3\times 40^2 + 3\times 40^2\right]$

$= 11200K\ MW$

Option (d)

$P_1 = 30MW$

$P_2 = 45MW$

$P_3 = 45MW$

$P_L = K\left[30^2 + 3\times 45^2 + 3\times 45^2\right]$

$= 13050K\ MW$

So, option (a) gives minimum losses.

Q.9 (a)

From coordination equation

$$\frac{dF_n}{dP_{Gn}}\cdot\frac{1}{1-\frac{\partial P_L}{\partial P_{Gn}}} = \lambda$$

Given $P_L = 0.5P_{G1}^2$

$$\frac{\partial P_L}{\partial P_{G1}} = P_{G1} \text{ and } \frac{\partial P_L}{\partial P_{G2}} = 0$$

$$\Rightarrow \frac{dF_n}{dP_{G1}}\cdot\frac{1}{1-P_{G1}} = \frac{dF_2}{dP_{G2}}\cdot\frac{1}{1-0}$$

$$\Rightarrow 10000\times\frac{1}{1-P_{G1}} = 12500$$

$$1-P_{G1} = \frac{100}{125} = \frac{4}{5}$$

$$P_{G1} = \frac{1}{5}p.u$$

As the base value is 100MVA

$$P_{G1} = \frac{1}{5}\times 100 = 20MVA$$

$$\Rightarrow P_L = 0.5P_{G1}^2$$

$$= 0.5\left(\frac{1}{5}\right)^2 = 0.02p.u.$$

$$\Rightarrow P_L = 0.02\times 100 = 2MVA$$

$$P_D = P_{G1} + P_{G2} - P_L$$

$$40 = 20 + P_{G2} - 2$$

$$\Rightarrow P_{G2} = 22MVA$$

Q.10 (d)

Correct option is (D).

The fuel cost functions for plant P_1 and P_2 are

$$C_1 = 0.05P_{g_1^2} + AP_{g1} + B$$

$$C_2 = 0.10P_{g_2^2} + 3AP_{g2} + 2B$$

Given $P_{g1} + P_{g2} = 1000\,MW$

and $$\frac{dC_1}{dP_{g1}} = \frac{dC_2}{dP_{g2}} = 100$$

Also, from equations (i) and (ii), we have

$$\frac{dC_1}{dP_{g1}} = 2\times 0.05\ P_{g1} + A$$

$$\frac{dC_2}{dP_{g2}} = 2\times 0.10\ P_{g2} + 3A$$

Substituting equation (iii) in above expressions, we get

$$0.1\ P_{g1} + A = 100$$

$$0.2\ P_{g2} + 3A = 100$$

$$0.3P_{g2} - 0.2P_{g2} = 200$$

Hence, solving the equations (iii) and (v), we obtain

$P_{g1} = 800MW$

and $P_{g2} = 200MW$

Therefore, the ratio of load shared by plants P_1 and P_2 is

$$\frac{P_{g1}}{P_{g2}} = \frac{800}{200} = \frac{4}{1}$$

Q.11 Sol.

Correct answer is 0

Given fuel costs,

$C_1(P_1) = 0.01\ P_1^2 + 30P_1 + 10$;

where $100\ MW < P_1 < 150\ MW$

$C_2(P_2) = 0.05\ P_2^2 + 10P_2 + 10$;

where $100\ MW < P_2 < 180\ MW$

Total load, $P_D = 200\ MW$

So, P1+ P2 = 200

…….(1)

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For economical scheduling, the required condition is

$$\frac{dC_1}{dP_1} = \frac{dC_2}{dP_2}$$

Now, We have

$$\frac{dC_1}{dP_1} = 0.02P_1 + 30$$

$$\frac{dC_2}{dP_2} = 0.1P_2 + 10$$

On equating the above equations,

$$0.02P_1 + 30 = 0.1P_2 + 10$$

$$5P_2 - P_1 = 1000 \ldots\ldots\ldots(4)$$

On solving equations (1) and (4), we get,

$$P_2 = 200 \; and \quad P_1 = 0$$

But, the range of P_1 and P_2 are specifies as

100 MW < P_1 < 150 MW

100 MW < P_2 < 180 MW

So, both are operating at P_1=100, P_2=100,so total supply will be 200 MW

$$\frac{dC_1}{dP_1} = 0.02P_1 + 30 = 32 Rs./MW$$

$$\frac{dC_2}{dP_2} = 0.1P_2 + 10 = 20 Rs/MW$$

Q.12 (136.36)

Correct answer is 136.36

Initially P_1 and P_2 are chosen in such a way that

$$\frac{dC_1}{dP_1} = 76 Rs/MWh;$$

$$\frac{dC_2}{dP_2} = 68.8 Rs/MWh$$

Now, we calculate values of P_1 and P_2 as

$$0.02P_1 + 50 = 76$$

$$P_1 = 130MW$$

$$0.24P_2 + 40 = 68.8$$

$$P_2 = 120MW$$

So, Total demand = 120 + 130 = 250 MW

If generation cost is rescheduled to minimize the total cost, then incremental production cost should be equal, i.e.

$$0.02P_1 + 50 = 76$$

$$P_1 = 130MW$$

$$0.24P_2 + 40 = 68.8$$

$$P_2 = 120MW$$

$$0.02P_1 + 50 = 0.24P_2 + 40$$

$$0.02(250 - P_2) + 50 = 0.24P_2 + 40$$

$$P_2 = 136.6MW$$

Q.13 (400)

$$\frac{FB}{ED} = \frac{AB}{AD}$$

$$P_1 = 300\frac{X}{6}$$

$$P_1 = 50X$$

$$\frac{BG}{CH} = \frac{AB}{AC}$$

$$P_2 = 400\frac{X}{4}$$

$$= 100X$$

$$P_1 + P_2 = 600$$

$$X = 4$$

$$\therefore P_2 = 400MW$$

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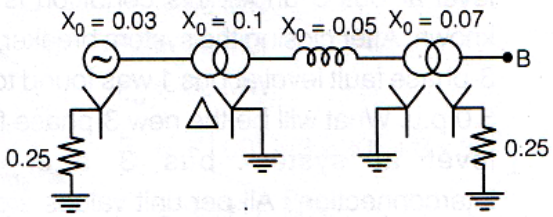
5 FAULTS ANALYSIS

Q.1 A 50 Hz alternator is rated 500MVA, 20kV, with $X_d = 1.0$ per unit and $X''_d = 0.2$ per unit. It supplies a purely resistive load of 400MW at 20 kV. The load is connected directly across the generator terminals when a symmetrical fault occurs at the load terminal. The initial rms current in the generator in per unit is

a) 7.22 b) 6.25
c) 3.22 d) 2.25

[GATE-2001]

Q.2 A generator is connected to a transformer which feeds another transformer though a short feeder. The zero sequence impedance values are expressed in p.u. on a common base and are indicated in figure .The The venin equivalent zero sequence impedance at point B (in p.u)is



a) 0.8+j0.6 b) 0.75+j0.22
c) 0.75+0.25 d) 1.5+j0.25

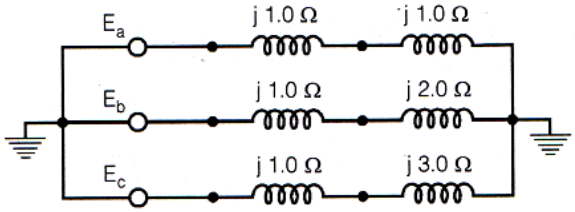
[GATE-2002]

Q.3 A 20-MVA, 6.6-kV, 3-phase alternator is connected to a 3-phase transmission line. The per unit positive –sequence. Negative – sequence and zero-sequence impedances of the alternator are j0.1, j0.1 and j 0.04 respectively. The neutral of the alternator is connected to ground through an inductive reactor of j 0.05 p.u. The per unit positive – negative – and zero –sequence impedances of the transmission line are j0.1, j0.1 and j 0.3 respectively. All per unit values are based on the machine ratings A solid ground fault occurs at one phase of the far end of the transmission line. The voltage of the alternator neutral with respect to ground during the fault is

a) 513.8V b) 889.9V
c) 1112.0V d) 642.2V

[GATE-2003]

Q.4 A three- phase alternator generating unbalanced voltages is connected t o an unbalanced load through a 3-phase transmission line as sown in figure. The neural of the alternator and the star point of the load are solidly grounded. The phase voltages of the alternator are $E_a = 10\angle 0°V E_b = 10\angle -90°V, E_c = 10\angle 120°V$ The positive sequence component of the load current is



a) $1.310\angle -107°A$
b) $0.332\angle -120°A$
c) $0.996\angle -120°A$
d) $3.510\angle -81°A$

[GATE-2003]

Q.5 A 3- Phase generator rated at 110MVA, 11kV is connected through circuit breakers to a transformer. The generator is having direct axis sub-transient reactance $X''_d = 19\%$ transient reactance $X'_d = 26\%$ and synchronous reactance =130%.The generator is operating at no load

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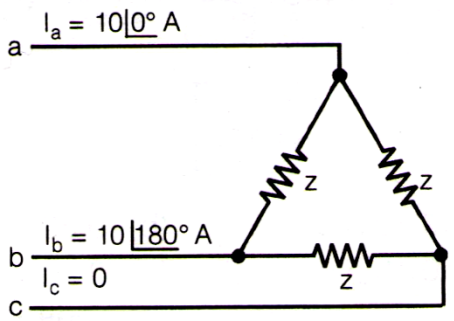
and rated voltage when a three phase short circuit fault occurs between the breakers and the transformer .The magnitude of initial symmetrical rms current in the breakers will be

a) 4.44kA b) 22.20kA
c) 30.39kA d) 38.45kA

[GATE-2004]

Q.6 A 3–phase transmission line supplies Δ – connected load Z. The conductor 'c' of the line develops an open circuit fault as shown in figure. The currents in the lines are as shown on the diagram. The +ve sequence current component in line 'a' will be



a) $5.78\angle -30°$A
b) $5.78\angle 90°$A
c) $6.33\angle 90°$A
d) $10.00\angle -30°$A

[GATE-2004]

Q.7 A500MVA, 50Hz, 3-phase turbo-generator produces power at 22kV. Generator is Y –connected and its neutral is solidly grounded. Its sequence reactance are $X_1 = X_2 = 0.15 \text{and} X_0 = 0.05\text{pu}$ it is operating at rated voltage and disconnected from the rest of the system (no load). The magnitude of the sub-transient line current for single line to ground fault at the generator terminal in pu will be

a) 2.851 b) 3.333
c) 6.667 d) 8.553

[GATE-2004]

Data for questions 81 & 82 are given below. Solve the problems and choose the correct answers

At a 220 kV substation of a power system., it is given that the three-phase fault level is 4000MVA and single -line to ground fault level is 5000MVANeglecting the resistance and the shunt susceptances of the system.

Q.8 The positive sequence driving point reactance at the bus is

a) 2.5Ω b) 4.033Ω
c) 5.5Ω d) 12.1Ω

[GATE-2005]

Q.9 The zero sequence driving point reactance at the bus is

a) 2.2Ω b) 4.84Ω
c) 18.18Ω d) 22.72Ω

[GATE-2005]

Q.10 Three identical star connected resistors of 1.0p.u. are connected to an unbalanced 3 phase supply. The load neutral is isolated. The symmetrical components of the line voltages in p.u. are: $V_{ab1} = X\angle\theta_1 V_{ab2} = Y\angle\theta_2$ If all the p.u. calculations are with the respective base values, the phase to neutral sequence voltages are

a) $V_{an1} X\angle(\theta_1 + 30°)$

b) $V_{an1} X\angle(\theta_1 - 30°)$
$V_{an2} Y\angle(\theta_2 - 30°)$
$V_{an2} Y\angle(\theta_2 + 30°)$

c) $V_{an1} = \frac{1}{\sqrt{3}} X\angle(\theta_1 - 30°)$

d) $V_{an1} = \frac{1}{\sqrt{3}} X\angle(\theta_1 - 60°)$

$V_{an2} = \frac{1}{\sqrt{3}} Y\angle(\theta_2 + 30°) V_{an2}$

$= \frac{1}{\sqrt{3}} Y\angle(\theta_2 - 60°)$

[GATE-2006]

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Q.11 A three phase balanced star connected voltage source with frequency ω rad/s is connected to a stat connected balanced load which is purely inductive. The instantaneous line currents and phase to neutral voltages re denoted by (i_a, i_b, i_c) and (V_{an}, V_{bn}, V_{cn}) respectively, and their rms values are demoted by V and l
If

$$R=\begin{bmatrix}V_{an},V_{bn},V_{cn}\end{bmatrix}\begin{bmatrix}0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}\\ -\frac{1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}}\\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & 0\end{bmatrix}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}$$

then the magnitude of R is
a) 3Vl b) Vl
c) 0.7Vl d) 0
[GATE-2007]

Q.12 Suppose we define sequence transformation between "a-b-c" and "p-n-o" variables as follows:

$$\begin{bmatrix}f_a\\ f_b\\ f_c\end{bmatrix}=K\begin{bmatrix}1 & 1 & 1\\ \alpha^2 & \alpha & 1\\ \alpha & \alpha^2 & 1\end{bmatrix}\begin{bmatrix}f_p\\ f_n\\ f_0\end{bmatrix}$$

Where $\alpha = e^{j\frac{2\pi}{3}}$ and k is a constant
Now, ifit is given that

$$\begin{bmatrix}V_p\\ V_n\\ V_0\end{bmatrix}=K\begin{bmatrix}0.5 & 0 & 0\\ 0 & 0.5 & 0\\ 0 & 0 & 2.0\end{bmatrix}\begin{bmatrix}i_p\\ i_n\\ i_0\end{bmatrix}\text{ and}$$

$$\begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix}=z\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}\quad\text{then}$$

a) $z=\begin{bmatrix}1.0 & 0.5 & 0.75\\ 0.75 & 1.0 & 0.5\\ 0.5 & 0.75 & 1.0\end{bmatrix}$

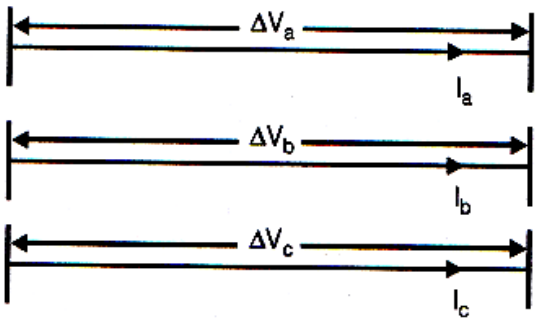
b) $z=\begin{bmatrix}1.0 & 0.5 & 0.5\\ 0.5 & 1.0 & 0.5\\ 0.5 & 0.5 & 1.0\end{bmatrix}$

c) $z=3k^2\begin{bmatrix}1.0 & 0.75 & 0.5\\ 0.5 & 1.0 & 0.75\\ 0.75 & 0.5 & 1.0\end{bmatrix}$

d) $z=\frac{K^2}{3}\begin{bmatrix}1.0 & -0.5 & -0.5\\ -0.5 & 1.0 & -0.5\\ -0.5 & -0.5 & 1.0\end{bmatrix}$

[GATE-2007]

Q.13 A 3-phase transmission line is shown in figure:



Voltage drop across the transmission line is given by the following equation:

$$\begin{bmatrix}\Delta V_a\\ \Delta V_b\\ \Delta V_c\end{bmatrix}=\begin{bmatrix}Z_s & Z_m & Z_m\\ Z_m & Z_s & Z_m\\ Z_m & Z_m & Z_s\end{bmatrix}\begin{bmatrix}I_a\\ I_b\\ I_c\end{bmatrix}$$

Shunt capacitance off the line can be neglect. If the line has positive sequence impedance of 15Ω and zero sequence impedance of 48Ω, then values of Z_s and Z_m will be
a) $Z_s=31.5\Omega; Z_m=16.5\Omega$
b) $Z_s=26\Omega; Z_m=11\Omega$
c) $Z_s=16.5\Omega; Z_m=31.5\Omega$
d) $Z_s=11\Omega; Z_m=26\Omega$
[GATE-2008]

Data for Questions 14, 15 & 16are given below. Solve the problems and choose the correct answers.

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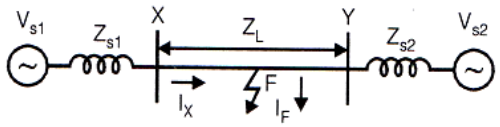


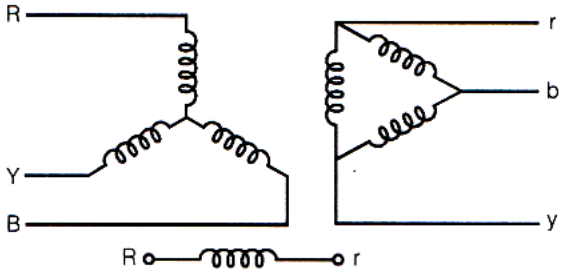
Given that: $V_{s1} = V_{s2} = 1 + j0 \text{p.u.}$ + ve sequence impedance are $Z_{s1} = Z_{s2} = 0.001 + j0.01 \text{p.u.}$ and $Z_L = 0.006 + j0.06 \text{p.u.} 3\Phi$ Base MVA=100, voltage base = 400kV (L-L). Nominal system frequency =50Hz. The reference voltage fro phase 'a' is defined as $V(t) = V_m \cos(\omega t)$. A symmetrical 3Φ fault occurs at centre of the line, i.e. at point 'F' at time 'to ' the +ve sequence impedance from source S_1 to point 'F' equals (0.004+j0.04) p.u The wave form corresponding to phase 'a' fault current is – ve and in magnitude at its maximum initial value. Assume that the negative sequence are equal to +ve sequence impedances and the zero sequence (Z) are 3 times +ve sequence (Z).

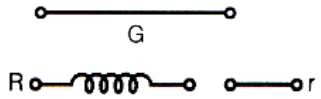
Q.14 The instant (t_0) of the fault will be
a) 4.682ms b) 9.667ms
c) 14.667ms d) 19.667ms
[GATE-2008]

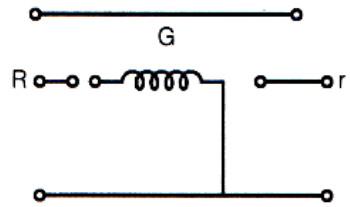
Q.15 The rms value of the ac component of fault current (I_x) will be
a) 3.59kA b) 5.07kA
c) 7.18kA d) 10.15kA
[GATE-2008]

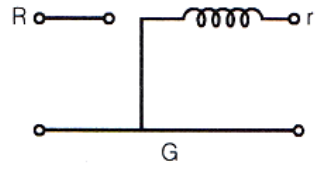
Q.16 Instead of the three phase fault, if a single line to ground fault occurs on phase 'a' at point 'F' with zero fault impedance, then the rms of the ac component of fault current (I_x) for phase 'a' will be
a) 4.97pu b) 7.0pu
c) 14.93pu d) 29.85pu
[GATE-2008]

Q.17 The zero –sequence circuit of the three phase transformer shown in the figure is



a)


b)


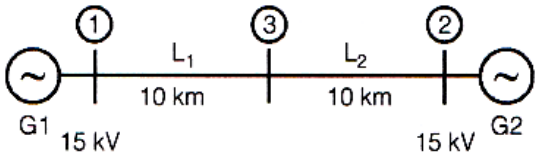
c)


d)

[GATE-2010]

Statement for Linked Answer Questions 18 & 19

Two generator units G1 and G2 are connected by 1`5kV line with bus at the mid-point as shown below.



G1 =250 MVA, 15kV positive sequence reactance
X=25% on its own base.
G2 =100 MVA, 15kV positive sequence reactance
X=10% on its own base.
L_1 and L_2 =10km Positive sequence reactance
$X = 0.225\Omega / \text{km}$ on its own base.

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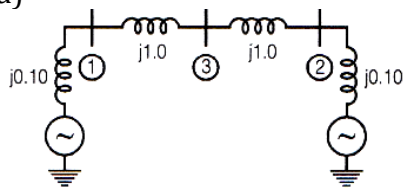
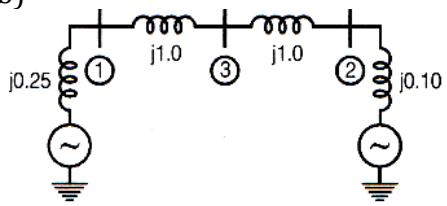
Q.18 For the above system, the positive sequence diagram with the p.u. values on the100MVA common base is

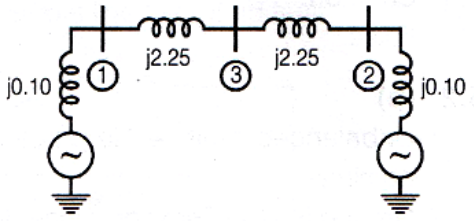
a)



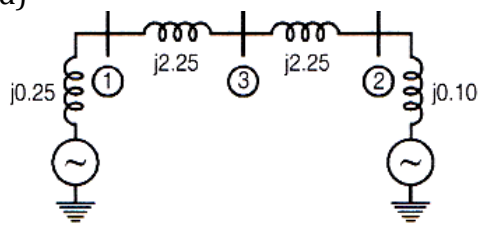
b)



c)



d)



[GATE-2011]

Q.19 In the above system, the three phase fault MVA at the bus 3 is

a) 82.55MVA b) 85.11MVA
c) 170.91MVA d)181.82MVA

[GATE-2011]

Q.20 The sequence components of the fault current are as follows: $I_{positive}$ = j1.5pu,

$I_{negative}$ =-j0.5pu,I_{zero} =-j1pu,

The type of fault in the system is

a) LG b) LL
c) LLG d) LLLG

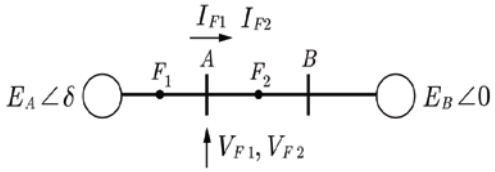
[GATE-2012]

Q.21 For a power system network with n nodes, Z_{33} of its bus impedance matrix is $j0.5$ per unit. The voltage at node 3 is $1.3\angle -10^0$ per unit. If a capacitor having reactance of $-j3.5$ per unit is now added to the network between node 3 and the reference node, the current drawn by the capacitor per unit is

(A) $0.325\angle -100^0$ (B) $0.325\angle 80^0$
(C) $0.371\angle -100^0$ (D) $0.433\angle 80^0$

[GATE-2012]

Q.22 Three-phase to ground fault takes place at locations $F1$ and $F2$ in the system shown in the figure.

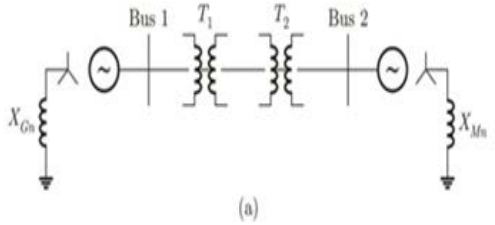


If the fault takes place at location F_1, then the voltage and the current at bus A are V_{F1} and I_{F1} respectively. If the fault takes place at location F_2, then the voltage and the current at bus A and V_{F2} and I_{F2} respectively. The correct statement about voltages and currents during faults at F_1 and F_2 is

(a) V_{F1} leads I_{F1} and V_{F2} leads I_{F2}
(b) V_{F1} leads I_{F1} and V_{F2} lags I_{F2}
(c) V_{F1} lags I_{F1} and V_{F2} leads I_{F2}
(d) V_{F1} lags I_{F1} and V_{F2} lags I_{F2}

[GATE-2014]

Q.23 A 2-bus system and corresponding zero sequence network are shown in the figure



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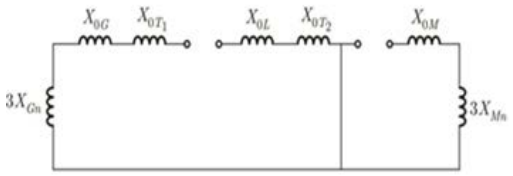
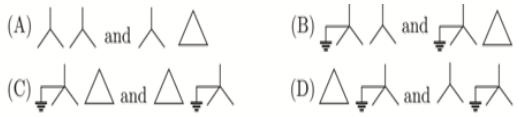


The transformers T_1 and T_2 connected as



[GATE-2014]

Q.24 In an unbalanced three phase system, phase current $I_a = 1\angle -90^0$ pu, negative sequence current $I_{b2} = 4\angle -150^0$ pu , zero sequence current $I_{C3} = 3\angle -90^0$ pu. The magnitude of phase current I_b in pu is

(a) 1.00 (b) 7.81
(c) 11.53 (d) 13.00

[GATE-2014]

Q.25 A three phase, 100 MVA, 25 kV generator has solidly grounded neutral. The positive, negative, and the zero sequence reactances of the generator are 0.2 pu,0.2 pu and 0.05 pu, respectively, at the machine base quantities. If a bolted single phase to ground fault occurs at the terminal of the unloaded generator, the fault current in amperes immediately after the fault is____.

[GATE-2014]

Q.26 Determine the correctness or otherwise of the following Assertion (A) and the Reason (R).

Assertion : Fast decoupled load flow method gives approximate load flow solution because it uses several assumptions.

Reason : Accuracy depends on the power mismatch vector tolerance.

(a) Both (A) and (R) are true and (R) is the correct reason for (A).

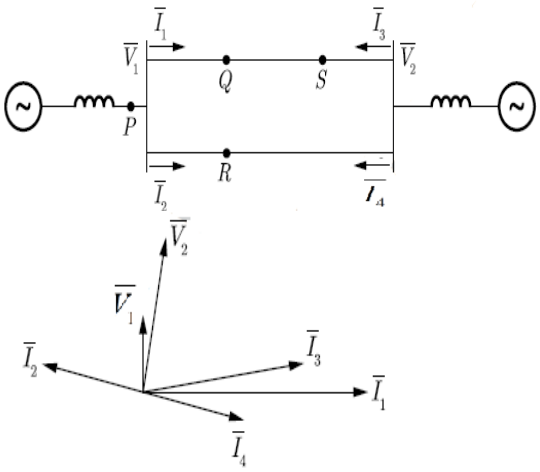
(b) Both (A) and (R) are true and (R) is not the correct reason for (A).

(c) Both (A) and (R) are false.

(d) (A) is false and (R) is true

[GATE-2015]

Q.27 A sustained three-phase fault occurs in the power system shown in the figure. The current and voltage phasors during the fault (on a common reference), after the natural transients have died down, are also shown. Where is the fault located?



(a) Location P
(b) Location Q
(c) Location R
(d) Location S

[GATE-2015]

Q.28. The magnitude of three-phase fault currents at buses A and B of a power system are 10 pu and 8 pu, respectively. Neglect all resistances in the system and consider the pre-fault system to be unloaded. The prefault voltage at all buses in the system is 1.0 pu. The voltage magnitude at bus B during a three-phase fault at bus A is 0.8 pu. The voltage magnitude at bus A during a three-phase fault at bus B, in pu, is ___?

[GATE-2016]

Q.29 A 30 MVA, 3-phase, 50 Hz, 13.8 kV, starconnected synchronous generator has positive,negative and zero sequence reactances, 15%,

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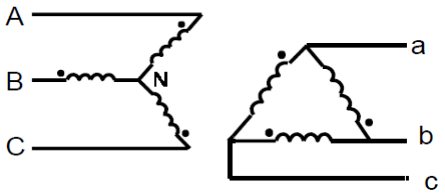
15% and 5% respectively. A reactance (X_n) is connected between the neutral of the generator and ground. A double line to ground fault takes place involving phases 'b' and 'c', with a fault impedance of j0.1 p.u. The value of X_n (in p.u.) that will limit the positive sequence generator current to 4270 A is_____ .

[GATE-2016]

Q.30 If the star side of the star-delta transformer shown in the figure is excited by a negative sequence voltage, then



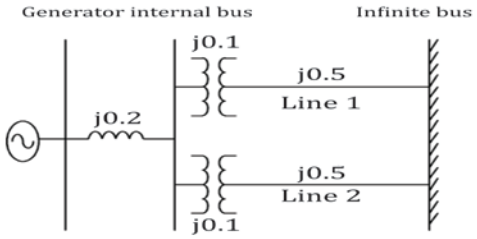
(A) V_{AB} leads V_{ab} by 60°
(B) V_{AB} lags V_{ab} by 60°
(C) V_{AB} leads V_{ab} by 30°
(D) V_{AB} lags V_{ab} by 30

[GATE-2016]

Q.31 A 50MVA, 10KV, 50HZ, star-connected, unloaded three - phase alternator has a synchronous reactance of 1p.u and a sub – transient reactance of 0.2p.u. If a 3 - phase terminals, the ratio of initial and final values of the sinusoidal component of the short circuit current is _____.

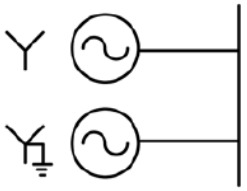
[GATE-2016]

Q.32 The single line diagram of a balanced power system is shown in the figure. The voltage magnitude at the generator internal bus is constant and 1.0p.u. the p.u reactances of different components in the system are also shown in the figure. The infinite bus voltage magnitude is 1.0p.u. A three phase fault occurs at the middle of line 2.The ratio of the maximum real power that can be transferred during the pre – fault condition to the maximum real power that can be transferred under the faulted condition is _____.



[GATE-2016]

Q.33 Two identical unloaded generators are connected in parallel as shown in the figure. Both the generators are having positive, negative and zero sequence impedances of j0.4pu., j0.3pu., and j0.15pu., respectively. If the pre - fault voltage is 1pu, for a line - to -ground (L – G) fault at the terminals of the generators, the fault current, in pu.,is _____.



[GATE-2016]

Q.34 The positive, negative and zero sequence reactance of a wye – connected synchronous generator are0.2 pu. 0.2 pu and 0.1 pu. The minimum value of the inductive reactance, in pu.required to be connected between neutral and ground so that the fault current does not exceed 3.75 pu if a single line to ground fault occurs at the terminals is ____ (assume fault

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impedance to be zero). (Give the answer up to one decimal place)

[GATE-2017]

Q.35 The positive negative and zero sequence impedances of a 125 MVA, three-phase, 15.5 kV, star-grounded, 50 Hz generator are *j* 0.1pu , *j* 0.05 pu and *j* 0.01 pu respectively on the machine rating base. The machine is unloaded and working at the rated terminal voltage. If the grounding impedance of the generator is *j* 0.01 pu , then the magnitude of fault current for a b-phase to ground fault (in kA) is _____ (up to 2 decimal places).

[GATE-2018]

Q.36 The positive, negative and zero sequence impedances of a three phase generator are Z_1, Z_2 and Z_0 respectively. For a line-to-line fault with fault impedance Z_f, the fault current $I_{f1} = kI_f$ where I_f is the fault current with zero fault impedance. The relation between Z_f and k is

(A) $Z_f = \dfrac{(Z_1 - Z_3)(1-k)}{k}$

(B) $Z_f = \dfrac{(Z_1 + Z_2)(1+k)}{k}$

(C) $Z_f = \dfrac{(Z_1 - Z_2)k}{1-k}$

(D) $Z_f = \dfrac{(Z_1 + Z_2)k}{1+k}$

[GATE-2018]

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(b)	(b)	(d)	(d)	(c)	(a)	(d)	(d)	(b)	(c)	(d)	(b)	(b)	(a)
16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
(a)	(c)	(c)	(a)	(d)	(d)	(c)	(b)	(c)	15393	(b)	(b)	0.84	1.07
30	**31**	**32**	**33**	**34**	**35**	36							
(d)	5	1.07	6	0.1	73.52	(A)							

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EXPLANATIONS

Q.1 (b)

For a purely resistive load the MVA and MW limits will be same.

For three phase symmetrical fault

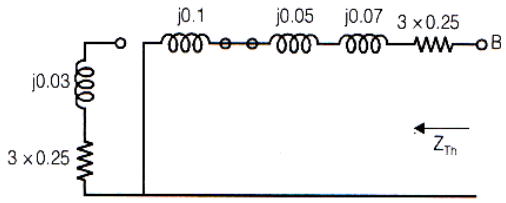
$$I_f = \frac{E_f}{X_1}$$

$X_1 = 0.2$ pu at 500 MVA base

$$(X_1)_{400MVA} = 0.2 \times \frac{400}{500} = 0.16$$

$$(I_f)_{pu} = \frac{1}{0.16} = 6.25 pu$$

Q.2 (b)



$$Z_{Th} = 0.75 + j0.22$$

Q.3 (d)

For alternator

$Z_{1_g} = j0.1$ p.u.

$Z_{2_g} = j0.1$ p.u. and

$Z_{0_g} = j0.04$ p.u.

For line

$Z_{1/l} = j0.1$ p.u

$Z_{2/l} = j0.1$ p.u

$Z_{0/l} = j0.3$ p.u

$Z_n = j0.05$ p.u

Equivalent Sequence Impedances;

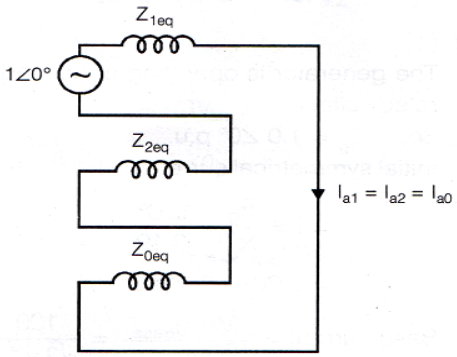
$$Z_{1eq} = Z_{1_g} + Z_{\frac{1}{l}} = j0.1 + j0. = j0.2 \text{ p.u}$$

$$Z_{2eq} = Z_{2_g} + Z_{\frac{2}{l}} = j0.1 + j0. = j0.2 \text{ p.u.}$$

$$Z_{0eq} = Z_{0_g} + Z_{\frac{0}{l}} + 3Z_n$$

$$= j0.04 + j0.3 + 3 \times j0.05 = j0.49 \text{ p.u.}$$

For single line to ground fault



$$I_{a1} = I_{a2} = I_{a0} = \frac{1\angle 0}{Z_{1eq} + Z_{2eq} + Z_{0eq}}$$

$$= \frac{1\angle 0}{j(0.2 + 0.2 + 0.49)}$$

Fault current

$= I_f = 3I_{a1} = -j3.3708$ p.u.

Voltage of neutral w.r.t ground

$V_n = I_f \times Z_n = -j3.3708 \times j0.05$

Per phase base voltage $= V_p$

$$= \frac{6.6}{\sqrt{3}} kV = \frac{6.6}{\sqrt{3}} \times 10^3 V$$

$$V_n = \frac{6.6}{\sqrt{3}} \times 0.16854 \times 10^3 = 642.2V$$

Q.4 (d)

Since both are grounded, we can take it as 3 independent circuits

Hence, $I_a = \frac{E_a}{Z_a} = \frac{10\angle 0°}{2j} = -5jA$

$$I_b = \frac{E_b}{Z_b} = \frac{10\angle -90}{3j} = 3.33\angle -180$$

$$I_c = \frac{E_c}{Z_c} = \frac{10\angle -120}{4j} = 2.5\angle 30° A$$

$$I_{a1} = 1/3\left(I_a + \alpha I_b + \alpha^2 I_c\right)$$

$$= 1/3[5\angle -90 + 3.33\angle -(180 - 120) + 2.5\angle(240 + 30)]$$

$$= 1/3(5\angle 90 + 3.33\angle -602.5\angle 270)$$

$$= 3.510\angle -81° A$$

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Q.5 **(c)**

The generator is operating at no-load ad related voltage

So, $E_g = 1.0\angle 0°$ p.u.

Initial symmetrical current

$$= I = \frac{E_g}{X_d} = \frac{1\angle °}{j0.19}$$

$$I = 5.26\angle -90° \text{ p.u.}$$

$$Base current = \frac{(MVA)_{Base}}{\sqrt{3}(kV)_{Base}}$$

$$= \frac{100}{\sqrt{3}\times 11} kA$$

$|I| = 5.26 \times$ Base current

$$= 5.26 \times \frac{100}{\sqrt{3}\times 11} \text{kA}$$

$= 30.37$kA

Q.6 **(a)**

$I_a = 10\angle 0° A$

$I_b = 10\angle 180°$

And $I_c = 0A$

$\alpha = 1\angle 120°$

Positive sequence current component in line 'a'

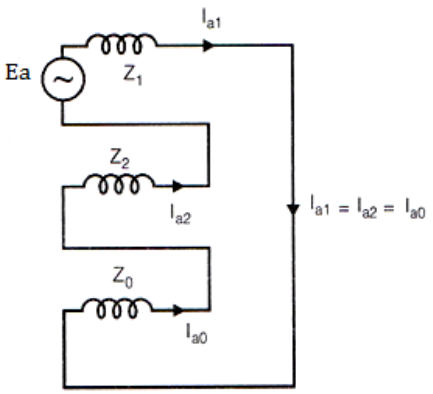
$$I_{a_1} = \frac{1}{3}\left[I_a + \alpha I_b + \alpha^2 I_c\right]$$

$$= \frac{1}{3}\left[\begin{matrix} 10\angle 0° + (1\angle 120°)\times(10\angle 180°) \\ +(1\angle 240°)\times 0 \end{matrix}\right]$$

$$I_{a_1} = 5.77\angle -30° A$$

Q.7 **(d)**

For single –line ground fault



Since, the generator is operating at no-load and rated voltage

$E_a = 1\angle 0$p.u.

$Z_1 = jX_1 = j0.15$p.u.

$Z_2 = jX_2 = j0.15$p.u.

And $Z_0 = jX_0 = j0.05$p.u.

$$Ia_1 = I_{a2} = I_{a0} = \frac{E_a}{Z_1 + Z_2 + Z_0}$$

$$= \frac{1\angle 0°}{j0.15 + j0.15 + j0.05}$$

$= 2.857\angle 90°$pu

Fault current

$= 3Ia_1 = 3 \times 2.857 = 8.57$pu

Q.8 **(d)**

Fault level (in MVA) $\sqrt{3}\times$prefaultline Voltage (kV)$\times$ fault current (in kA)

Pre-fault line voltage $= V_{prefault}$

$= 220$kV

$3-\Phi$fault

$3-\Phi$ fault level=4000MVA

$$\sqrt{3} V_{prefault} I_f = 4000\text{MVA}$$

$$I_f = \frac{4000\times 10^6}{\sqrt{3}\times 220\times 10^3} = 10.5\text{kA}$$

Let positive sequence driving point reactance $= X_1$

$$X_1 = \frac{\sqrt{3}V_{prefault}/\sqrt{3}}{I_f}$$

$$\Rightarrow X_1 = \frac{220/\sqrt{3}}{10.5} = 12.1\Omega$$

Q.9 **(b)**

Let negative sequence reactance $= X_2$

Assuming $X_2 = X_1$

And zero sequence reactance $= X_0$

In single –line to ground fault,

Fault level (MVA) =5000 MVA

$$\text{Fault current} = I_f = \frac{\text{Fault-level}}{\sqrt{3}\times V_{prefault}}$$

$$= \frac{5000\times 10^6}{\sqrt{3}\times 220\times 10^3}$$

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$\Rightarrow I_f = 13.12kA$

In SLG fault

Positive sequence current

$= I_{a1} = \frac{I_f}{3} = \frac{13.12}{3}$

$= 4.37kA$

$I_{a1} = \frac{V_{prefault}(Perphae)}{X_1 + X_2 + X_0}$

$4.37 = \frac{220/\sqrt{3}}{2X_1 + X_0}$

$= \frac{127}{2 \times 12.1 + X_0}$

$X_0 \approx 4.84\Omega$

Q.10 (c)

In positive sequence,Phase sequence is abc

Assuming

$V_{an_1} = V\angle 0°$ and

$V_{bn_1} = V\angle -120°$

$V_{ab_1} = V_{an_1} - V_{bn_1}$

$= V\angle 0° - V\angle -120°$

$\Rightarrow V_{ab_1} = \sqrt{3}V\angle 30°$

$\sqrt{3}V_{an1}\angle 30°$

So, if $V_{ab_1} = x\angle\theta_1$

$V_{an_1} = \frac{V_{ab1}}{\sqrt{3}\angle 30°}$

$= \frac{x\angle\theta_1}{\sqrt{3}\angle 30°}$

$= \frac{x}{\sqrt{3}}\angle\theta_1 - 30°$

In negative sequence,

Phase sequence is acb Assuming

$V_{an_2} = V\angle 0°$ and

$V_{bn_2} = V\angle -120°$

$V_{ab_2} = V_{an_2} - V_{bn_2}$

$= V\angle 0 - V\angle 120°$

$\Rightarrow V_{ab_2} = \sqrt{3}V\angle 30°$

$\sqrt{3}V_{an2}\angle -30°$

So, if $V_{ab_2} = Y\angle\theta_2$

$V_{an_2} = \frac{V_{ab2}}{\sqrt{3}\angle -30°}$

$= \frac{Y\angle\theta_1}{\sqrt{3}\angle -30°}$

$= \frac{Y}{\sqrt{3}}\angle\theta_2 + 30°$

Q.11 (d)

$R = \frac{1}{\sqrt{3}}\left[V_{an}(i_b - i_c) + V_{bn}(i_c - i_a) + V_{cn}(i_a - i_b)\right]$

$R = \frac{1}{\sqrt{3}}\left[V_{an}i_{bc} + V_{bn}i_{ca} + V_{cn}i_{ab}\right]$

Assuming phase sequence abc

Taking V_{an} as the reference

$V_{an} = V\angle 0°$

$V_{bn} = V\angle -120°$ and

$V_{cn} = V\angle 120°$

V is the rms value of V_{an}, V_{bn}, and V_{cn}

L is the rms value of i_a, i_b, i_c

As the load is purely inductive , i_a lags V_{an} by 90°

So, $i_a = I\angle -90°$

Similarly , $i_b = I\angle -210°$ and

$i_c = I\angle 30°$

$i_{bc} = i_b - i_c = I\angle -210° - I\angle 30°$

$= \sqrt{3}I\angle 180°$

$i_{ca} = i_c - i_a = I\angle 30° - I\angle -90°$

$= \sqrt{3}I\angle 60°$

$i_{ab} = i_a - i_b = I\angle -90° - I\angle -210°$

$= \sqrt{3}I\angle 60°$

$R = \frac{1}{\sqrt{3}}\left[V_{an}i_{bc} + V_{bn}i_{ca} + V_{cn}i_{ab}\right]$

$R = \frac{1}{\sqrt{3}}\begin{bmatrix} V\angle 0° \times \sqrt{3}\angle -180° + \angle -120° \times \sqrt{3}\angle -60° \\ + V\angle -120° \times \sqrt{3}I\angle -60° \end{bmatrix}$

$R = VI\left[I\angle -180° + I\angle -60° + \angle 60°\right]$

$= 0$

Q.12 (b)

Here, $\begin{bmatrix} V_p \\ V_n \\ V_0 \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2 \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ I_0 \end{bmatrix}$

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Where, $\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = [Z]\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$ ...(i)

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = K\begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} I_p \\ I_n \\ I_0 \end{bmatrix}$$

$$= KA\begin{bmatrix} I_p \\ I_n \\ I_0 \end{bmatrix}$$

Similarly, $V_{ph} = K[A]V_{sequence}$

$$=K[A]\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2 \end{bmatrix}\begin{bmatrix} I_{sequence} \end{bmatrix}$$

$$=K[A]\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2 \end{bmatrix}\frac{\begin{bmatrix} A^{-1} \end{bmatrix}}{K} I_{ph} \quad ....(ii)$$

Comparing eqn (i) with (ii)

$$\therefore Z=A\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2 \end{bmatrix}\begin{bmatrix} A^{-1} \end{bmatrix}$$

$$=\frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2 \end{bmatrix}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ 1 & 1 & 1 \end{bmatrix}$$

$$=\begin{bmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{bmatrix}$$

Q.13 (b)

Positive sequence impedance
=Negative sequence impedance
$Z_s - Z_m = 15$ ...(i)
Zero sequence impedance
$Z_s + 2Z_m = 48$ ...(ii)
Solving equation (i) and (ii), we get
$Z_s = 26\Omega; Z_m = 11\Omega$

Q.14 (a)

Voltage, $V = V_m \cos\omega t$
The current after fault

$$i(t) = Ae^{-(R/L)t} + \frac{\sqrt{2}V}{|Z|}\cos(\omega t - \theta)$$

At the instant of fault $t = t_0, i = 0$

$$0 = Ae^{-(R/L)t_0} + \frac{\sqrt{2}V}{|Z|}\cos(\omega t_0 - \theta)$$

$$Ae^{-(R/L)t_0} + \frac{\sqrt{2}V}{|Z|}\cos(\omega t_0 - \theta)$$

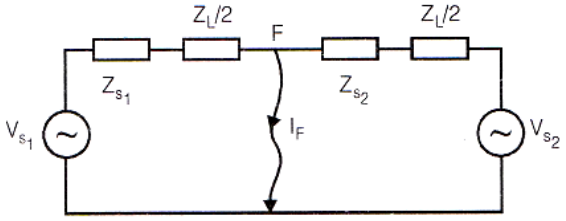
Maximum value of dc offset

$$Ae^{-(R/L)t_0} = \frac{\sqrt{2}V}{|Z|}\cos(\omega t_0 - \theta)$$

=Negative max
$Z = 0.004 + j0.004$
$|Z|\angle\theta = 0.0402\angle 84.3°$
$\theta = 84.3°$
$\omega t_o - \theta = 0$
$t_o = \theta/\omega$
$= 4.682$ms

Q.15 (a)

Fault occurs at mid point 'F'



Thevenins equivalent

$V_s = V_{S_1} = V_{S_2} = 1.0\angle 0 p.u.$

$$Z_1 = \left(Z_{S_1} + \frac{Z_L}{2}\right) \| \left(Z_{S_2} + \frac{Z_L}{2}\right)$$

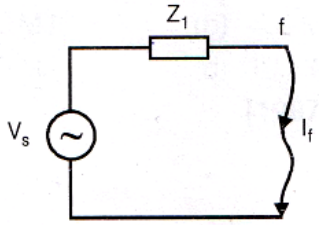
As, $Z_{S_1} = Z_{S_2} = 0.001 + 0.01 p.u.$

And $Z_L = 0.006 + j\,0.06$

$$Z_1 = \frac{1}{2}\left(Z_{S_1} + \frac{Z_L}{2}\right)$$

$$= \frac{1}{2}\left(0.001 + 0.01 + \frac{0.006 + j0.006}{2}\right)$$

$Z_1 = 0.002 + j0.02$



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$$\text{Fault current} = I_f = \frac{V_s}{Z_1}$$

$$= \frac{1\angle 0°}{0.002 + j0.02}$$

$$= 49.75\angle -84.29 \text{p. u.}$$

$$= |I_f| \text{p. u} = 49.75$$

$$\text{Base current} = \frac{\text{BaseMVA}}{\sqrt{3}\text{Voltage Base}} \text{kA}$$

$$I_B = \frac{100}{\sqrt{3}\times 400} kA$$

$$|I_f| = |I_f|_{\text{p.u.}} \times I_B$$

$$= 49.75 \times \frac{100}{\sqrt{3}\times 400} kA$$

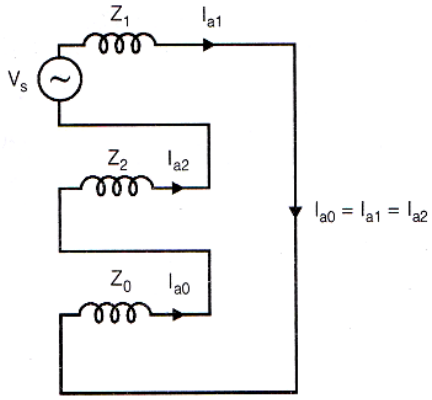
$$= I_x^f = \frac{|I_f|}{2} = \frac{7.18}{2} \text{kA} = 3.59 \text{kA}$$

Q.16 (c)

$Z_1 = 0.002 + j0.02$ pu

$Z_2 = Z_1 = 0.002 + j0.02$ pu

$Z_0 = 3Z_1 = 0.006 + j0.006$ pu



$$I_{a0} = I_{a1} = I_{a2} = \frac{V_s}{Z_1 + Z_2 + Z_0}$$

$$= \frac{V_s}{Z_1 + Z_2 + 3Z_1}$$

$$= \frac{V_s}{5Z_1} = \frac{1\angle 0°}{5\times(0.002 + j0.02)}$$

$$= 9.95\angle -84.29 \text{p. u.}$$

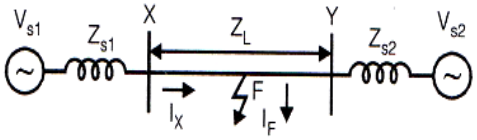
$$\text{Fault current} = |I_f|_{\text{p.u.}} = 3|I_{a0}|$$

$$= 3 \times 9.95 = 29.85 \text{p. u.}$$

$$I_x^f = \frac{|I_f|_{\text{p.u.}}}{2} = \frac{29.85}{2} = 14.93 \text{p.u.}$$

Q.17 (c)

- Equivalent circuit for the zero sequence network depends upon the impedances met by the zero sequence currents flowing through the three phases and their sum$3I_{a0}$, flowing through the neutral impedance and retiring through the ground or a neutral conductor.
- If these are no complete path for zero sequence current in a circuit, the zero sequence impedance is infinite.
  Thus a Y- connected circuit with ungrounded neutral has infinite impedance to zero sequence currents.
- A delta –connected circuit provides no path for zero sequence currents flowing in the line, The zero –sequence currents being single phase, circulate within the winding .Hence viewed from its terminals its zero sequence impedance is infinite.



Given that :

$V_{s1} = V_{s2} = 1 + j\,0$ p.u. + ve sequence impedance are

$Z_{s1} = Z_{s2} = 0.001 + j\,0.01$ p.u. and

$Z_L = 0.006 + j\,0.06$ p.u.3 Φ

Base MVA=100, voltage base =400kV(L-L). Nominal system frequency =50Hz. The reference voltage fro phase 'a' is defined as $V(t) = V_m cos(\omega t)$. A symmetrical 3Φ fault occurs at centre of the line, i.e. at point 'F' at time 'to ' the +ve sequence impedance from source S_1 to point 'F' equals (0.004+j0.04) p.u The wave form corresponding to phase 'a' fault current is –ve and in magnitude at its maximum initial value. Assume that the negative

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sequence are equal to +ve sequence impedances and the zero sequence (Z) are 3 times +ve sequence (Z).

Q.18 (a)

New MVA Base

$= (\text{MVA}_B)_{new} = 100\text{MVA}$

$Z_{p.u.\,(new)} = Z_{p.u.\,(old)} \times \frac{(\text{MVA}_B)_{new}}{(\text{MVA}_B)_{old}} \times \frac{(\text{kV}_B)^2_{old}}{(\text{kV}_B)^2_{new}}$

$(\text{kV}_B)_{old} = (\text{kV}_B)_{new} = 15\text{kV}$

On 100MVA and 15 kV base,

$X_{G2} = 0.1\text{p.}$ (remains same)

$X_{G1} = 0.25 \times \frac{100}{250} = 0.1\text{p.u}$

Positive sequence reactance of L_1 and $L_2 = X_L = 0.225 \times 10 = 2.25\Omega$

Base impedance $= Z_B = \frac{(\text{kV}_B)^2_{new}}{(\text{MVA}_B)_{new}}$

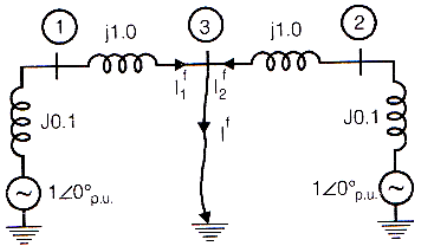
$= \frac{15^2}{100} = 2.25\Omega$

$X_L\,(\text{in pu}) = \frac{2.25}{2.25} = 1\text{p.u.}$

{p.u reactance of section L_1 and L_2}

Hence, option (a) is correct.

Q.19 (d)



Fault current $= I^f = I_1^f + I_2^f$

$I_1^f = I_2^f = \frac{1\angle 0°}{j1.0 + j0.1} = -j0.9091\text{p.u.}$

$I^f = -j1.8182\text{p. u.}$

Fault level $= 1 \times 1.8182\text{p. u.}$

Fault level (in MVA) $= 1.8182 \times 100$

$= 181.82$ MVA

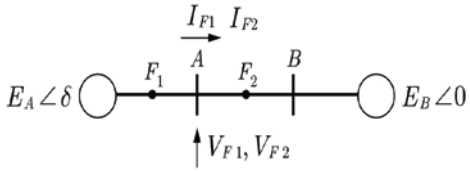
Q.20 (c)

Only LLG fault has a unique property that the sum of all sequence components of the fault current is zero.

Q.21 (c)

Correct option (C).

We have the given system as



As fault always require/demand reactive power, so voltage should lead current.Using this condition, we have the following observations for the given system :

At fault F_2 which is not near to source require reactive power, hence V_{F2} leads I_{F2}

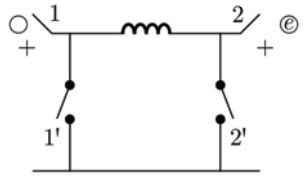
Fault F_1 is near the source, so the current will lead voltage for active requirements,

i.e.V_{F1} lags I_{F1}

Q.22 (b)

Correct option is (B).

As the winding and neutral has affect then we represent transformer in zero sequence network using switch diagram.



Switches 1, 1' → Primary

Switches 2, 2' → Secondary winding

1, 2 → Series switches

1', 2' → Shunt switches

Series switches are closed when transformer is star-connected.

Shunt switches are closed when transformer is delta-connected.

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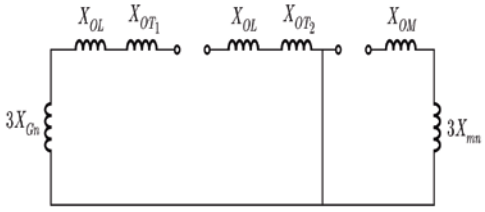
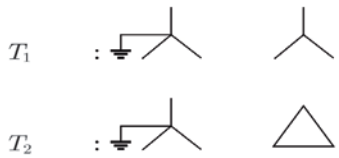
For ground effect $3X_0$.



Here, on T_1 side series switch are closed hence star-connection and grounded due to $3X_{Gn}$ .On T_2 side, shunt switches are closed hence one delta and one star with ground.



Q.23 (c)

Correct option is (C).

For the unbalanced three phase system, we have

$I_{a1} = 1\angle -90^0$ pu;

$I_{b2} = 4\angle -150^0$ pu;

$I_{C0} = 3\angle 90^0$ pu;

The phase current is given by

$I_a = I_{a1} + I_{a2} + I_{a0}$

Now, we have

$I_{b2} = a\, I_{a2}$

So, for the given system

$4\angle -150^0 = 1\angle 120^0 I_{a2}$

or $I_{a2} = 4\angle -270^0$

Substituting these values in equation (i), we get

$I_a = 1\angle -90^0 = I_{a1} + 4\angle 270^0 + 3\angle 90^0$

$or\ I_{a1} = 1\angle -90^0 - 4\angle -270^0 - 3\angle 90^0$

$= 8\angle -90^0$

$So,\ I_{b1} = a^2 I_{a1}$

$= 1\angle 24^0 \times 8\angle -90^0 = 8\angle 150^0$

Thus, we obtain

$I_b = I_{b1} + I_{b2} + I_{b0}$

$= 8\angle 150^0 + 4\angle -150^0 + 3\angle 90^0$

$= 11.53\angle 154.3^0$ pu

Q.24 (15403.698)

Correct answer is 15403.698 .

For single line-to-ground fault, the symmetrical component of current (in pu)

$$I_{a1} = \frac{E_{a1}}{z_0 + z_1 + z_2} = \frac{1}{0.2 + 0.2 + 0.05} = 2.22 \text{ pu}$$

The magnitude of fault current

$I_f = 3I_{a1} = 3 \times 2.22 = 6.67$ pu

Base value of current

$$I_{base} = \frac{100 \times 10^6}{\sqrt{3} \times 25 \times 10^3} = 2309.40 \text{ A}$$

So actual value of fault current

$I_f = 6.67 \times 2309.40$

$= 15403.698$ A

Q.25 (a)

Correct option is (A).

In fast-decoupled load flow method, some terms are neglected to make gain faster.

For decoupled load flow, we have

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta |V|}{|V|} \end{bmatrix}$$

Here H , N , M, and L are elements of Jacobian. To make the system faster, we put N = 0 and M = 0

So, the resulting system is

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta |V|}{|V|} \end{bmatrix}$$

This gives the approximate load flow gain.

Now, the statement given in Reason (R) is Accuracy depends on the power mismatch vector tolerance.

As accuracy depend upon tolerance, so it is also correct.

Hence, both Assertion (A) and Reason (R) are correct but Reason (R) is not correct explanation of Assertion (A).

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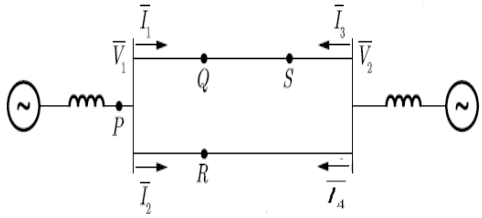
Q.26 (d)

Correct option is (D).

In the given phasor diagram, we can observe that all the current except I2 are lagging in nature. In the power system, if there is any fault, then current always lagging in nature because mostly line are inductive in nature. If current is leading,

I2 will be opposite in direction that shown in figure. So, we get the actual current direction flow diagram as



Hence, fault should be at point Q only.

In other case, if fault is at point s , then current I2 and I4 will flow in the direction R-S-Q.

Q.27 (d)

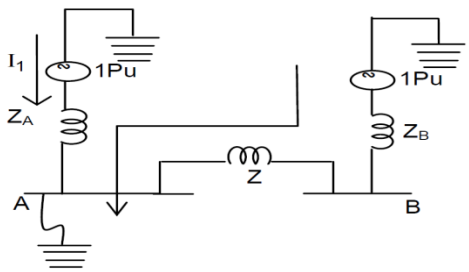
Thevenin's equivalent circuit between bus (3) and reference bus Z_{33}=j0.5

Thevenin equivalent voltage between 3rd bus and ref

$V_{th}=1.3\angle -10°$ p.u.

$$I_c=\frac{1.3\angle -10°}{j0.5-j3.5}=0.433\angle 80° \, p.u.$$

Q.28 (0.832)



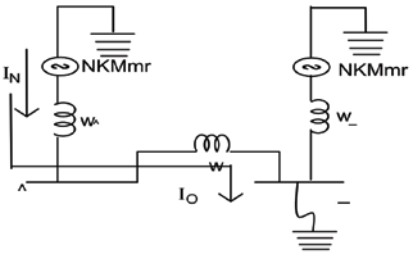
when fault is at Bus 'A'

$$10=\frac{1}{Z_A}+\frac{1}{Z+Z_B}$$

$$\therefore I_2=\frac{0.8}{2}=\frac{1}{z+z_B}$$

$$\Rightarrow 0.8\left(z+z_B\right)=z$$

$$\Rightarrow z=4z_B$$



Fault at Bus B :

$8 = I_x + I_y$

$$8=\frac{1}{z_B}+\frac{1}{z+z_A}$$

From equation (2)

$$8=\frac{1}{z_B}+\frac{1}{4z_B+z_A}$$

$32z_B^2+8z_Az_B=5z_B+z_A$

From equation (1) $50z_Az_B+z_A$

From (3) & (4)

$ZA = 0.76z_B$

Now, we need to calculate Bus ' A ' voltage

when fault is at Bus 'B'

Assume bus (A) voltage is V_A

$$8=\frac{1}{z_B}+\frac{1}{z+z_A}=\frac{1}{z_B}+\frac{1}{4z_B+z_A}$$

$z_B=0.151\Rightarrow z_A=0.114,\ z=0.604$

From fig (2) $\Rightarrow$

$$8=\frac{1}{z_B}+\frac{VA}{z}\Rightarrow\frac{1}{0.151}+\frac{v_A}{0.604}$$

$\boxed{v_A=0.832\,pu}$

Ans : 0.832

Q.29 (1.08)

Given a 30 MVA, 3. Ph, 50 Hz, 13.8 kV

$Z_1=0.15,\ z_2=0.15,\ z_0=0.05$ pu

$z_f=0.1$ pu $z_n=?$;

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$$I_{bare} = \frac{30 \times 10^6}{\sqrt{3} * 13.8 \times 10^3}$$

$$I_{a1}(pu) = 4270\,A : = 1255.1A$$

$$I_{a1}(pu) = \frac{4270\,A}{1255} = 3.4\,pu$$

$$\text{w.r.t. } I_{a1} = \frac{E_f}{z_1 + \frac{z_2\left(z_0 + 3z_f + 3z_n\right)}{z_2 + z_0 + 3z_f + 3z_n}}$$

$$z_1 + \frac{z_2\left(z_0 + 3z_f + 3z_n\right)}{z_2 + z_0 + 3z_f + 3z_n} = \frac{1.0}{3.4}$$

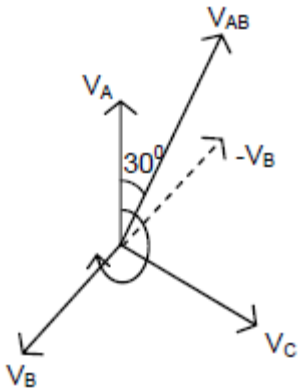
$$0.15 + \frac{(0.15)(0.05 + 0.3 + 3z_n)}{0.15 + 0.05 + 0.3 + 3z_n} = \frac{1.0}{3.4}$$

$$\Rightarrow \; z_n = \; 1.08$$

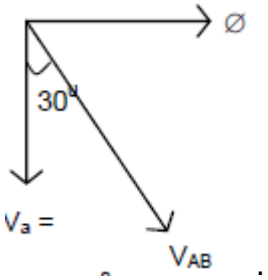
Ans : 1.08

Q.30 (d)

Negative sequence on primary:



n secondary side



V_{AB} lags V_{ab} by 30°

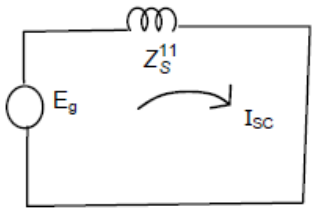
Q.31 (5)

Given 50MVA, 10KV alternator

ZS = 1.0 PU

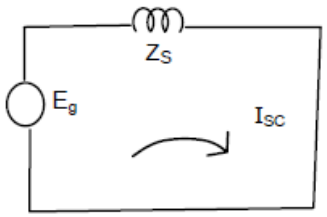
$Z_s^{11} = 0.2\,PU$

Immediately after the short ckt (During transient period)



$$\Rightarrow I_{sc} = \frac{1.0}{1.0} = 1PU$$

At steady state

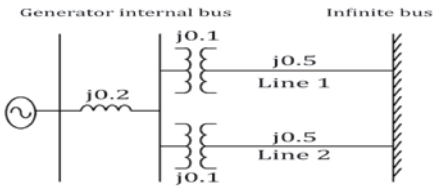


$$\Rightarrow I_{sc} = \frac{1.0}{1.0} = 1PU$$

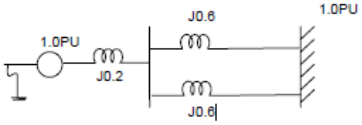
$$\frac{\text{Initial}}{\text{Final}} = \frac{5}{1.0} = 5$$

Ans : 5

Q.32 (2.3)

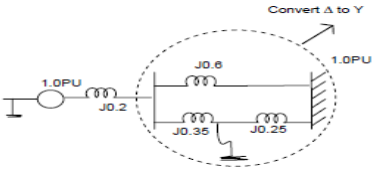


Without fault :



$$Pmax = \frac{(1.0)(1.0)}{X_q} = \frac{(1.0)(1.0)}{j0.5} = 2\,PU$$

During the fault :



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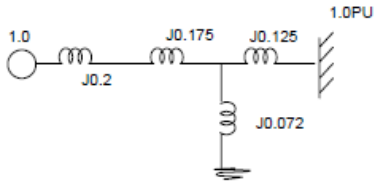
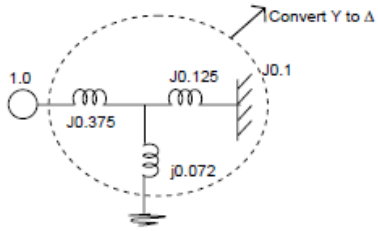
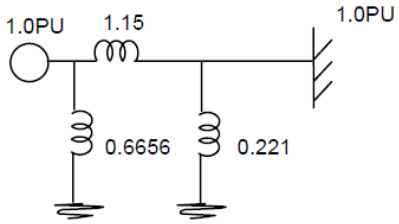
The above circuit can be drawn as follows.







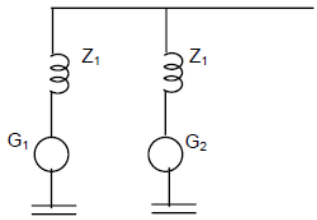
$$P_{max} = \frac{(1.0)(1.0)}{1.15} = 0.869\,PU$$

$$\text{The ratio} = \frac{P_{\text{pre fault}}}{P_{\text{during fault}}} = \frac{2}{0.869} = 2.3$$

Ans: 2.3

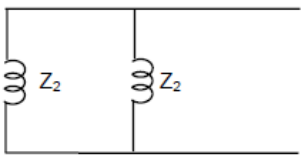
Q.33 (6)

Two generators in parallel



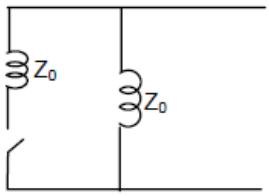
* Equivalent positive seq. impedance.

$$Z_{1eq} = \frac{(0.4)(0.4)}{0.8} = 0.2\,PU$$



* Equation negative sequence impedance.

$$Z_{2eq} = \frac{(0.3)(0.3)}{0.6} = 0.15\,PU$$



* Equation zero sequence impedance is

$Z_{0eq} = 0.15$ PU

(Q 1st generator neutral is disconnected form ground)

$$I_{a1} = \frac{Eg}{Z_{1eq} + Z_{2eq} + Z_{0eq}} = \frac{1.0}{0.2 + 0.15 + 0.15}$$

$$= 2\,PU$$

$$I_f = 3I_{a1}\,(Q\ L-G\ \text{fault})$$

$$= (3)(2) = 6\,PU$$

Ans : 6

Q.34 (0.1)

$Z_1 = 0.2, Z_2 = 0.2, Z_0 = 0.1$

$V = 1\ pu, I_{fault} = 3.75$

fault current for single line to ground fault,

$$I_{fault} = 3I_{a1} = \frac{3V}{Z_1 + Z_2 + Z_0 + 3Z_n}$$

$$3.75 = \frac{3x1}{0.2+0.2+0.1+3Z_n}$$

$$Z_n = 0.1pu$$

Q.35 (73.5263)

Given:

(i) Positive sequence impedance Z1 = j0.1 pu

(ii) Negative sequence impedance Z2 = j0.05 pu

(iii)Zero sequence impedance Z0 = j0.01 pu

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(iv) Grounding impedance $Z_g = j0.01$ pu

$$I_f = \frac{3Ea1}{Z_1+Z_2+Z_0+3Z_n}\ pu$$

$$I_f(KA) = I_f(pu) \times I_{base}$$

$$I_{base} = \frac{125}{\sqrt{3}\times 15.5}\times 10^3 = 4656.050\ (A)$$

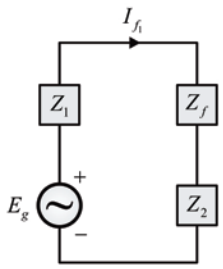
$$I_f = \frac{3\times 1\times 4656.050}{0.1+0.05+0.01+3(0.01)}$$

$$= 73.5236\ (KA)$$

Q.36 (A)

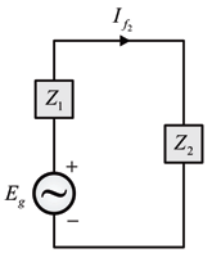
Sol. Given : Line to line fault

Case I : Fault current with Z_f



$$I_{f1} = \frac{\sqrt{3}E_g}{Z_1+Z_2+Z_f}$$

Case II : Fault current without Z_f



$$I_{f2} = \frac{\sqrt{3}E_g}{Z_1+Z_2}$$

As, $I_{f1} = kI_{f2}$

$$\frac{\sqrt{3}E_g}{Z_1+Z_2+Z_f} = \frac{k\sqrt{3}E_g}{Z_1+Z_2}$$

$$Z_1+Z_2 = k\left(Z_1+Z_2\right)+kZ_f$$

$$Z_f = \frac{\left(Z_1+Z_2\right)(1-k)}{k}$$

Hence, the correct option is (A).

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6 POWER SYSTEM STABILITY

Q.1 A transmission line has a total series reactance of 0.2p.u. Reactive power compensation is applied at the mid – point of the line and t is controlled such that the mid-point voltage of the transmission line is always maintained at 0.98p.u. If voltage at both ends of the linear maintained at 1.0p.u. Then the steady state power transfer limit of the transmission line is

a)9.8p.u. b)4.9 p. u.
c)19.6p.u. d)5 p. u.

[GATE-2002]

Q.2 A generator delivers power of 1.0p.u. to an infinite bus through a purely reactive network. The maximum power that could be delivered by the generator is2.0p.u. A three –phase fault occurs at the terminals of the generator which reduces the generator output to zero. The fault is cleared after t_c second. The original network is then restored .the maximum swing of the rotor angle is found to be $\delta_{max} = 110$ electrical degree. Then the rotor angle in electrical degrees at $t = t_c$ is

a) 55 b) 70
c) 69.14 d) 72.4

[GATE-2003]

Q.3 A 800 kV transmission line is having per phase lie inductance of 1.1mH/km and per phase line capacitanceof 11.68 nF/km.Ignoring thelength of the line,its ideal power transfer capability in MW is

a)1204MW b)1504MW
c)2085MW d)2606 MW

[GATE-2004]

Q.4 A new generator having $E_g = 1.4\angle 30°$ pu [equivalent to $(1.212+j0.70)$ pu] synchronous reactance 'X_s' of 1.0 pu on the system base, is to be connected to a bus having voltage V, in the existing power system. This existing poser system can be represented by Thevenin's voltage $E_{th} = 0.9\angle 0°$p in series with The venin's impedance $Z_{th} = 0.25\angle 90°$ pu The magnitude of th bus voltage V_t of the system in p.u. will be

a)0.990 b)0.973
c)0.963 d)0.900

[GATE-2004]

Q.5 A 50Hz, 4-pole 500MVA 22kV turbo-generator is delivering rated MVA at 0.8 power factor. Suddenly a fault occurs reducing is electric power output by 40% .Neglect losses and assumes constant power input to the shaft. The accelerating torque in the generator in MN m at the time of the fault will be

a)1.528 b)1.018
c)0.848 d)0.509

[GATE-2004]

Q.6 An 800kV transmission line has a maximum power transfer capacity of P. If it is operated at 400kV with the series reactance unchanged, then new maximum power transfer capacity is approximately

a)P b)2p
c)P/2 d)P/4

[GATE-2005]

Q.7 A generator with constant 1.0p.u. terminal voltage supplies power through a step-up transformer of 0.12p.u. reactance and a double – circuit lien to an infinite bus bar as shown in the figure. The infinite bus

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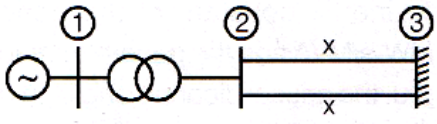
voltage is maintained at 1.0p.u. Neglecting the resistances and susceptances of the system, the steady state stability power limit of the system is 6.25 p. u. If one of the double –circuit is tripped, then resulting steady state stability power limit in p. u. will be



a)12.5p.u. b)3.125p.u.
c)10.0p.u. d)5.0 p.u.

[GATE-2005]

Statement for common data Questions 8 & 9

A generator feeds power to an infinite bus through a double circuit transmission line A 3-phase fault occurs at the middle point of one of the lines. The infinite bus voltage is 1pu, the transient internal voltage of the generator is 1.1 pu and the equivalent transfer admittance during fault is 0.8pu.The 100MVA generator has an inertia constant of 5MJ/MVA and it was delivering 1.0pu power prior of the fault with rotor power angle of $30°$ The system frequency is 50Hz.

Q.8 The initial accelerating power (in p .u.) will be

a)1.0 b)0.6
c)0.56 d)0.4

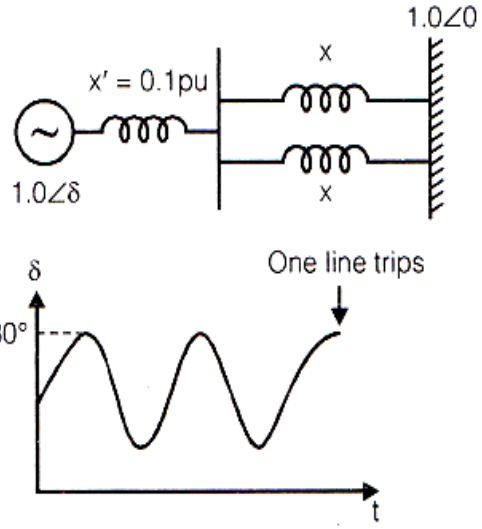
[GATE-2006]

Q.9 If the initial accelerating power is X p.u. the initial acceleration in elect deg/ sec, and the inertia constant in MJ-sec /elect deg respectively will be

a)31.4X,18 b)1800X,0.056
c)X/1800,0.056 d)X/31.4,18

[GATE-2006]

Q.10 Consider a synchronous generator connected to an infinite bus by two identical parallel transmission lines. The transient reactance X' of the generator is 0.1 pu and the mechanical power input to it is constant at 1.0pu Due to some previous disturbance, the rotor angle (δ) is undergoing an un damped oscillation , with the maximum value of (δ) equal to $130°$ as shown in the figure. The maximum value of the per unit line reactance X such that the system does not lose synchronism subsequent to this tripping is



a)0.87 b)0.74
c)0.67 d)0.54

[GATE-2007]

Q.11 An isolated 50Hz synchronous generator is rated at 15MW which is also the maximum continuous power limit of its prime mover .It I equipped with a speed governor with 5% droop. Initially, the generator is feeding three loads of 4MW each at 50Hz. All of theseloads is programmed to trip permanentlyif the frequency falls below 48 Hz. If an additional load of 3.5MW is connected then the frequency will settle down to

a)49.417Hz b)49.917Hz
c)50.083Hz d)50.583Hz

[GATE-2007]

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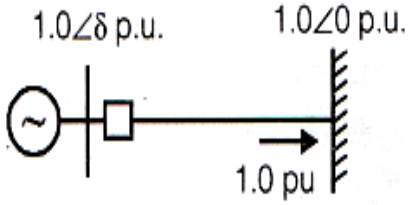
Q.12 A lossless single machine infinite bus power system is shown below:



The synchronous generator transfers 1.0per unit of power to the infinite bus. The critical clearing time of circuit breaker is 0.28 s. If another identical synchronous generator is connected in parallel to the existing generator and each generator is scheduled to supply 0.5per unit of power, then the critical clearing time of the circuit breaker will

a) reduce to 0.14 s
b) reduce but will be more than0.14s
c) remain constant at0.28 s
d) Increase beyond 0.28 s

[GATE-2008]

Q.13 A 500 MW, 21kV, 50Hz, 3-Phase, 2pole synchronous generator having a rated p.f. =0.9 has a moment of inertia of $27.5 \times 10^3 \text{kg} - \text{m}^2$. The inertia constant (H) will be

a)2.44MJ/MVA b)2.71MJ/MVA
c)4.88MJ/MVA d)5.42MJ/MVA

[GATE-2009]

Q.14 A cylindrical rotor generator delivers 0.5 pu power in the steady state to an infinite bus through a transmission line of reactance 0.5pu. The generator no –load voltage is 1.5 pu and the infinite bus voltage is 1pu. The inertia constant of the generator is 5MW-s/MVA and the generator reactance is 1p.u.the critical clearing angle, in degrees, for a three phase dead short circuit fault at the generator terminal is

a)53.5 b)60.2
c)70.8 d)79.6

[GATE-2012]

Q.15 A synchronous generator is connected to an infinite bus with excitation voltage E_f = 1.3 pu. The generator has a synchronous reactance of 1.1 pu and is delivering real power (P) of 0.6 pu to the bus. Assume the infinite bus voltage to be 1.0 pu. Neglect stator resistance. The reactive power (Q) in pu supplied by the generator to the bus under this condition is ____.

[GATE-2014]

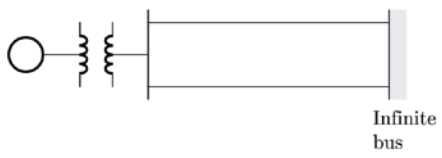
Q.16 There are two generators in a power system. No-load frequencies of the generators are 51.5 Hz and 51 Hz, respectively, and both are having droop constant of 1Hz/MW. Total load in the system is 2.5 MW. Assuming that the generators are operating under their respective droop characteristics, the frequency of the power system in Hz in the steady state is _____.

[GATE-2014]

Q.17 A 50 Hz generating unit has H - constant of 2 MJ/MVA. The machine is initially operating in steady state at synchronous speed, and producing 1 pu of real power.The initial value of the rotor angle δ is 5°, when a bolted three phase to ground short circuit fault occurs at the terminal of the generator. Assuming the input mechanical power to remain at 1 pu, the value of _ in degrees, 0.02 second after the fault is_____

[GATE-2015]

Q.18 The figure shows the single line diagram of a single machine infinite bus system.



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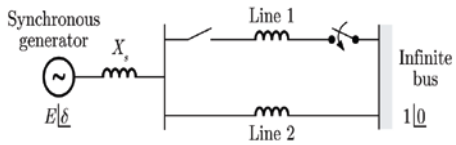
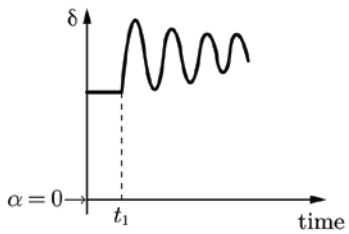
The inertia constant of the synchronous generator H = 5 MW-s/MVA. Frequency is 50 Hz. Mechanical power is 1 pu. The system is operating at the stable equilibrium point with rotor angle d equal to 30c. A three phase short circuit fault occurs at a certain location on one of the circuits of the double circuit transmission line. During fault, electrical power in pu is $P_{max} \sin\delta$. If the values of δ and $d\delta/dt$ at the instant of fault clearing are 45^0 and 3.762 radian/s respectively, then P_{max} (in pu) is _____.

[GATE-2014]

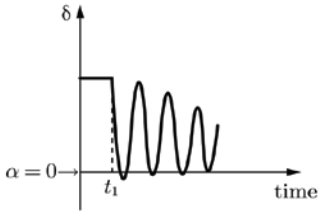
Q.19 The synchronous generator shown inthe figure is supplying active power to aninfinite bus via two short, lossless transmission lines, and is initially in steady state. The mechanical power input to the generator and the voltage magnitude E are constant. If one line is tripped at time t_1 by opening the circuit breakers at two ends (although there is no fault), then it is seen that the generator undergoes a stable transient. Which one of the following waveforms of the rotor angle _shows the transient correctly ?



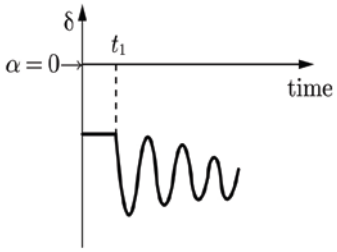
(A)



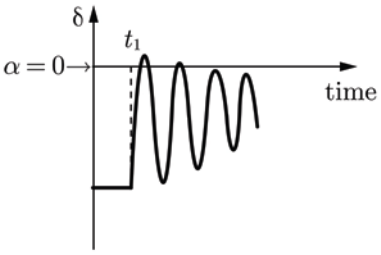
(B)



(C)



(D)



[GATE-2015]

Q.20 The figure shows the single line diagram of a power system with a double circuit transmission line. The expression for electrical power is 1.5 sin δ , where δ is the rotor angle. The system is operating at the stable equilibrium point with mechanical power equal to 1 pu. If one of the transmission line circuits is removed, the maximum value of δ , as the rotor swings is 1.221 radian. If the expression for electrical power with one transmission line circuit removed is P_{max} sin δ , the value of P_{max} in pu is _____. (Give the answer up to three decimal places)

[GATE-2017]

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Q.21 A 3 – phase, 2 – pole, 50 Hz, synchronous generator has a rating of 250 MVA, 0.8 pf lagging. The kinetic energy of the machine at synchronous speed is 100 MJ. The machine is running steadily at synchronous speed and delivering 60 MW power at a power angle of 10 electrical degrees. If the load is suddenly removed, assuming the acceleration is constant for 10 cycles, the value of the power angle after 5 cycles is_____ electrical degrees.

[GATE-2017]

ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(c)	(c)	(c)	(b)	(b)	(d)	(d)	(c)	(b)	(c)	(a)	(d)	(a)	(d)
15	**16**	**17**	**18**	**19**	**20**	**21**							
0.11	50	5.9	(a)	0.23	1.22	12.7							

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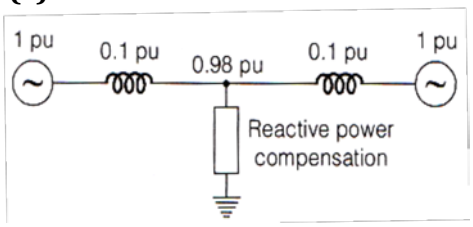
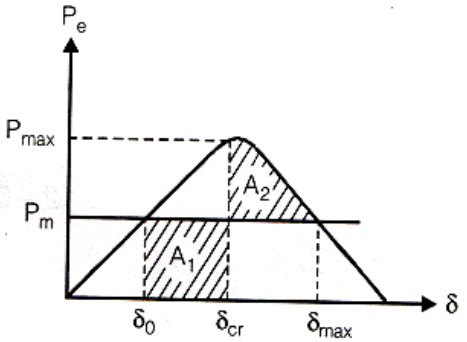
EXPLANATIONS

Q.1 **(c)**



$$P_{ss}=\frac{1\times0.98}{0.1}+\frac{1\times0.98}{0.1}=19.6pu$$

Q.2 **(c)**



Power generated by the generator

$P_e = P_{max}\sin\delta$

At δ_0

P_e =1p.u.

P_{max} =2p.u.

δ_{cr} =rotor angle at t=t_c

$P_e = P_{max}\sin\delta$

$1=2\delta_0$

$\delta_0 = 30°$

During fault ,P_e becomes zero and the fault is cleared at δ_{cr} Mechanical input to the generator remains constant , $P_m = 1$p.u.

Applying equal areal criterion

$A_1 = A_2$

$$A_1 = \int_{\delta_0}^{\delta_{cr}} (P_m - 0)\,d\delta = P_m(\delta_{cr}-\delta_0) \quad ...(i)$$

$$A_2 = \int_{\delta_{cr}}^{\delta_{max}} (P_{max}\sin\delta - P_m)\,d\delta$$

$$= P_{max}(\cos\delta_{cr}-\cos\delta_{max}) - P_m(\delta_{max}-\delta_{cr}) \quad ...(ii)$$

Equating equation (i) and (ii)

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

$$\cos\delta_{cr} = \frac{1}{2}\times(110\times30)\times\frac{\pi}{180} + \cos 110$$

$$\delta_{cr} = 69.14°$$

Q.3 **(c)**

Parameter of the line

Inductance =L=1.1mH/km

Capacitance = C = 11.68nFmH / km

Surge impedance of the line

$$= Z_s = \sqrt{\frac{L}{C}} = \sqrt{\frac{1.1\times10^{-3}}{11.68\times10^{-9}}}$$

$$\Rightarrow Z_s = 306.88\Omega$$

Ideal power transfer capability

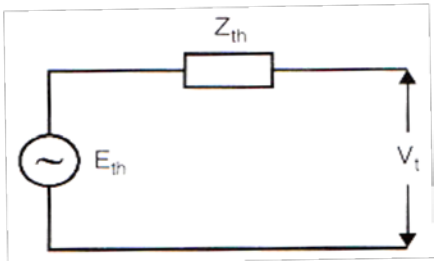
$$= \frac{V_{l\text{-}l}^2}{Z_s} = \frac{(800\times10^3)^2}{306..88}$$

$$\approx 2085\times10^6$$

$$\approx 2085MW$$

Q.4 **(b)**

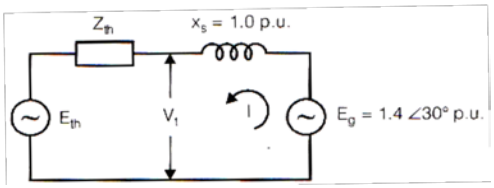
Thevenin's equivalent of existing system



Where

$Z_{th} = 0.25\angle90°$p.u.

$E_{th} = 0.9\angle0°$p.u.



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$$I = \frac{E_g - E_{th}}{j X_s + Z_{th}} = \frac{1.4\angle 30° - 0.9\angle 0°}{j\,1 + 0.25\angle 90°}$$

$= 0.56 - j0.25$p.u.

$V_t = E_g - jIx_s$

$= 1.4\angle 30°(0.56 - j0.25) \times (j1)$

$= 0.973\angle 8.27°$p.u.

$|V_t| = 0.973$p.u.

Q.5 (b)

Before fault, mechanical input (P_m) =Electrical output (Pe)

$= 500 \times 0.8 = 400$MW

After fault, mechanical input remains same $= P_m = 400$MW

While electrical output reduces by 40%

So, electrical output at the time of fault

$= (P_e)_f = 0.6 \times 400 = 240$MW

Accelerating Power = $P_a = P_m - (P_e)_f$

=400-240=160 MW

Synchronous speed (in rad/sec) $= \omega_s$

$$= \frac{2\pi N_s}{60} = \frac{2\pi \times 1500}{60}$$

$= 157$rad / sec

$P_a = T_a \omega_s$

$$\Rightarrow T_a\,(\text{accelerating Torque}) = \frac{P_a}{\omega_s}$$

$$= \frac{160}{157} \text{MN} - \text{m}$$

$= 1.018$MN – m

Q.6 (d)

Power transfer capacity αV^2

$$\frac{P_1}{P_2} = \frac{V_1^2}{V_2^2}$$

$$= P_2 = P_1 \times \left(\frac{V_2}{V_1}\right)^2$$

$$= P \times \left(\frac{400}{800}\right)^2 = \frac{P}{4}$$

Q.7 (d)

Induced emf of the generator $= |t_g| = 1$p.u.

Terminal voltage $= |V_t| = 1$p.u.

Reactance of transformer $= X \,||\, X = \frac{X}{2}$

Steady state stability power limit

$$= P_1 = \frac{|E_g||V_t|}{X_t + \frac{X}{2}} = \frac{|x|}{0.12 + \frac{X}{2}}$$

$$6.25 = \frac{1}{0.12 + \frac{X}{2}}$$

$X = 0.08$p.u.

When one of the double circuit is tripled, steady state stability power limit

$$= P_2 = \frac{|E_g||V_t|}{X_t + X} = \frac{|x|}{0.12 + 0.08} = 5 \text{ p.u.}$$

Q.8 (c)

Before fault

Electrical power delivered by the generator $= P_e = 1.0$p.u.

Mechanical input to the generator $= P_m$ At steady state,

$P_m = P_e = 1.0$p.u.

During fault

Initial rotor angle $= \delta = 30°$

Internal voltage of the generator $= |E_g|$

$= 1.1$p.u.

Voltage of the bus $= |V| = 1$p.u.

Equivalent transfer admittance =0.8

Transfer reactance $= x = \frac{1}{0.8} = 1.25$

$(P_e)_f$ = Electrical power deliveres by the generator

During fault $= \frac{|E_g||V_t|}{x} \sin\delta$

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$(P_e)_f = \frac{1.1\times1}{1.25}\sin 30° = 0.44\text{p.u}$

Mechanical input do not change during fault

So, $(P_m)_f = 1\text{p.u.}$

Accelerating power

$= P_a = (P_m)_f - (P_e)_f$

$\Rightarrow P_a = 1-0.44 = 0.56\text{p.u.}$

Q.9 (b)

Inertia constant (in MJ-s/elect deg)

$=M=\frac{GH}{180f}$

Where, G=Machine rating

=100MVA

H= Inertia constant in MJ/MVA

=5MJ/MVA

$M = \frac{GH}{180f} = \frac{5\times100}{180\times50}$

=0.056 MJ-s/elect deg

$M_{(inp.u.)} = \frac{H}{180f} = \frac{5}{180\times50}$

$\alpha =$ Acceleration in elect deg / sec

$M\alpha = P_a$

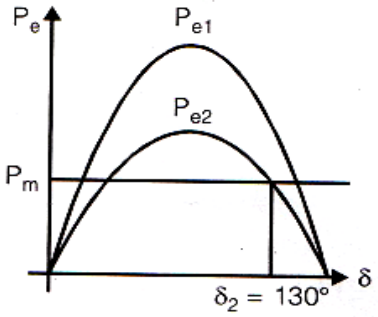
$P_a =$ Accelerating power $= X$

$\alpha = \frac{P_a}{M} = \frac{X}{(5/180\times50)}$

$=1800X$ elct deg / sec

Q.10 (c)

The curve P_{e_1} and P_{e_2} represents power before the tripping of one line and after the tripping respectively



$P_{emax2} = \frac{EV}{X_2}$

$X_2 = 0.1+X$

For max value of X system will not losses synchronization, if at δ_2

$P_{e2} = P_m$

$\Rightarrow \frac{EV}{X_2}\sin\delta_2 = P_m$

$\frac{1\times1}{X_2}\sin130° = 1$

$X_2 = 0.77$

$\Rightarrow X = 0.67$

Q.11 (a)

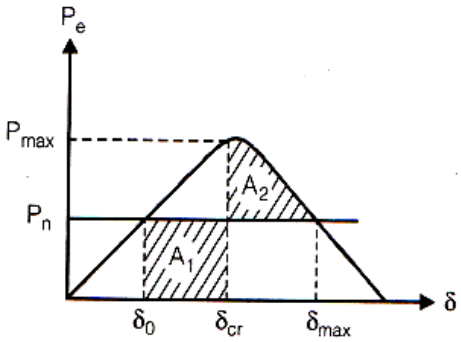
Here, change in (freq). w.r.t to power

$\left(\frac{5}{15}\right)\times3.5 = 1.16\%$

$\therefore \Delta f = 0.583$

$\therefore f = 50-0.583 = 49.417\text{Hz}$

Q.12 (d)



For such faults

δ_{cr} is given by

$\delta_{cr} = \cos^{-1}(\pi-2\delta_0)\sin\delta_0 - \cos\delta_0] \ldots.(i)$

And

t_{cr} =critical cleaning time

$= \left(\frac{2H(\delta_{cr}-\delta_0)}{\pi f P_m}\right)^{1/2} \quad \ldots(ii)$

Case 1:

When only one generator is connected Mechanical input to the generator (P_{m_1})

= Electrical power delivered by the gerator (P_{e_1})

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$\Rightarrow P_{m_1} = P_{e_1} = 1\text{p.u.}$

Case 2:

When two generator connected in parallel Electrical power delivered by each generator

$\left(P_{e_2}\right) = 0.5\text{p.u.}$

Mechanical input to each generator

$\left(P_{m_2}\right) = P_{e_2} = 0.5\text{p.u.} = \dfrac{P_{m_1}}{2}$

Assuming δ_0 in each case same

$\delta_{0_1} = \delta_{0_2} = \delta_0$

So, δ_{cr} will also be same in both cases, (from equation (i)

$t_{cr} \propto \dfrac{1}{\sqrt{P_m}} \left(\delta_{cr}, \text{H and} \delta_0 \text{are same}\right)$

$\therefore t_{cr_2} = \sqrt{\dfrac{P_{m_1}}{P_{m_2}}} \times t_{cr_1}$

$t_{cr_2} = \sqrt{\dfrac{P_{m_1}}{P_{m_1}/2}} \times 0.28$

$= \sqrt{2} \times 0.28 = 0.396\,\text{sec}$

Q.13 (a)

J = moment of inertia

$= 27.5 \times 10^3\,\text{kg} - \text{m}^2$

Synchronous speed $= N_s$

$= \dfrac{120f}{P} = \dfrac{120 \times 50}{2} = 300\text{rpm}$

Kinetic energy of the rotor

$= \dfrac{1}{2} j\omega_s^2 = \dfrac{1}{2} \times 27.5 \times 10^3 \times (314.16)^2$

K.E.=1357MJ

G=Machine rating $= \dfrac{500}{pf} = \dfrac{500}{0.9}$

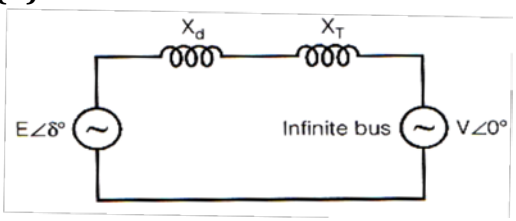
$= 555.55\text{MVA}$

Inertial constant

$H = \dfrac{\text{K.E.}}{G} = \dfrac{1357}{555.55}$

$= 2.44\text{MJ/MVA}$

Q.14 (d)



$P_e = \dfrac{|E||V|}{(X_d + X_T)} \sin\delta_0$

$0.5 = \dfrac{1.5 \times 1}{(1+0.5)} \sin\delta_0$

$\delta_0 = \sin^{-1}(0.5) = 30° = \dfrac{\pi}{6}$

Critical clearing angle

$\delta_{cr} = \cos^{-1}\left[(\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0\right]$

$= \cos^{-1}\left[\left(\pi - \dfrac{\pi}{3}\right) \times \dfrac{1}{2} - \dfrac{\sqrt{3}}{2}\right]$

$= \cos^{-1}(0.18) = 79.56°$

Q.15 (0.1092)

Correct answer is 0.1092 .

As active power in synchronous generator is given by

$$P = \frac{E_f V}{X_s} \sin\,\delta$$

δ = Load angle

$$0.6\,\frac{1.3 \times 1}{1.1} \sin\delta$$

$\left\{ E_f = 1.3\text{ pu, V} = 1\text{ pu,} \right.$

$\left. X_s = 1.1\ ph,\ P = 0.6\ pu \right\}$

$\sin\,\delta = \dfrac{0.6 \times 1.1}{1.3 \times 1}$

$\sin\,\delta = 0.5077$

$\delta = 30.504^0$

Reactive power is given by

$$Q = \frac{E_f V}{X_s} \cos\,\delta - \frac{V^2}{X_s}$$

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$$= \frac{1.3 \times 1}{1.1} \cos\left(30.504^0\right) - \frac{1^2}{1.1}$$

$$Q = 1.1818 \times 0.8616 - 0.9090$$

$$Q = 0.1092 \text{ pu}$$

Q.16 (50)

Since the generators are in parallel, they will operate at the same frequency ^f h at steady loss. Let load on generator G_1 is P_1 and on G_2 is P_2. Then we can write for generator G_1 Now in steady state total load is 2.5MW, so load by second generator is (2.5 - P_1).

For G_2 we write

$$\frac{51.5}{P_1} = \text{droop constant}$$

$$\frac{51.5 - f}{P_1} = 1$$

$$51.5 - f = P_1$$

$$\frac{51 - f}{2.5 - P_1} = 1$$

$$51 - f = 2.5\ P_1$$

Adding eq (i) and (ii), we get

$$51.5 - f + 51 - f = P_1 + 2.5 - P_1$$

$$102.5 - 2f = 2.5$$

$$2f = 100$$

$$f = 50 \text{ Hz}$$

Q.17 (5.9)

Given

Inertia constant, H = 2 MJ/MVA.

Initial rotor angle = 5°

Pm = 1 P.U.

Here, mechanical momentum is

$$m = \frac{GH}{\pi f} = \frac{2}{180\text{x}50} = \frac{1}{4500} P.U$$

A bolted three phase to ground short circuit fault occurs at the terminal of the generator, so

$$m\alpha = P_m - P_c$$

$$m = \frac{P_m - 0}{\alpha} = 4500 \text{ deg/ sec}$$

Hence, the change in angle is

$$\Delta\delta = \frac{1}{2} x t^2$$

$$= \frac{1}{2} x 4500 x (0.2)^2$$

$$= 4500 x 0.01 x 0.02$$

$$= 9000 x 10^{-4}$$

$$\Rightarrow \Delta\delta = 0.9°$$

After 0.02 sec, we have

$$\delta = \delta_1 + \Delta\delta$$

$$= 5 + 0.9$$

$$= 5.9°$$

Q.18 (0.23)

Given H = 5MW-S/MVA

f = 50 Hz

P_m = 1 pu

δ = 30°

at the instance of fault clearing

δ = 45°, $\frac{d\delta}{dt} = 3.762$ rad/s

$$\frac{d^2\delta}{dt^2} = \frac{1}{M}[P_m - P_e]$$

$$\frac{d\delta}{dt} = \left[\frac{2}{M}\int_{\delta 0}^{\delta}(P_m - P_e)ds\right]^{1/2}$$

$$= \left[\frac{2}{4/\pi f}\int_{30}^{45°}(1 - P_{max}\sin\delta)ds\right]^{1/2}$$

$$3.762 = \left[\frac{2 \times \pi \times 50}{5}(\delta + P_{max}\cos\delta)_{30}^{45}\right]^{1/2}$$

$$141.52 = 20\pi\ \{(45° - 30°) + P_{max}(\cos 45° - \cos 30°)\}$$

P_{max} = 0.24 pu

Q.19 (a)

Correct option is (A).

Since, it is generator, so rotor angle _ is also positive. So, options (C) and (D) are incorrect. Again, if one line is tripped, then due to unstable operation of generator, δ increases.

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Waveform shown in option (A) satisfies the condition.

Q.20 (1.220)

$P_{e1} = P_{max} \sin \delta_0$

$P_s = 1pu$

Initially Pa = 0 = Ps = Pe1

$1 = 1.5 \sin\delta_0$

$\delta_0 = \sin^{-1}\left(\frac{1}{1.5}\right) = 41.81030°$

$P_{e2} = P_{max} \sin \delta_{max};$

$\delta_{max} = 1.22°$

$= 1.22x\frac{180}{\pi} = 69.90085°$

$P_{max1} = \frac{P_s(\delta_{max} - \delta_0)}{\cos\delta_0 - cos\delta_{max}}$

$= \frac{(69.90085° - 41.81030°)x\frac{\pi}{180}}{\cos 41.81030° - cos69.90085°}$

$= 1.22$

Q.21 (12.7)

$\cos\phi = 0.8lag$

$G = 250MVA$

$P = 2$

$KE = \frac{1}{2}J\omega_s^2$

$10^6 x1000 = \frac{1}{2}J(2\pi N_s)^2$

$N_s = \frac{120x50}{2} rpm; P_a = P_s - P_e = 0$

$\Rightarrow P_s = 60MW$

$J = 5.62$

$P_e = \frac{EV}{X}\sin\delta_0$

$60x10^6 = \frac{EV}{X}\sin 10°$

$P_{max} = \frac{EV}{X} = 345.52x10^6$

$P_a = P_s - P_e (0 \text{ initially } P_s = P_e)$

$P_a = P_s (\therefore P_e = 0 \text{ when load is removed})$

$P_a = P_s = 60MW$

$M = \frac{GH}{\pi f} = \frac{250xH}{\pi f}$

$H = \frac{KE}{\text{Rating of the machine}} = \frac{1000X10^6}{250X10^6} = 4$

$\delta(t) = \left(\frac{P_a}{2M}\right)t^2 + \delta_0$

$\delta_0 = 10elec \deg$

$P_a = 60MW$

$M = \frac{250x10^6x4}{11x50} = 6.366x10^6$

1 cycle $\rightarrow$ 20 m sec

5 cycles $\rightarrow$ 100 m sec

$\delta(t)|_{t=100msec} = \left(\frac{60x10^6}{2x6.366x10^6}\right)x\frac{180}{\pi}x(100x10^{-3})^2 + 10$

$= 12.7$

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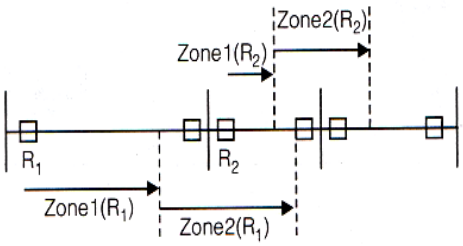
7 SWITCH GEAR AND PROTECTION

Q.1 Consider the problem of relay coordination for the distance relay R1 and R2 on adjacent lines of a transmission system figure. The zone 1



and zone 2 settings for both the relays are indicated on the diagram. Which of the following indicates the correct time setting for the zone 2 of relays R1 and R2?

a) $TZ2_{R1}$=0.6s,$TZ2_{R2}$=0.3s

b) $TZ2_{R1}$=0.3s,$TZ2_{R2}$=0.6s

c) $TZ2_{R1}$=0.3s,$TZ2_{R2}$=0.3s

d) $TZ2_{R1}$=0.1s,$TZ2_{R2}$=0.3s

[GATE-2002]

Q.2 The interrupting time of a circuit breakers is the period between the instant of

a) initiation of short circuit and the arc extinction on an opening operation
b) Energizing of the trip circuit and the arc extinction on an opening operation
c) Initiation of short circuit and the parting of primary arc contacts
d) energizing of the trip circuit and the parting of primary arc contacts

[GATE-2003]

Q.3 A list of relays and the power system components protected by the relays are given in List-1 and List –II respectively Choose the correct match from the four choices given below:

List –I	**List –II**
A. Distance relay	1.Transformers
B. Under frequency	2.Turbines
C. Differential relay	3.Busbars
D. Buchholz relay	4.Shunt capacitors
	5.Alternators
	6.Transmission lines

Codes:

	A	**B**	**C**	**D**
a)	6	5	3	1
b)	4	3	2	1
c)	5	2	1	6
d)	6	4	5	3

[GATE-2003]

Q.4 The transmission line distance protection relay having the property of being inherently directional is

a) impedance relay
b) MHO relay
c) OHM relay
d) reactance relay

[GATE-2004]

Q.5 A lightning stroke discharges impulse current of 10kA (peak) on a400kV transmission line having surge impedance of 250 Ω .The magnitude of transient over- voltage travelling waves in either direction assuming equal distribution from the point of lighting strike will be

a) 1250V b) 1650V
c) 2500kV d) 2900kV

[GATE-2004]

Q.6 Keeping in view the cost and overall effectiveness, the following circuit breakers is best suited for capacitor bank switching

a) vacuum b) air blast
c) SF_6 d) oil

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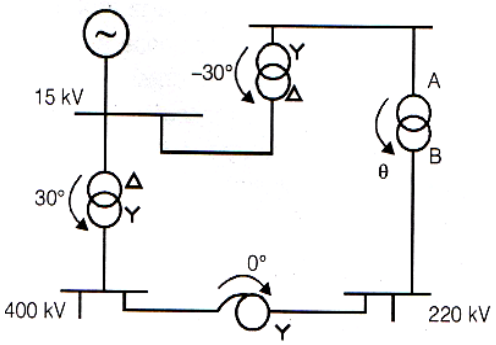
[GATE-2006]

Q.7 In a biased differential relay the bias is defined as a ratio of

a) number of turns of restraining and operating coil
b) Operating coil current and restraining coil current
c) Fault current and operating coil current
d) Fault current and restraining coil current

[GATE-2006]

Q.8 Consider the transformer connections in a part of a power system shown in the figure. The nature of transformer connections and phase shifts are indicated for all but one transformer Which of the following connections, and the corresponding phase shift θ, should be used for the transformer between A and B?

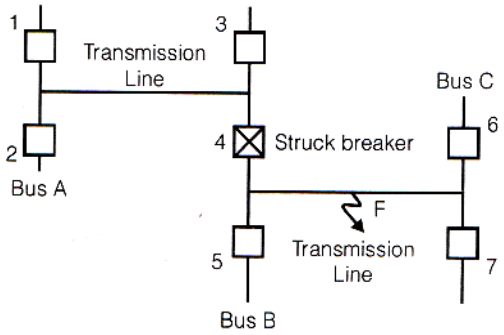


Autotransformer

a) Star –Star $(\theta = 0°)$
b) Star –Delta $(\theta = -30°)$
c) Delta- Star $(\theta = 30°)$
d)Star-Zigzag $(\theta = 30°)$

[GATE-2007]

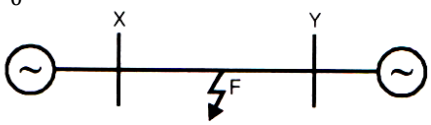
Q.9 Consider the protection system shown in the figure below. The circuit breakers numbered from 1 to 7 are of identical type. A single line to ground fault with zero fault impedance occurs at the midpoint of the line (at point F) but circuit breakers 4 fails to operate ("Stuck breaker") if the relays are coordinated correctly , a valid sequence of circuit breaker operation is



a)1,2,6,7,3,5 b)1,2,5,5,7,3
c)5,6,7,3,1,2 d)5,1,2,3,6,7

[GATE-2007]

Q.10 A two machine power system is shown below. Transmission line XY has positive sequence impedance of $Z_1\Omega$ and zero sequence impedance of $Z_0\Omega$



An 'a' phase to ground fault with zero fault impedance occurs at the centre of the transmission line .Bus voltage at X and line current form X to F for phase 'a' are given by V_a Volts and l_a Amperes., respective Then the impedance measured the ground distance relay located at the terminal X of line XY will be given by

a) $Z_1 / 2\Omega$ b) $Z_0 / 2\Omega$
c) $(Z_0 + Z_1)/2\Omega$ d) $V_a / l_a\Omega$

[GATE-2008]

Q.11 Voltage phasors at the two terminals of a transmission line of length 70km have a magnitude of 1.0per unit but are 180 degrees out of phase. Assuming that the maximum load current in the line is $1/5^{th}$ of minimum 3-phase fault current. Which one of the following transmission line protection

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schemes will NOT pick up for these conditions?

a) Distance protection using mho relays with zone -1 set to pick up at80% of the line impedance
b) Directional overcorrect protection set to pick up at 1.25 times the maximum load current
c) Pilot relaying system with directional comparison scheme
d) Pilot relaying system with segregated phase comparison scheme

[GATE-2008]

Q.12 Match the items in List-I (Type of transmission line) with the items in List –II (Type of distance relay preferred) and select the correct answer using the codes given below the lists

List-I	**List-II**
A Short Line	1.Ohm Relay
B. Medium Line	2.Reactance Relay
C. Long Line	3. Mho Relay

	A	**B**	**C**
a)	2	1	3
b)	3	2	1
c)	1	2	3
d)	1	3	2

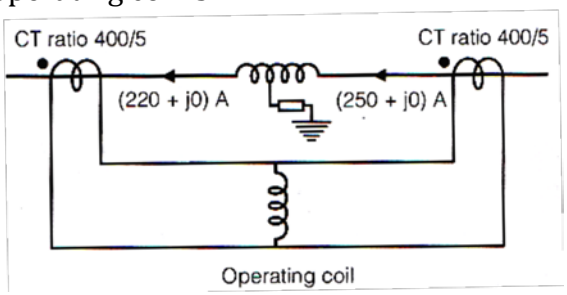
[GATE-2009]

Q.13 A three –phase, 33 kV oil circuit breaker is rated 1200A, 2000MVA, 3s. The symmetrical breaking current is

a) 1200A b) 3600A
c) 35kA d) 104.8kA

[GATE-2010]

Q.14 Consider a stator winding of an alternator with an internal high-resistance ground fault.The currents under the fault condition are as shown in the figure. The winding is protected using a differential current scheme with current transformers of ratio 400/5 A as shown. The current through the operating coil is

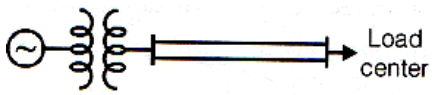


a)0.1875A b)0.2A
c)0.375A d)60kA

[GATE-2010]

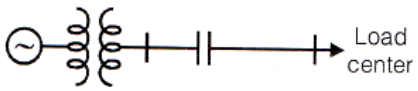
Q.15 A nuclear power station of 500MW capacity is located at 300km away from a load center. Select the most suitable power evacuation transmission configuration among the following options

a)



132 kV, 300 km double circuit

b)



132 kV, 300 km single circuit with 40% series capacitor compensation

c)

400 kV, 300 km single circuit

d)

400 kV, 300 km double circuit

[GATE-2011]

Q.16 A negative sequence relay is commonly used to protect.

a) an alternator
b) a transformer
c) a transmission line
d) a bus bar

[GATE-2011]

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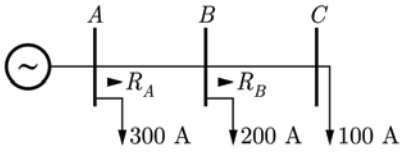
Q.17 The over current relays for the line protection and loads connected at the buses are shown in the figure.



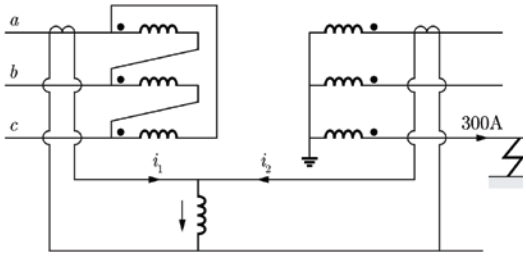
The relays are IDMT in nature having the characteristic

$$t_{op} = \frac{0.14 \times \text{Time Multiplier Setting}}{(\text{Plug Setting Multiplier})^{0.02} - 1}$$

The maximum and minimum fault currents at bus *B* are 2000 A and 500 A respectively. Assuming the time multiplier setting and plug setting for relay R_B to be 0.1 and 5 A respectively, the operating time of R_B (in seconds) is____.

[GATE-2014]

Q.18 A 3-phase transformers rated for 33 kV/11 kV is connected in delta/star as shown in figure. The current transformer (CTs) on low and high voltage sides have a ratio of 500/5. Find the currents i_1 and i_2, if the fault current is 300 A as shown in figure.



(A) $i_1 = 1/\sqrt{3}$ A, $i_2 = 0$ A

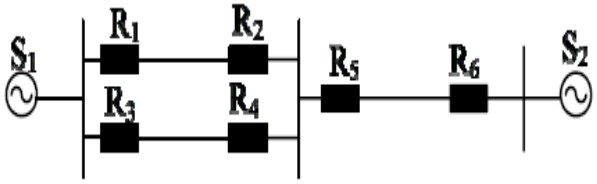
(B) $i_1 = 0$ A, $i_2 = 1$ A

(C) $i_1 = 0$ A, i_2 $\sqrt{3}$A

(D) $i_1 = 1/\sqrt{3}$ A, $i_2 = 1/\sqrt{3}$A

[GATE-2015]

Q.19 A power system with two generators is shown in the figure below. The system (generators, buses and transmission lines) is protected by six over current relays R_1 to R6. Assuming a mix of directional and non directional relays at appropriate locations, the remote backup relays for R_4 are



(A) R_1, R_2 (B) R_2, R_6

(C) R_2, R_5 (D) R_1, R_6

[GATE-2016]

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ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(c)	(b)	(a)	(b)	(a)	(a)	(a)	(a)	(c)	(d)	(a)	(a)	(c)	(c)
15	**16**	**17**	**18**	**19**									
(d)	(a)	0.226	(a)	(d)									

EXPLANATIONS

Q.1 **(c)**

Q.2 **(b)**

Note:

When a fault occurs in the protected circuit , the connected to the CT actuates and closes its contact Current flows from the battery in the trip circuit. As the trip coil of the breakers is energized the circuit breaker operating mechanism is actuated.

Q.3 **(a)**

Note:

Buccholz Relay is used to protect transformers which operates when the oil level in the conservator pipe of a transformer is lowered by the accumulation or by an incipient breakdown of insulation (slowly developing fault).

A differential relay is a suitably connected over current relay operating on the two ends of a protected element.

Q.4 **(b)**

MHO relay has the property of being inherently directional.

Note:

$Q=k_3|V||I|\cos(\theta-\tau)-(-k_1)|V|^2$

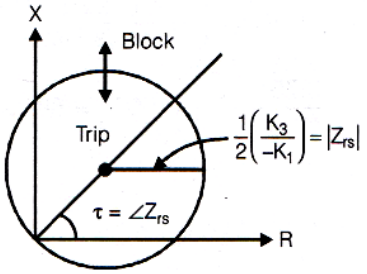
For relay operation

$Q>0$

$k_3|V||I|\cos(\theta-\tau)-(-k_1)|V|^2>0$

$$\frac{|V|}{|I|}=|z|<\frac{k_3}{-k_1}\cos(\theta-\tau) \quad ....(i)$$

The right had side of equation (i) is a circle with central located o the line determined by the parameter τ and passing through, the origin.



Q.5 **(a)**

The impulse current of 10KA (peak) will be equally divided in both directions since there is equal distribution on both sides. Then, magnitude of transient over voltage

$\left(\frac{10}{2}\right)$KA×250 =1250kv

Q.6 **(a)**

The arc time constant is the least (a few μs) in vacuum circuit breakers as compared to other breaker types. The rapid building up of dielectric strength after final arc extinction (20kV/ μs) is unique feature of VCBs. These arcs, therefore, ideally suited for capacitor switching

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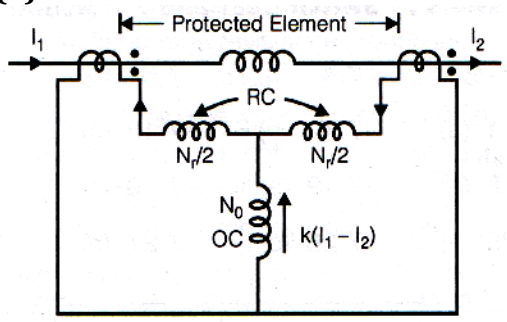
Q.7 **(a)**



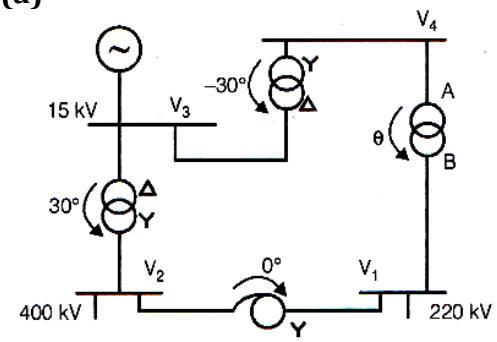
$$N_0 k|I_1 - I_2| > \frac{N_r}{2} k|I_1 + I_2|$$

$$|I_1 - I_2| > \frac{N_r}{N_0}\left|\frac{I_1 + I_2}{2}\right|$$

Where N_0 = Number of turns of the operating coil

N_r = Number of turns of the restraining coil. The relay operates when the magnitudes of the difference in the currents at the two ends of a protected exceeds a certain percentage $((N_r/N_0)/100)$ of half the magnitude of their sum.Hence the name percentage differential relay.

Q.8 **(a)**



TakingV_1 as the reference

$V_1 = 220\angle 0°\text{kV}$

$\angle\theta_1 = 0°$

Phase difference V_2 and $V_1$is 0°

So, $V_2 = 400\angle 0°\text{kV}$

V_2 leads V_3 by 30° kV

So, $V_3 = 15\angle 30°\text{kV}$

$\angle\theta_3 = -30°$

V_3 lagss V_4 by 30°

$\angle\theta_3 = \angle\theta_4 - 30°$

$\angle\theta_4 = \angle\theta_3 + 30° = -30° + 30° = 0°$

phase different

between V_1 and V_4 is θ

$\theta = \angle\theta_1 - \angle\theta_4$

$= 0 - 0 = 0°$

So, option (a) is correct

Q.9 **(c)**

If they are co- ordinate correctly due to fault in a particular section, relay in that section must operate first, then relay in nearby section if first fails, it is back up protection ,Thus the sequence is [5,6,7,3,1,2]

Q.10 **(d)**

As the ground distance relay is located at terminal x

Impedance measured by the relay

$$= \frac{\text{Busvoltage}}{\text{current}} = \frac{V_a}{I_a}$$

Q.11 **(a)**

Distance protection using mho relay with zone I set to 80% of the line impedance will not provide protection.

Q.12 **(a)**

Impedance Relay

Impedance relay is a voltage restrained over current relay

$T = k_1 I^2 - k_2 V^2$

Reactance Relay

Reactance relay is an over – current relay with directional restraint

$T = k_1 I^2 - k_3 VI \sin\theta$

Mho Relay

Mho relay is a voltage restrained direction relay.

$T = k_3 VI\cos\cos(\theta - t) - k_2 V^2$

Mho relay is inherently directional.

Q.13 **(c)**

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Rated MVA of circuit breaker =200MVA

$\sqrt{3}\times|V(\text{line}|_{\text{rated}} \times \text{Symmetrical breaking}$

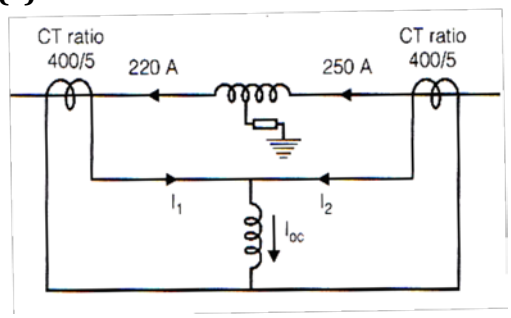
Current =rated MVA of CB

Symmetrical breaking current

$=\frac{200}{\sqrt{3}\times 33}$

=35kA

Q.14 (c)



$l_1=200\times\left(\frac{5}{400}\right)=2.75A$

$l_2=250\times\left(\frac{5}{400}\right)=3.125A$

Current through operating coil $=l_{oc}$

$=l_2-l_1=3.125-2.75$

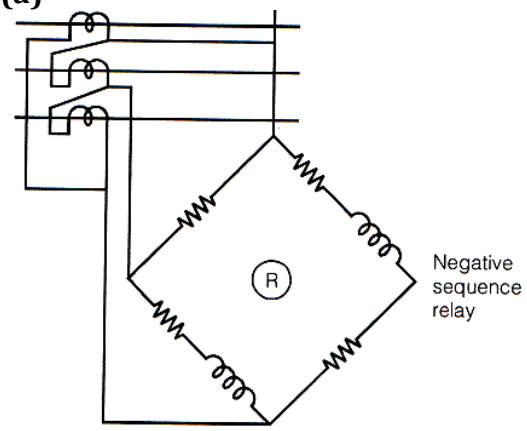
=0.375A

Q.15 (d)

For transmission of bulk power of very long distance high voltage (400kV) is used.

To increase reliability, double circuit is used.

Q.16 (a)

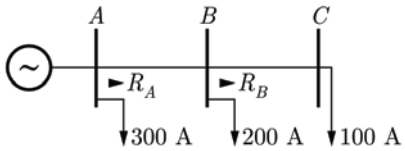


The negative sequence current segregating network is used, the output of which is proportional to the generator negative phase sequence current and is fed into a relay with an inverse square law characteristic

Q.17 (0.226)

Correct answer is 0.226.

We have the circuit,



The operating time of relays is given as

$$t_{op}=\frac{0\ 14\times \text{Time Multiplier Setting}(\text{TMS})}{(\text{Plug Setting Multiplier})^{0.02}-1}$$

For relay *RB* , we have

$TMS = 0.1$

$$\text{PSM}=\frac{\text{maximum fault current}}{\text{CT ratio}}$$

$$=\frac{2000}{500/5}=20$$

Substituting the values in equation (i), we get

$$t_{op}=\frac{0.14\times 0.1}{(20)^{0.02}-1}=\frac{0.14\times 0.1}{0.617}$$

0.226

Q.18 (a)

Correct option is (A).

Given that 3-phase transformer 33/11 kV is connected in delta-star connection.

Since, fault is in star connected side, so all the current flow through fault and no current will pass through circuit of secondary side, i.e.

$i_2 = 0$

By using transformer equation, we have

Primary kVA = Secondary kVA

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or $\sqrt{3} \times V_L I_L = \sqrt{3}\, V_L I_L$

$$\text{or} \sqrt{3} \times 33000 \times I_L = \sqrt{3} \times 11000 \times \left(300 \times \frac{5}{500} \right)$$

So, $I_L = 1A$

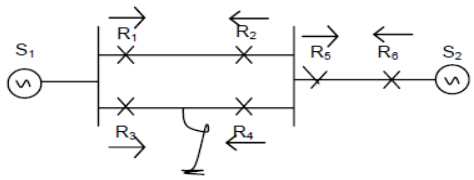
Since, primary side is delta connected. So, we have

$$I_L = \sqrt{3} I_{ph}$$

or $\sqrt{3} I_{ph} = 1$

Hence, $I_{ph} = \frac{1}{\sqrt{3}} A$

Q.19 (d)



* If a fault was taken place b/w (3) & (4) R_3 & R_4 must operate.

* If R_4 is failed to operate, then

to limit $I_1 \rightarrow R_1$ must operate

to limit $I_2 \rightarrow R_6$ must operate.

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GENERATING POWER STATION

Q.1 In thermal power plants, the pressure in the working fluid cycle is developed by
a) Condenser
b) super heater
c) Feed water pump
d) turbine

[GATE-2004]

Q.2 For harnessing low variable water heads, the suitable hydraulic turbine with high percentage of reaction and runner adjustable vanes is
a) Kaplan b) Francis
c) Pelton d) impeller

[GATE-2004]

Q.3 Out of the following plant categories
i)Nuclear
ii)Run-of river
iii)Pump Storage
iv) Diesel
The base load power plants are
a)(i) and (ii)
b)(ii) and (iii)
c)(i),(ii) and(iv)
d)(i) (iii) and (iv)

[GATE-2009]

Q.4 Base load power plants are
P: wind farms.
Q: run-of-river plants.
R: nuclear power plants.
S: diesel power plants.
(A) P, Q and S only
(B)
(B) P, R and S only
(C) P, Q and R only (D) Q and R only

[GATE-2015]

ANSWER KEY:

1	2	3	4
(a)	(a)	(c)	(d)

Q.1 **(a)**
Note:
Condenser: The functions of condenser are
i) To provide vacuum at outlet of steam turbine
ii) To condense the stream and pass on the condensate to boiler feed.
Super –heater is a device used to convert saturated steam or wet steam into dry steam used for power generation process

Q.2 **(a)**
Kaplan is used for run –of river and poundage stations with heads of up to 70m (low head) this type has an axial-flow rotor with variable –pitch blades.

Q.3 **(c)**
Pumped storage plants supply power –during peak loads.
Note: Base load –plant
(i) Low operating const
(ii) Capability of working continuously long period=0

Q.4 **(d)**
Base load plants are those plants which supply power for 24 hours. So nuclear,thermal and hydro plant (which runs by water of river) are in the category of Base load.
Peak load plant are those plants which supply power on peak time, like diesel plant, renewable energy developed plant. So, in this category wind, diesel are
included.

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9 LOAD FLOW STUDIES

Q.1 A power system consists of 2 areas (Area 1 ad Area 2) connected by a single tie-line. It is required to carry out a load flow study on this system While entering the network data, the tie line data (connectivity and parameters) is inadvertently left out. If the load flow program is run with this incomplete data.

a) The load flow will converge only if the slack bus is specified in area1
b) The load flow will converge only if the slack bus is specified in area 2
c) The load flow will converge if the slack bus is specified in either area 1 or area 2
d) The load flow will not converge if only one slack bus is specified

[GATE-2002]

Q.2 A power system consist of 300buses out of which 20 buses are generator bus, 25 buses are ones with reactive power support and 15 buses are the ones with fixed shunt capacitors .All the other buses are load buses. It is proposed to perform a load flow analysis in the system using Newton Raphson method. The size of the Newton Raphson Jacobian matrix is

a) 553×553 b) 540 × 540
c) 555×555 d) 554×554

[GATE-2003]

Q.3 The bus impedance matrix of a 4-bus power system is given by

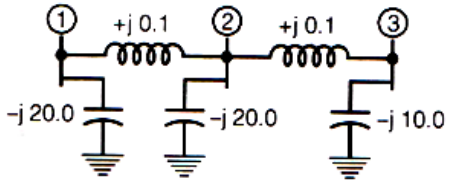
$$Z_{bus} = \begin{bmatrix} j0.3435 & j0.2860 & j0.2723 & j0.2277 \\ j0.2860 & j0.3408 & j0.2586 & j0.2414 \\ j0.2723 & j0.2586 & j0.2791 & j0.2209 \\ j0.2277 & j0.2414 & j0.2209 & j0.2791 \end{bmatrix}$$

A branch having an impedance of j0.2Ω is connected between bus 2 and the reference. Then the values of Z_{22new} and Z_{23new} of the bus impedance matrix of the modified network are respectively

a) j0.5408Ω and j0.4586Ω
b) j0.1260Ω and j0.0956Ω
c) j0.5408Ω and j0.0956Ω
d) j0.1260Ω and j0.1630Ω

[GATE-2003]

Q.4 The network shown in the given figure has impeaches in p.u, as indicated. The diagonal element Y22 of the bus admittance matrix Y_{BUS} of the network is



a) -j19.8 b) +j20.0
c) +j0.2 d) -j19.95

[GATE-2005]

Q.5 The Gauss Seidel load flow method has following disadvantages. Tick the incorrect statement.

a) Unreliable convergence
b) Slow convergence
c) Choice of slack bus affects convergence
d) A good initial guess for voltages is essential for convergence

[GATE-2006]

Statement for common data 6 & 7

For a power system the admittance and impedance matrices for the fault studies are as follows

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$$Y_{bus} = \begin{bmatrix} -j8.75 & j1.25 & j2.50 \\ j1.25 & -j6.25 & j2.50 \\ j2.50 & j2.50 & -j5.00 \end{bmatrix}$$

$$Z_{bus} = \begin{bmatrix} j0.16 & j0.08 & j0.12 \\ j0.08 & j0.24 & j0.16 \\ j0.12 & j0.16 & j0.34 \end{bmatrix}$$

The pre –fault voltages are 1.0p.u. at al the buses. The system unloaded prior to the fault. A solid 3 phase fault takes place at bus 2.

Q.6 The post fault voltages at buses 1 and 3 in per unit respectively are

a) 0.24,0.63 b) 0.31,0.76
c) 0.33, 0.67 d) 0.67,0.33

[GATE-2006]

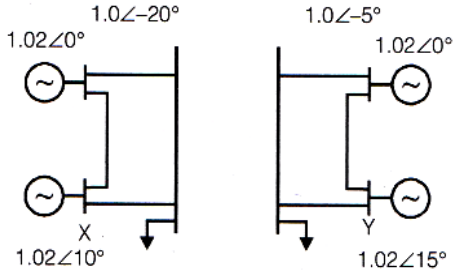
Q.7 The per unit fault feeds from generators connected buses 1 and 2 respectively are

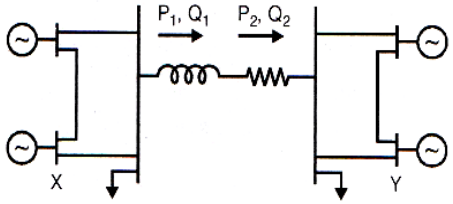
a) 1.20,2.51 b) 1.55,2.61
c) 1.66,2.50 d) 5.00,2.50

[GATE-2006]

Q.8 Consider the two power system shown in figure A below, which are initially not interconnected, and are operating in steady state at the same frequency .Separate load flow solutions are computed individually for the two systems, corresponding to this scenario. The bus voltage phasors so obtained are indicated on figure A. These two isolated systems are now interconnected by short transmission line as shown in figure B, and it is found that

$P_1 = P_2 = Q_1 = Q_2 = 0$





The bus voltage phase angular difference between generator bus X and generator bus Y after the interconnection is

a) 10° b) 25°
c) –30° d) 30°

[GATE-2007]

Q.9 For the Y-bus matrix of a 4-bus system given in per unit, the buses having shunt elements are

$$Y_{BUS} = j\begin{bmatrix} -5 & 2 & 2.5 & 0 \\ 2 & -10 & 2.5 & 4 \\ 2.5 & 2.5 & -9 & 4 \\ 0 & 4 & 4 & -8 \end{bmatrix}$$

a) 3and 4 b) 2 and 3
c) 1 and 2 d) 1,2and 4

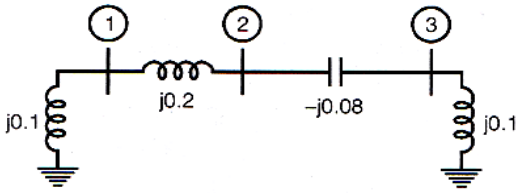
[GATE-2009]

Q.10 Considers two buses connected by an impedance of $(0+j5)\Omega$. The bus 1 voltage is $100\angle 30°$ V, and bus 2 voltage is $100\angle 0°$. The real and reactive power supplied by bus 1, respectively are

a) 1000W,268VAR
b) -1000W,-134VAR
c) 276.9W,-56.7VAR
d) -276.9W,56.7VAR

[GATE-2010]

Q.11 A three-bus network is shown in the figure below indicating the p.u. impedance of each element.



The bus admittance matrix, Y-bus, of the network is

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a) $j\begin{bmatrix} o.3 & -0.2 & 0 \\ -0.2 & 0.12 & 0.08 \\ 0 & 0.08 & 0.02 \end{bmatrix}$

b) $j\begin{bmatrix} -15 & 5 & 0 \\ 5 & 7.5 & -12.5 \\ 0 & -12.5 & 2.5 \end{bmatrix}$

c) $j\begin{bmatrix} 0.1 & 0.2 & 0 \\ 0.2 & 0.12 & -0.08 \\ 0 & -0.08 & 0.10 \end{bmatrix}$

d) $j\begin{bmatrix} -10 & 5 & 0 \\ 5 & 7.5 & 12.5 \\ 0 & 12.5 & -10 \end{bmatrix}$

[GATE-2011]

Q.12 The bus admittance matrix of a three-bus three-line system is

$$Y=j\begin{bmatrix} -13 & 10 & 5 \\ 10 & -18 & 10 \\ 5 & 10 & -13 \end{bmatrix}$$

If each transmission line between the two buses is represented by an equivale π-network, the magnitude of the shunt susceptance of the line connecting bus 1 and 2 is

a) 4 b) 2
c) 1 d) 0

[GATE-2012]

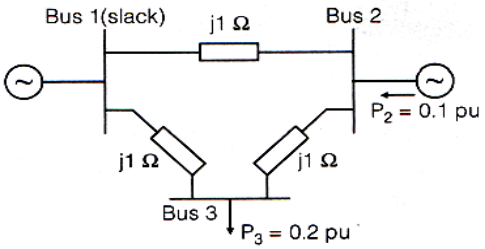
Q.13 A single-phase load is supplied by a single-phase voltage source. If the current flowing from load to the source is $10\angle -150°$ A and if the voltage at the load terminals is $100\angle -60°$ V, then the

a) Load absorbs real power and delivers reactive power
b) Load absorbs real poor and absorbs reactive power
c) Load delivers real power and delivers reactive power
d) Load delivers real power and absorbs reactive power

[GATE-2013]

Statement for linked Answer Questions 14 & 15

In the following network, the voltage magnitudes at all buses are equal to 1.pu., the voltage phase angels are very small, and the line resistances are very small, and the line resistance are negligible. All the line reactance are equal to $j1\Omega$



Q.14 The voltage phase angles in rad at buses 2 and 3 are

a) $\theta_2=-0.1,\theta_3=-0.2$ b) $\theta_2=0,\theta_3=-0.1$
c) $\theta_2=0.1,\theta_3=0.1$ d) $\theta_2=0.1,\theta_3=0.2$

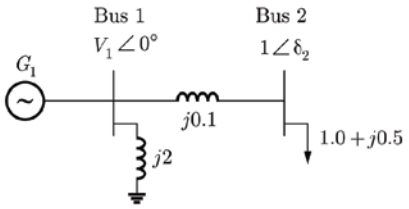
[GATE-2013]

Q.15 If the base impedance and the line – to line base voltage are 100Ω and 100kV, respectively, then the real power in MW delivered by the generator connected at the slake bus is

a) -10 b) 0
c) 10 d) 20

[GATE-2013]

Q.16 A two bus power system shown in the figure supplies load of 1.0 + j0.5 p.u.



The values of V_1 in p.u. and δ_2 respectively are

(A) 0.95 and 6.00^0
(B) 1.05 and -5.44^0
(C) 1.1 and -6.00^0
(D) 1.1 and -27.12^0

[GATE-2014]

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Q.17 A 183 bus power system has 150 PQ buses and 32 PV buses. In the general case, to obtain the load flow solution using Newton-Raphson method in polar coordinates, the minimum number of simultaneous equations to be solved is ____.

[GATE-2014]

Q.18 A 3-bus power system network consists of 3 transmission lines. The bus admittance matrix of the uncompensated system is

$$\begin{bmatrix} -j6 & j3 & j4 \\ j3 & -j7 & j5 \\ j4 & j & -j8 \end{bmatrix} \text{pu}$$

If the shunt capacitance of all transmissions line is 50% compensated, the imaginary part of the 3rd row 3rd column element (in pu) of the bus admittance matrix after compensation is

(A) -j7.0 (B) -j8.5
(C) -j7.5 (D) -j9.0

[GATE-2015]

Q.19 In a 100 bus power system, there are 10 generators. In a particular iteration of Newton Raphson load flow technique (in polar co-ordinates), two of the PV buses are converted to PQ type. In this iteration,

(A) the number of unknown voltage angles increases by two and the number of unknown voltage magnitudes increases by two.

(B) the number of unknown voltage angles remains unchanged and the number of unknown voltage magnitudes increases by two.

(C) the number of unknown voltage angles increases by two and the number of unknown voltage magnitudes decreases by two.

(D) the number of unknown voltage angles remains unchanged and the number of unknown voltage magnitudes decreases by two.

[GATE-2015]

Q.20 A power system has 100 buses including 10 generator buses, for the load flow analysis using Newton –Raphson, method in polar coordinates, the size of the Jacobian is

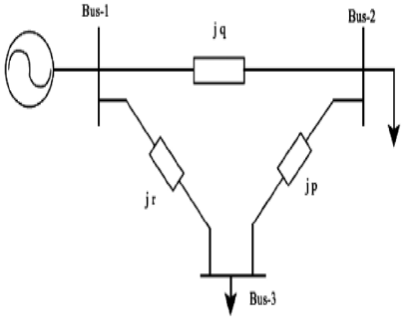
(A) 189 × 189 (B) 100 × 100
(C) 90 × 90 (D) 180 × 180

[GATE-2016]

Q.21 A 10 – bus power system consists of four generator buses indexed as G1, G2, G3, G4 and six load buses indexed as L1, L2, L3, L4, L5, L6. The generator but G1 is considered as slack bus, and the load buses L3 and L4 are voltage controlled buses. The generator at bus G2 cannot supply the required reactive power demand, and hence it is operating at its maximum reactive power limit. The number of non – linear equations required for solving the load flow problem using Newton – Raphson method in polar form is _____.

[GATE-2017]

Q.22 A 3 – bus power system is shown in the figure below, where the diagonal elements of Y – bus matrix are: $Y_{11} = -j12\,pu; Y_{22} = -j15\,pu$ *and* $Y_{33} = -j7\,pu$



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The per unit values of the lines reactance p, q and r shown in the figure are.

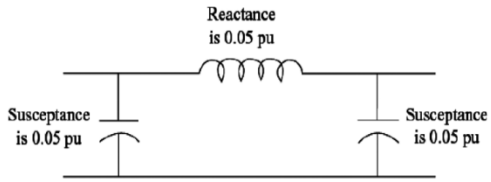
(A) p = –0.2, q = –0.1, r = –0.5
(B) p = 0.2, q = 0.1, r = 0.5
(C) p = –5, q = –10, r = –2
(D) p = 5, q = 10, r = 2

[GATE-2017]

Q.23 The bus admittance matrix for a power system network is

$$\begin{bmatrix} -j39.9 & j20 & j20 \\ j20 & -j39.9 & j20 \\ j20 & j20 & -j39.9 \end{bmatrix} \text{pu.}$$

There is a transmission line, connected between buses 1 and 3. Which is represented by the circuit shown in figure.



If this transmission line is removed from service, what is the modified bus admittance matrix?

(a) $\begin{bmatrix} -j19.9 & j20 & 0 \\ j20 & -j39.9 & j20 \\ 0 & j20 & -j19.9 \end{bmatrix} \text{pu.}$

(b) $\begin{bmatrix} -j39.95 & j20 & 0 \\ j20 & -j39.9 & j20 \\ 0 & j20 & -j39.95 \end{bmatrix} \text{pu.}$

(c) $\begin{bmatrix} -j19.95 & j20 & 0 \\ j20 & -j39.95 & j20 \\ 0 & j20 & -j19.95 \end{bmatrix} \text{pu.}$

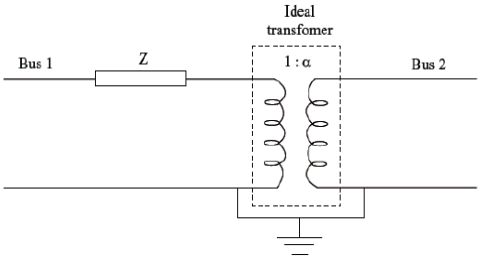
(d) $\begin{bmatrix} -j19.95 & j20 & j20 \\ j20 & -j39.95 & j20 \\ j20 & j20 & -j19.95 \end{bmatrix}$

[GATE-2017]

Q.24 In a load flow problem solved by Newton –Raphson method with polar coordinates,the size of the Jacobian is 100 × 100, If there are 20 PV buses in addition to PQ buses and a slack bus. The total number of buses in the system is _____.

[GATE-2017]

Q.25 The figure shows the per – phase representation of a phase – shifting transformer connected between buses 1 and 2, where α is a complex number with non – zero real and imaginary parts.



For the given circuit, Ybus and Zbus are bus admittance matrix and bus impedance matrix, respectively, each of size 2 × 2.Which one of the following statements is true?

(A) Both Ybus and Zbus are symmetric
(B) Ybus is symmetric and Zbus is unsymmetric
(C) Ybus is unsymmetric and Zbus is symmetric
(D) Ybus and Zbus are unsymmetric

[GATE-2017]

Q.26 The per unit power output of a salient pole generator which is connected to an infinite bus is given by the expression, $P = 1.4\sin\delta + 0.15\sin 2\delta$, where δ is the load angle. Netwton Raphson method is used to calculate the value of δ for P = 0.8 pu . If the initial guess is 300 , then its value (in degree) at the end of the first iteration is

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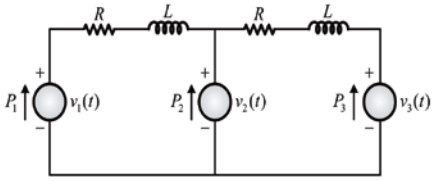
(A) 150^0 (B) 28.48^0
(C) 28.74^0 (D) 31.20^0
[GATE-2018]

Q.27 A 1000×1000 bus admittance matrix for an electric power system has 8000 non zero elements. The minimum number of branches (transmission lines and transformers) in this power system are _____ (up to 2 decimal places).

[GATE-2018]

Q.28 In the figure, the voltages are
$V_1(t) = 100\cos(\omega t)$,
$V_2(t) = 100\cos(\omega t + \pi/18)$
$V_3(t) = 100\cos(\omega t + \pi/36)$.

The circuit is in sinusoidal steady state, and $R << \omega L$, P_1 P_2 *and* P_3 are the average power outputs. Which one of the following statements is true ?



(A) $P_1 = P_2 = P_3 = 0$
(B) $P_1 < 0, P_2 > 0, P_3 > 0$
(C) $P_1 < 0, P_2 > 0, P_3 < 0$
(D) $P_1 > 0, P_2 < 0, P_3 > 0$

[GATE-2018]

ANSWER KEY

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(a)	(b)	(b)	(d)	(a)	(d)	(c)	(a)	(c)	(a)	(b)	(b)	(b)	(b)
15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
(c)	(b)	332	(b)	(b)	(a)	14	(b)	(b)	61	(d)	(c)	3500	(c)

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EXPLANATIONS

Q.1 **(d)**

If the slack bus is specified in the same area in which program is being initialized, it will converge otherwise it will not .Hence the slack bus is to be specified in both the areas.

Q.2 **(b)**

Total number of buses =N=300

Number of generator bus $=n_1=20$

Number of buses with reactive power support $=n_2=25$

Number of buses with fixed shunt capacitors $=n_3=15$

Number of voltages controlled bus $=n=n_2+n_3=40$

x = Number of PQ buses

$=2N-(n_1+n)$

$=2\times300-(20+40)=540$

Size of N-R Jacobian matrix =xxx

540×540

Q.3 **(b)**

$$Z_{B(new)}=Z_{B(old)}-\frac{1}{Z_{jj}+Z_b}\begin{bmatrix}Z_{1j}\\ M\\ Z_{nj}\end{bmatrix}\begin{bmatrix}Z_{j1} & L & Z_{jn}\end{bmatrix}$$

New elements (Z_b) is connected between j^{th} and reference bus.

And reference bus

Here j=2,b=4

$$\therefore \frac{1}{Z_{ij}+Z_b}\begin{bmatrix}Z_{12}\\ Z_{22}\\ Z_{32}\\ Z_{42}\end{bmatrix}\begin{bmatrix}Z_{21} & Z_{22} & Z_{23} & Z_{24}\end{bmatrix}$$

$$=\frac{1}{(j0.3408+j0.2)}\begin{bmatrix}j0.2860\\ j0.3408\\ j0.2586\\ j0.2414\end{bmatrix}$$

$$\begin{bmatrix}j0.2860 & j0.3408 & j0.2586 & j0.2414\end{bmatrix}$$

We are required only changes in $Z_{22}Z_{23}$

$$\begin{bmatrix}- & - & - & -\\ - & j0.2147 & j0.16296 & -\\ - & - & - & -\\ - & - & - & -\end{bmatrix}$$

$Z_{22(new)}=Z_{22(old)}=-j0.2147$

$=j0.1260$

$Z_{23(new)}=Z_{23(old)}-j0.2586-j0.16296$

$=j0.0956\Omega$

Q.4 **(d)**

Impedance between bus (1)and bus (2)

$=Z_{12}=j0.1$

$$\text{Admittance}=Y_{12}=\frac{1}{Z_{12}}=\frac{1}{j0.1}$$

$=-j10\text{p.u.}$

Impedance between bus (2) and bus (3)

$=Z_{23}=j0.1$

$$\text{Admittance}=Y_{23}=\frac{1}{Z_{23}}=\frac{1}{j0.1}$$

$=-j10\text{p.u.}$

Impedance between bus (2) and ground

$=Z_{20}=-j20\text{p.u.}$

$$\text{Admittance}=Y_{20}=\frac{1}{Z_{20}}=\frac{1}{-j20}$$

$=-j0.05\text{p.u.}$

$Y_{22}=Y_{20}+Y_{12}+Y_{23}$

$=j0.05-j10-j10$

$=-j19.95\text{p.u.}$

Q.5 **(a)**

1. The time taken to perform one iteration of the computation is relatively smaller in case of G-S method but the number of iterations

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required by G-S method for a particular system and they increase with the increases in the size of the system. This results in slow convergence.

2. The convergence characteristics of G-S method is sometimes very seriously affected by the selection of a particular bus may result in poor convergence.

Q.6 **(d)**

Q.7 **(c)**

Y_{ii} = sum of the admittance directly connected to i^{th} bus

$Y_{iL} = Y_{iO} + Y_{i1} \ldots Y_{in} = (Y_{ii}\text{excluded})$

$Y_{ik} = -Y_{ik}$

So, $Y_{11} = Y_{10} + Y_{12} + Y_{13}$

$Y_{12} = -Y_{12}$

$Y_{13} = -Y_{13}$

$Y_{10} = Y_{11} + Y_{12} + Y_{13}$

$= -j8.75 + j1.25 + j2.5$

$\Rightarrow Y_{10} = -15\text{p.u.}$

Similarly,

$Y_{20} = Y_{22} + Y_{21} + Y_{23}$

$Y_{20} = -6.25 + j1.25 + j2.5$

$\Rightarrow Y_{20} = -j2.5\text{p.u.}$

$$Z_{10} = \frac{1}{Y_{10}} = \frac{1}{-j5} = j0.2$$

$$Z_{20} = \frac{1}{Y_{20}} = \frac{1}{-j2.5} = j0.4$$

$$I_{Gi}^{f} = \frac{E_{Gi} = V_i^t}{Z_{i0}}$$

[Current fed by generator I during fault]

$E_{G1} = E_{G2} = 1\angle 0°$

[The system was unloaded]

Current fed by generator 1

$$I_{G1}^{f} = \frac{E_{G1} = V_1^t}{Z_{10}} = \frac{1\angle 0° - 0.67\angle 0°}{j0.2}$$

$= 1.65\angle -90°\text{p.u.}$

Current fed generator 2,

$$I_{G2}^{f} = \frac{E_{G2} = V_2^t}{Z_{20}} = \frac{1\angle 0° - 0°}{j0.4}$$

$= 2.5\angle -90°\text{p.u.}$

Q.8 **(a)**

As $P_1 = P_2 = 0$ and $Q_1 = Q = 0$

There is no energy transfer, so both bus bar voltage and its phase angle should be same. Assuming both bus bar phase angle zero. So, phase – angle of $x = \angle x = 30°$

And phase 0angle of $y = \angle y$

$= 20°$ Phase angular difference

$= \angle x - \angle y = 30° - 20°$

$= 10°$

Q.9 **(c)**

$$Y_{BUS} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix}$$

Here,

$Y_{11} = Y_{10} + Y_{12} + Y_{13} + Y_{14} = -5j$ ...(i)

$Y_{22} = Y_{20} + Y_{22} + Y_{23} + Y_{24} = -10j$ ...(ii)

$Y_{33} = Y_{30} + Y_{32} + Y_{33} + Y_{34} = -9j$ ...(iii)

$Y_{33} = Y_{40} + Y_{42} + Y_{43} + Y_{44} = -8j$ ...(iv)

$Y_{12} = Y_{21} = -Y_{12} = 2j$

$Y_{13} = Y_{31} = -Y_{13} = 2.5j$

$Y_{14} = Y_{41} = -Y_{14} = 0J$

$Y_{23} = Y_{32} = -Y_{23} = 2.5j$

$Y_{24} = Y_{42} = -Y_{24} = 4j$

$Y_{34} = Y_{43} = -Y_{34} = 4j$

From eq(i) $Y_{10} = Y_{11} - Y_{12} - Y_{13} - Y_{14}$

$= -5j + 2j + 2.5j + 0.j = -0.5j$

From eq (ii)

$Y_{20} = Y_{22} - Y_{12} - Y_{23} - Y_{24}$

$= 10j + 2j + 2.5j + 4j$

$= -1.5j$

From eq(iii)

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$$Y_{30} = Y_{33} - Y_{31} - Y_{32} - Y_{34}$$
$$= -9j + 2.5j + 2.5j + 4j$$
$$= 0$$
From eq(iv)
$$Y_{40} = Y_{44} - Y_{31} - Y_{41} - Y_{43}$$
$$= -8j - 0 + 4j + 4j$$

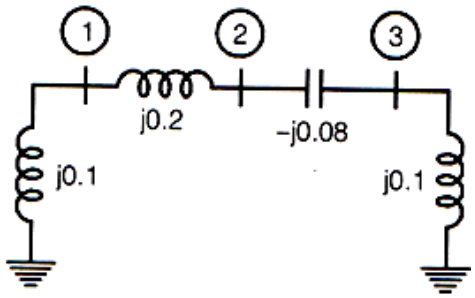
Q.10 (a)

$V_1 = 100\angle 30°\text{V and} V_2 = 100\angle 0°$ V

as $\delta_1 > \delta_2$ current will flow from bus 1 to bus 2

$$Z = 0 + j5\Omega$$
$$I = \frac{V_1 - V_2}{Z}$$
$$= \frac{100\angle 30° - 100\angle 0°}{j5}$$
$$= 10.35\angle 15°\text{A}$$
Complex power $= S = P + j\theta = V_1 I^*$
$$P + jQ = 100\angle 30° \times (10.35\angle 15°)^*$$
$$\approx 1000 + j268$$
$P = 1000$W and $Q = 268$VAR

Q.11 (b)

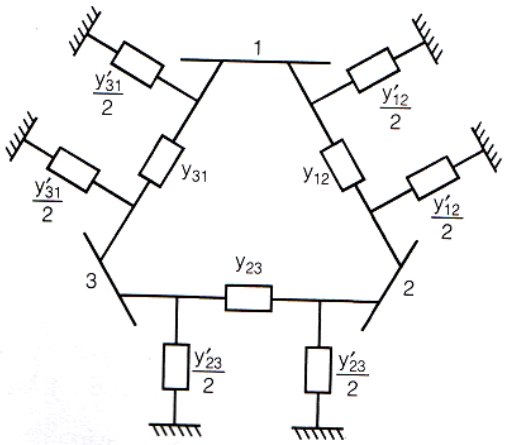


$$Z_{10} = j0.1$$
$$\Rightarrow Y_{10} = \frac{1}{Z_{10}} = \frac{1}{j0.1} = -j10\text{p.u.}$$
$$Z_{12} = j0.2$$
$$\Rightarrow Y_{12} = \frac{1}{Z_{12}} = \frac{1}{j0.2} = -j5\text{p.u.}$$
$$Z_{23} = -j0.8$$
$$\Rightarrow Y_{23} = \frac{1}{Z_{23}} = \frac{1}{-j0.8} = j12.5\text{p.u.}$$
$$Z_{30} = j0.1$$
$$\Rightarrow Y_{30} = \frac{1}{Z_{30}} = \frac{1}{j0.1} = -j10\text{p.u.}$$
$$Y_{11} = Y_{10} + Y_{12} = -j10 - j5$$
$$= -j15\text{p.u.}$$
$$Y_{12} = Y_{21} = -Y_{12} = -(-j5) = j5\text{p.u.}$$
$$Y_{31} = Y_{13} = -Y_{13} = 0$$
$$Y_{22} = Y_{12} + Y_{23} = -j5 + j12.5$$
$$= j.75\text{p.u.}$$
$$Y_{33} = Y_{30} + Y_{23} = -j10 + j12.5$$
$$= j2.5\text{p.u.}$$
$$Y_{BUS} = j\begin{bmatrix} -15 & 5 & 0 \\ 5 & 7.5 & -12.5 \\ 0 & -12.5 & 2.5 \end{bmatrix}$$

Q.12 (b)

Y_{ik} = Series admittance of the line connecting buses in and k

$\frac{Y_{ik}}{2}$ = Half line charging admittance in bus admittance matrix



$$Y_{11} = \frac{Y'_{11}}{2} + \frac{Y'_{31}}{2} + Y_{12} + Y_{31} = -j13$$
$$Y_{12} = -Y_{12} = j10$$
$$Y_{23} = -Y_{23} = j10$$
$$Y_{31} = -Y_{31} = j5$$
$$\therefore Y'_{12} + Y'_{31} = 2[j13 + j10 + j5] = j4$$
Similarly
$$Y'_{12} + Y'_{23} = 2[j18 + j10 + j10] = j4$$
$$Y'_{23} + Y'_{31} = 2[-j13 + j10 + j5] = j4$$
$$\Rightarrow Y'_{12} = j6 - j4 = j2$$

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Q.13 (b)

The current lag the voltage .Hence the load is lagging in nature. So it will absorb reactive power.

Q.14 (b)

$P_1 + P_2 + P_3 = 0$

$P_1 + j0.1 - j0.2 = 0$

$P_1 = j0.1$ p. u.

No power flow in between bus 1 and 2

$P_{12} \propto \sin(\theta_1 - \theta_2) = 0$

$\theta_1 - \theta_2 = 0$

As bus 1 is a slack bus

$\theta_1 = 0$

$\Rightarrow \theta_2 = 0$

Now $P_{23} = \frac{V_2 V_3}{X}\sin(\theta_2 - \theta_3)$

Or $0.1 = \frac{1\times 1}{1}\sin(\theta_2 - \theta_3)$

$\Rightarrow \theta_2 - \theta_3 = \sin^{-1}(0.1)$

$= 0.10016\ ;\ 0.1$

$\theta_3 = -0.1$

Q.15 (c)

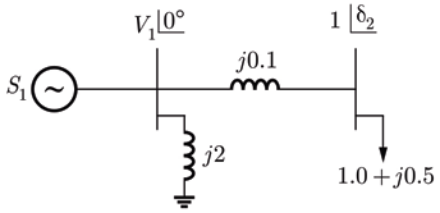
$P_1 = 0.1$pu

$= 0.1 \times \frac{(100\text{kV})^2}{100} = 10\text{MW}$

Q.16 (b)

Correct option is (B).

Given the two bus power system,



Now, the current through impedance Z is given by

$I = \frac{V_1 - V_2}{Z}$

For the given system, we have

$V_1 = V_1\angle 0^0$; $V_2 = 1\angle\delta_2$, $z = 0.1\angle 90^0$

So, we obtain the current

$I\angle\theta = \frac{V_1\angle 0^0 - 1\angle\delta_2}{0.1\angle 90^0} 1 + j0.5$

$or \quad V_1\angle 0^0 - 1\angle\delta_2 = 0.11\angle 116.56$

$or V_1 - (\cos\delta_2 - j\sin\delta_2)$

$= 0.11[\cos 111.56^0 + j\sin 116.36^0]$

Comparing the real and imaginary terms, we get

$-\sin\delta_2 = 0.11 \times \sin 116.36^0$

or $-\text{sind}\,\delta_2 = 0.098$

Q.17 (332)

Correct answer is 332.

Given, number of PQ buses = 150

number of PV buses = 32

For PQ buses, 2 equations are formed (one for P and other for Q)

For PV buses only 1 equation is formed (for Q only)

Thus, the minimum number of simultaneous equations, required to obtain the

load, is

Total number of equations =

Number of equation for PQ buses +

Number of equation for PV buses.

= 2 × (number of PQ buses)

+ 1 × (number of PV buses)

= 2 × (150) + 1 × (32)

= 332

Q.18 (b)

Correct option is (B).

Given bus admittance matrix,

$$\begin{bmatrix} -j6 & j3 & j4 \\ j3 & -j7 & j5 \\ j4 & j & -j8 \end{bmatrix}\text{pu}$$

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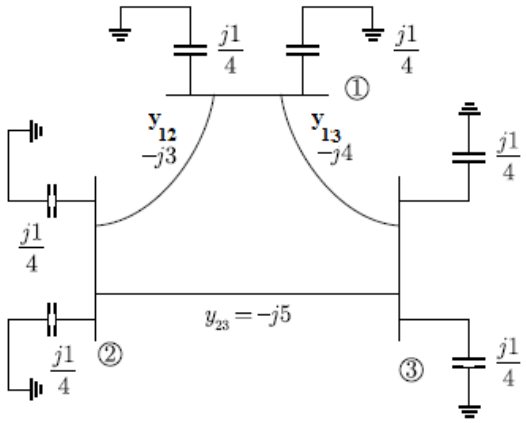
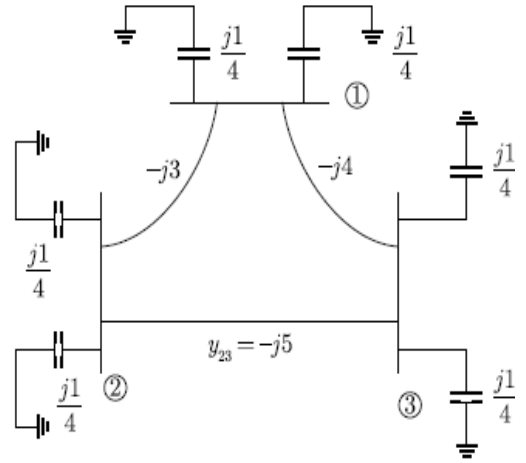
For the given data, we draw the schematic as



If shunt capacitance of all transmission line is 50% compensated, then ysh = j1/2 reduces to its half value, i.e.

$$y_{sh(new)} = \frac{j1}{4}$$

Therefore, the system becomes as



Hence, we get

$$y_{33} = y_{13} + y_{23} + y_{13(shunt)} + y_{23(shunt)}$$

$$= -j4 - j5 + j\frac{1}{4} + j\frac{1}{4}$$

$$= -j8.5$$

Q.19 (b)

Gen. buses = 10

$\therefore$ Load buses = 90A t every load bus $\rightarrow |v|$, δ must be calculated

At every gent bus $\rightarrow$ Q, δ must be calculated

i.e., at all buses, (δ) must be calculated. So,

voltage phase angle calculations will not change during iteration, two of the gen. buses changes to load buses [Q because of 'Q'violation]

$\therefore$ Total load buses = 92

$\therefore$ Voltage magnitude calculation will increase by two Choice (B)

Q.20 (A)

Total buses = 100

Gen buses = 10

$\therefore$ Load buses = 90 $\rightarrow$ (m)

Gen buses = 10 $\rightarrow$ n

Size of Jacobian matrix is

= [2m + (n −1)] [2m − (n −1)]

= [2 × 90 + (10 −1)] [2 × 90 + (10 −1)]

= 189 × 189

Choice (A)

Q.21 (14)

Total number of buses = n = 10

Number of generator buses + number ofvoltage controlled buses = m = 4

Number of PQ buses = 5

Number of equations = 2n – m – 2 = 20 – 4 – 2 = 14 Ans: 14 to 14

Q.22 (b)

$$Y_{11} = -j12\,pu = \frac{-j}{q} - \frac{j}{r}$$

$$\frac{q+r}{qr} = 12$$

$$Y_{22} = -j15 = \frac{-j}{q} - \frac{j}{p}$$

$$\Rightarrow \frac{q+p}{qp} = 15$$

$$Y_{33} = -j7 = \frac{-j}{r} - \frac{j}{p}$$

$$\Rightarrow \frac{r+p}{rp} = 7$$

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By solving (1), (2) & (3) verify from given options.
We get, p = 0.2, q = 0.1, r = 0.5

Q.23 (B)

$Y_{13} = j20(old\ value)$

If line between (1) & (3) is removed

$Y_{13} = 0(new\ value)$

$Y_{11} = -j39.9(old\ value)$

$Y_{11(new)} = -j39.9-(-j20) = -j19.95$

$Y_{33(new)} = -j39.9-(-j20) = -j19.95$

Q.24 (61)

$[J]_{(2n-m-2)\times(2n-m-2)}$

$2n - m - 2 = 100$

m = number of PV buses = 20

$2n - 20 - 2 = 100$

n = 61 Ans: 61 to 61

Q.25 (d)

Ybus and Zbus are unsymmetric

Q.26 (C)

$P = 1.4\sin\delta + 0.15\sin 2\delta,$

Given : $P = 1.4\sin\delta + 0.15\sin 2\delta, P = 0.8, \delta_0 = 30^0$

$$f(\delta) = 1.4\sin\delta + 0.15\sin 2\delta - 0.8$$

$$\delta_{n+1} = \delta_n - \frac{f(\delta)}{f'(\delta)}$$

$$\delta_1 = \delta_0 - \frac{1.4\sin\delta + 0.15\sin 2\delta - P}{1.4\cos\delta + 0.3\cos 2\delta}$$

$$\delta_1 = \frac{\pi}{6} - \frac{1.4\sin 30 + 0.15\sin 60 - 0.8}{1.4\cos 30 + 0.3\cos 60}$$

$$= 0.50164 \text{ rad}$$

$$\delta_1(30) = 28.74^0$$

Hence, the correct option is (C).

Q.27 (3500)

Given : A bus system of 1000 × 1000 contains 8000 non zero elements.

Method 1 :

The total number of elements

$= 1000 \times 1000 = 1000000$

% of sparcity =

$$\frac{1000000 - 8000}{1000000} \times 100$$

$$= \frac{992000}{1000000} \times 100 = 99.2\%$$

Hence the number of transmission lines $= \frac{n^2(1-x)-n}{2}$

$$= \frac{1000^2(1-0.992)-1000}{2}$$

$$= \frac{8000-1000}{2} = 3500$$

Hence, the minimum number of branches are **3500.**

Method 2 :

Number of non-zero element = 8000

Number of diagonal element = 1000

Number of non-zero off diagonal element = 7000

Hence, the minimum number of branches are **3500.**

Method 2 :

Number of non-zero element = 8000

Number of diagonal element = 1000

Number of non-zero off diagonal element = 7000

Hence,

Number of transmission lines

$$= \frac{\text{Number of non-zero off diagonal element}}{2}$$

$$= \frac{7000}{2} = 3500$$

Hence, the minimum number of branches are 3500.

Q.28 (C)

Given : The circuit is shown below,

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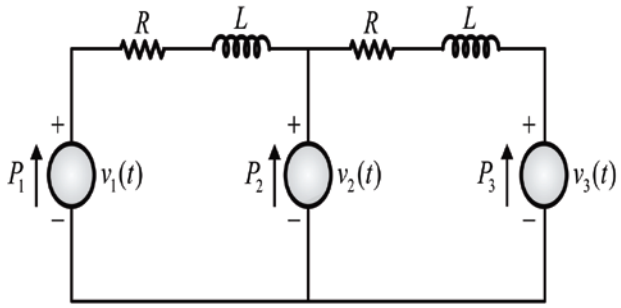

$$v_i(t) = 100\cos\omega t$$

$$v_2(t) = 100\left(\omega t + \frac{\pi}{18}\right)$$

$$v_3(t) = 100\cos\left(\omega t + \frac{\pi}{36}\right)$$

From the above expression, it is clear that v_2 is leading v_1 by 10^0 and v_3 is leading v_1 by 5^0.
Since, active power (P) is always flow from leading angle to lagging angle. Hence, the current will flow from v_2 (t) towards v_1 (t) and 3_v (t).
Hence $P_2 > 0$ and $P_1 < 0$ and $P_3 < 0$.
Hence, the correct option is (C).

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10 HIGH VOLTAGE DC TRANSMISSION

Q.1 Choose the appropriate auxiliary components of HVDC transmission system from the following
1. D.C. line inductor
2. A.C. line inductor
3. Reactive power sources
4. Distance relays on D.C. line
5. Series capacitance on A.C. line

a) 1 and 2 b) 1 and 3
c) 2 and 4 d) 4 and 5

[GATE-2003]

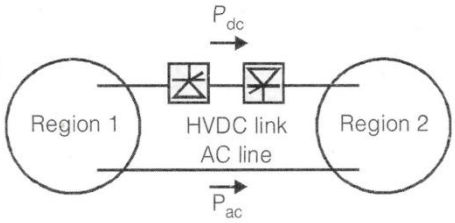
Q.2 High Voltage DC (HVDC) transmission is used for
a) bulk power transmission over very long distances
b) inter-connecting two systems with the same nominal frequency
c) eliminating reactive power requirement in the operation
d) minimizing harmonics at the converter station

[GATE-2005]

Q.3 An HVDC link consists of rectifier, inverter transmission line and other equipments. Which one of the following is true for this link?
a) The transmission line produces /supplies reactive power
b) The rectifier consumes reactive power & the inverter supplies reactive power from/to the respective connected AC systems
c) Rectifier supplies reactive power & the inverted consumes reactive power to/from the respective connected AC systems
d) Both the converters (rectifier and inverter) consume reactive power from the respective connected AC systems

[GATE-2006]

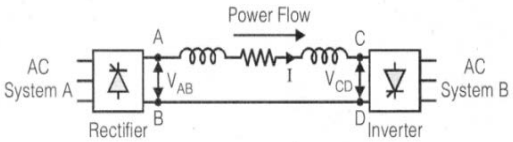
Q.4 Two regional systems, each having several synchronous generators and loads are interconnected by an ac line and a HVDC link as shown in the figure. Which of the following statements is true in the steady state?



a) Both regions need not have the same frequency.
b) The total power flow between the regions (P_{ac} + P_{dc}) can be changed by controlling the HDVC converters alone.
c) The power sharing between the ac line and the HVDC link can be changed by controlling the HDVC converters alone.
d) The directions of power flow in the HVDC link(Pdc) cannot be reversed.

[GATE-2007]

Q.5 Power is transferred from system A to system B by an HVDC link as shown in the figure. If the voltages V_{AB} and V_{CD} are as indicated in the figure, and I > 0, then



a) $V_{AB} < 0, V_{CD} < 0, V_{AB} > V_{CD}$
b) $V_{AB} > 0, V_{CD} > 0, V_{AB} < V_{CD}$
c) $V_{AB} > 0, V_{CD} > 0, V_{AB} > V_{CD}$
d) $V_{AB} > 0, V_{CD} < 0$

[GATE-2010]

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ANSWER KEY:

1	2	3	4	5
(b)	(a)	(b)	(c)	(c)

EXPLANATIONS

Q.1 (b)

- D.C. line inductor, reduces the harmonic current in the DC line and possible transient over current
- Converters and converter transformers consume reactive power .

The reactive power may be supplied from
(i)AC filter
(ii) Shunt Capacitors
(iii)AC network
(iv) Static compensator
(v)Synchronous condensers

Q.2 (a)

- HVDC system are economical for long distance bulk power transmission by Over head lines, due to reduced power and cable costs.
- The DC line is an asynchronous link and it can interconnect two rigid systems operating at different frequencies.
- Converters and converter transformers requires reactive power in the operation.
  The AC/DC converters are sources of harmonic on AC as well as DC side.

Q.3 (b)

The rectifier consumes reactive power ad inverter supplies reactive power from /to the respective connected Acv systems because o reactive power can be transmitted over a dc link.

Q.4 (c)

Both regions are connected by HVDC link as well as AC line .So AC link is possible when both regions have same frequency. By changing fringe angle (α) of converter, we can change the power sharing, between the AC line and HVDC link.

Q.5 (c)

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11 PER UNIT SYSTEM

Q.1 A 75 MVA, 10kV synchronous generator has X_d=0.4p.u. the X_d value (in p.u.) to a base of 100MVA 11kV is

a) 0.578 b) 0.279
c) 0.412 d) 0.44

[GATE-2001]

Q.2 The p.u. parameters for a 500 MVA machine on its own base are:
Interia M=20p.u. reactance, X=2p.u
The p.u. values of inertia and reactance on 100MVA common base, respectively, are

a) 4,04 b)100,10
c) 4,10 d)100,0.4

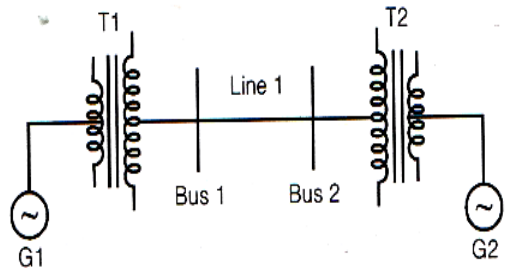
[GATE-2005]

Q.3 A generator is connected through a 20MVA, 13.8/138kV step down transformer, to a transmission line. At the receiving end of the line a load is supplied through a step down transformer of 10MVA, 138/69 kV rating .A 0.72p.u.load, evaluated on load side transformer ratings as base value, is supplied from the above system for system base values of 10MVA and 69kV in load circuit, the value of the load (in per unit) in generator circuit will be

a) 36 b) 1.44
c) 0.72 d) 0.18

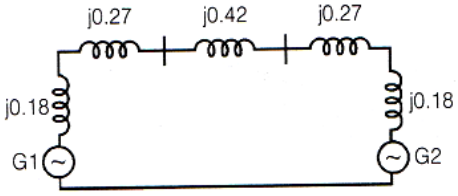
[GATE-2006]

Q.4 For the power system shown in the figure below, the specifications of the components are the following:
G1:25kV, 100MVA,X=9%
G2:25kV, 100MVA,X=9%
T1:25kV/220kV, 90MVA,X=12%
T2:220kV/25kV, 90MVA,X=12%
Line 1:2000kV,X=150ohms

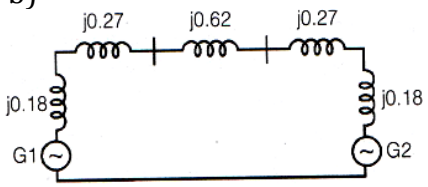


Choose 25kV as the base voltage at the generator G1, and 200MVA as the MVA base. The impedance diagram is

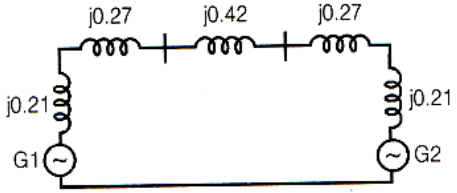
a)



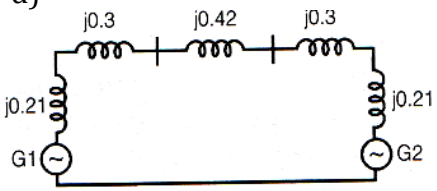
b)



c)



d)



[GATE-2010]

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ANSWER KEY:

1	2	3	4
(d)	(d)	(a)	(b)

EXPLANATIONS

Q.1 (d)

$$(X_d)_{new} = 0.4 \times \left(\frac{100}{75}\right)\left(\frac{10}{11}\right)^2 = 0.44077$$

Q.2 (d)

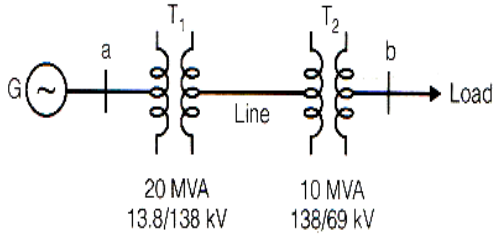
$$(M_{pu})_{new} = (M_{pu})_{old} \times \frac{(MVA)_{old}}{(MVA)_{new}}$$

$$= 20 \times \frac{500}{100} = 100 \text{p.u}$$

$$(X_{pu})_{new} = (X_{pu})_{old} \frac{(MVA)_{old}}{(MVA)_{new}} \times \frac{kV_{old}^2}{kV_{new}^2}$$

$$= 2 \times \frac{100}{500} = 0.4 [(kV)_{old} = (kV)_{new}]$$

Q.3 (a)



Base value on load circuit $(MVA)_B = 10MVA$ and $(kV)_B = 69kV$

Base impedance $= \frac{69^2}{10} = 476.1$

Values of load in ohm $= Z_L$

=Value of load in p.u. × base impedance

$\Rightarrow Z_L = 0.72 \times 476.1 = 342.8\Omega$

Base values in generator circuit,

$(MVA)_B = 20MVA$

$(kV)_B = 13.8kV$

Base impedance

$= Z_B = \frac{(kV)_B^2}{(MVA)_B} = \frac{13.8^2}{20}$

$\Rightarrow Z_B = 9.522\Omega$

$= \frac{Z_L}{Z_B} = \frac{342.8}{9.522} = 36$p.u.

Q.4 (b)

$$Z_{pu(new)} = Z_{pu(old)} \times \frac{(MVA_B)_{new}}{(MVA_B)_{old}} \times \frac{kV_{old}^2}{kV_{new}^2}$$

$(MVA_B)_{new} = 200MVA$ and

$(kV_B)_{new} = 25kV$

Base impedance $= Z_B = \frac{(kV_B)^2}{(MVA_B)}$

(kV_B) in line $= 220kV$

$Z_B = \frac{220^2}{200} = 242\Omega$

$X_{l\text{-}pu} = \frac{X_l}{Z_B} = \frac{150}{242} = 0.62$p.u.

G_1 : 25kV, 100MVA,

$X_{G1} = 0.09pu$

X_{G1} (on base 200MVA)

$= 0.09 \times \frac{200}{100}$

$= 0.18$p.u.

$\{(kV_B)_{old} = (kV_B)_{new}\}$

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G_2 : 2kV, 100MVA,

$X_{G2} = 0.09\text{pu}$

$X_{G2}(\text{on base } 200\text{MVA}) = 0.09 \times \frac{200}{100}$

$= 0.18\text{p.u.}$

T_1 : 25kV / 220kV, 90MVA

$X_{T1} = 0.12\text{p.u}$

$X_{T1}(\text{on base } 200\text{MVA}) = 0.12 \times \frac{200}{100}$

T_2 : 220kV / 25kV, 90MVA

$X_{T2} = 0.12\text{p.u}$

$X_{T2}(\text{on base } 200\text{MVA}) = 0.12 \times \frac{200}{100}$

$= 0.27\text{p.u}$

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12 POWER SYSTEM TRANSIENTS

Q.1 Total instantaneous power supplied by a 3-phase ac supply to a balanced R-L load is

a) zero
b) constant
c) pulsating with zero overage
d) pulsating with non- zero average

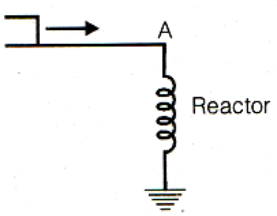
[GATE-2004]

Q.2 The insulation strength of an EHV transmission line is mainly governed by

a) load power factor
b) switching over –voltages
c) harmonics
d) corona

[GATE-2005]

Q.3 Consider a step voltage wave of magnitude 1pu travelling along a lossless transmission line that terminates in a rector .The voltage magnitude across the reactor at the instant the travelling wave reaches the reactor is



a) -1pu
b) 1pu
c) 2pu
d) 3pu

[GATE-2010]

ANSWER KEY:

1	2	3
(b)	(b)	(b)

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EXPLANATIONS

Q.1 **(b)**

Impedance of the load

$= Z_L = R + j\omega L = |Z| \angle \theta_L$

Where $\theta_L = \tan^{-1}\left(\frac{\omega L}{R}\right)$

Voltages of $3-\Phi$ supply

$V_a = V_m \sin\omega t$

$V_b = V_m \sin(\omega t - 120°)$

$V_c = V_m \sin(\omega t + 120°)$

$I_a = \frac{V_a}{Z_L} = \frac{V_m \sin\omega t}{|Z| \angle \theta_L}$

$= I_m = \sin(\omega t - \theta_L)$

Where $I_m = \frac{V_m}{|Z|}$

Similarly ,

$I_b = I_m \sin(\omega t - 120 - \theta_L)$ and

$I_c = I_m \sin(\omega t + 120 - \theta_L)$

Instantaneous power

$P = V_a I_a + V_b I_b + V_c I_c$

$$P = V_m I_m \left[\begin{array}{l} \sin\omega t.\sin(\omega t - \theta_L) + \sin(\omega t - 120°) \\ \sin(\omega t - 120 - \theta_L) + \sin(wt + 120 - \theta_L) \end{array}\right]$$

$$= \frac{V_m I_m}{2}\left[\left\{\begin{array}{l} \cos\theta_L - \cos(2\omega t - \theta_L) + \\ \{\cos\theta_L - \cos(2\omega t - 240 - \theta_L) \\ + \{\cos\theta_L - \cos(2\omega t + 240 - \theta_L) \end{array}\right\}\right]$$

$$\Rightarrow P = \frac{3V_m I_m}{2}\cos\Phi = \text{constant}$$

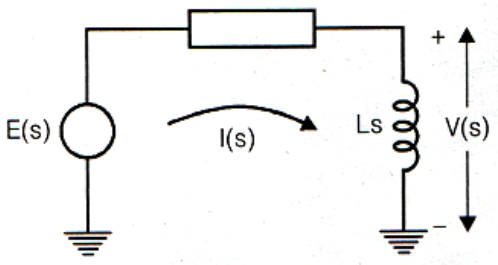
Q.2 **(b)**

At transmission lie voltage up to around 230 kV the insulation level is dictated by the requirement of protection against lighting For voltage from 230kV to 700kV, both switching transients and lighting over voltages must be accounted for in deciding the insulation levels. In EHV(>700kV) switching surges cause over voltages that lightning and are therefore mainly responsible for insulation level decision .

Q.3 **(b)**

Let surge impedance of the line $= Z_c$

E=Step voltage wave of magnitude 1 p.u.



$E(s) = \frac{1}{s}$

$I(s) = \frac{E(s)}{Z_C + Ls}$

$V(s)$=Voltage across the reactor

$$V(s) = \frac{\frac{1}{s}Ls}{L\left(\frac{2C}{L} + s\right)}$$

$V(t)|_{t=0} = 1.e^{-Z_c/Lt}$

At t = 0

The instant the travelling wave reaches the reactor

$V(t)|_{t=0} = 1.p.u$

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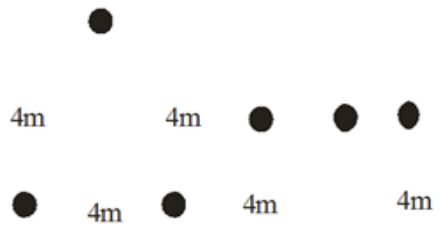
ASSIGNMENT QUESTIONS

Q.1 A medium line with parameters A, B, C, D is extended connecting a short line of impedance Z in series. The overall ABCD parameters of the series combination will be
a) A, AZ, C + D/Z, D
b) A, AZ + BC, CZ + D
c) A + BZ, B, C + DZ, D
d) AZ, B, C/Z, D

Q.2 The self-inductance of a long cylindrical conductor due to its internal flux linkages is kH/m. If the diameter of the conductor is doubled, then the self-inductance of the conductor due its internal flux linkages would be
a) 0.5 KH/m b) KH/m
c) 1.414 KH/m d) 4KH/m

Q.3 Two arrangements of conductors are proposed for a 3-phase transmission line : one with equilateral spacing of 4 m and the other, a flat with 4 m between the conductors as shown in the given figure.



The conductor diameter in each case is 2 cm. Assuming that the line is transposed in both cases. Which one of the following statements would be true?
(C_n = capacitance in F/m line to neutral, L = inductance in H/m per phase)
a) $C_{n1} = C_{n2}$ and $L_1 > L_2$
b) $C_{n1} > C_{n2}$ and $L_1 < L_2$
c) $C_{n1} < C_{n2}$ and $L_1 > L_2$
d) $C_{n1} > C_{n2}$ and $L_1 = L_2$

Q.4 When bundle conductors are used in place of single conductors, the effective inductance and capacitance will respectively
a) Increase and decrease
b) Decrease and increase
c) Decrease and remain unaffected
d) Remain unaffected and increase

Q.5 The inductance of a three-phase transmission line is 1.2 mH/phase/km. If the spacing of conductors and the radius of the conductor are doubled, then the inductance of the line will be
a) 4.8 mH/phase/km
b) 1.2 mH/phase/km
c) (In2) ×1.2 mH/phase/km
d) (1n 4) × 1.2 mH/phase/km

Q.6 The per-unit "regulation" of a short transmission line, having a per-unit resistance voltage drop v_r and a per-unit reactance voltage drop of v_x at rated current and, with power-factor cosθ, is given by
a) $(v_r + v_x)\cos\theta$ b) $(v_r + v_x)\sin\theta$
c) $v_r\cos\theta + v_x\sin\theta$ d) $v_r\sin\theta + v_x\cos\theta$

Q.7 The surge impedance of a 100 km long underground cable is 50 ohms. The surge impedance of a 40 km long similar cable would be
a) 20 ohms b) 50 ohms
c) 80 ohms d) 125 ohms

Q.8 A 3-phase overhead transmission line has its conductors horizontally spaced with spacing between adjacent conductors equal to `d`. If, now, the conductors of the lines are rearranged to form an equilateral of sides equal to `d`, then the

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a) Average capacitance as well as average inductance will increase
b) Average capacitance will decrease but the average inductance will increase
c) Average capacitance will increase but the average inductance will decrease
d) Surge impedance loading of the lines will increase

Q.9 A bundled conductor line compared to a single conductor line (with same conductor cross-sectional area and same mean distance between conductors) has

Self GMD	Mutual GMD	Per phase inductance
a) Lower	Nearly same	Higher
b) Higher	Lower	Nearly same
c) Higher	Nearly same	Lower
d) Lower	Higher	Higher

Q.10 A 3-phase circuit breaker is rated at 2000 MVA, 33 kV, its making current will be
a) 35 kA b) 49 kA
c) 70 kA d) 89 kA

Q.11 If the inductance and capacitance of a power system are respectively 1H and 0.01 μF and the instantaneous value of interrupted current is 10 A, then the voltage across the breaker contact will be
a) 50 kV b) 57 kV
c) 60 kV d) 100 kV

Q.12 In a 220kV system, the inductance and capacitance up to the circuit breaker location are 25 mH and 0.025 μF respectively. The value of resistor required to be connected across the breaker contacts which will give no transient oscillations, is
a) 25Ω b) 250Ω
c) 500Ω d) 1000Ω

Q.13 The inductance of single-phase two wire power transmission line per kilometer gets doubled when the
a) Distance between the wires is doubled.
b) Distance between the wires is increased fourfold.
c) Distance between the wires is increased as square of original distance
d) Radius of the wire is doubled.

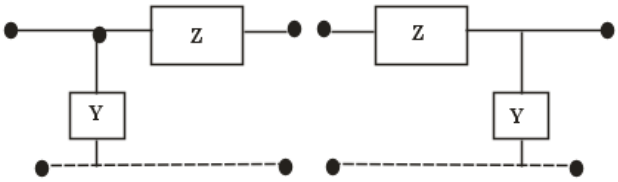
Q.14 A single – phase transmission line of impedance j0.8 ohm supplies a resistive load of 500 A at 300 V.The sending - end power factor is
a) Unity b) 0.8 lagging
c) 0.8 leading d) 0.6 lagging

Q.15 A surge voltage of 1000KV is applied to an overhead line with its receiving – end open. If the surge impedance of the line is 500Ω, then the total surge power in the line is
a) 2000MW b) 500MW
c) 2 MW d) 0.5MW

Q.16 In matrix form, the equation of a 4-terminal network representing a transmission line isgiven by

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

The two networks considered are



(A) (B)

The plausible transfer matrix for the networks (A) and (B) could be:

a) $\begin{bmatrix} 1 & YZ \\ 0 & Z \end{bmatrix}$ b) $\begin{bmatrix} Y & 0 \\ YZ & 1 \end{bmatrix}$

c) $\begin{bmatrix} 1 & Z \\ Y & (1+YZ) \end{bmatrix}$ d) $\begin{bmatrix} 1+YZ & Z \\ Y & 1 \end{bmatrix}$

The correct combination for the two networks (A) and (B), would be

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a) (i) and (ii) b) (i) and (ii)
c) (ii) and (iv) d) (iii) and (iv)

Q.17 If, in a short transmission line, resistance and reactance are found to be equal and regulation appears to be zero, then the load will
a) Have unity power factor
b) Have zero power factor
c) Be 0.707 leading
d) Be 0.707 lagging

Q.18 A short transmission line has a total resistance of 2Ω, reactance of 3Ω, current of 125 A and pf of 0.8. Regulation in percentage is equal to
a) 1.9 b) 0.38
c) 3.8 d) 0.19

Q.19 The self GMD of a conductor with three stands each of radius 'r' and touching each other is
a) $r(0.7788 \times 2 \times 2)^{1/3}$
b) $r(0.7788 \times 2 \times 2 \times 2)$
c) $r(0.7788 \times 2 \times 2 \times 2)^3$
d) $r(0.7788 \times 2 \times 2)^3$

Q.20 If a short transmission line is delivering to a lagging pf load, the sending –end pf would be (notations have their usual meaning)
a) $\frac{V_R \cos\varphi + IR \sin\varphi}{V_S}$
b) $\frac{V_R \cos\varphi + IR}{V_S}$
c) $\frac{V_R \sin\varphi + IR}{V_S}$
d) $\frac{V_R \sin\varphi + IR \cos\varphi}{V_S}$

Q.21 The ABCD constants of a 3-phase transmission line are
A= D=0.8 $\angle 1^0$
B = $170\angle 85^0\Omega$
C = 0.002 $\angle 90.4^0$ mho
The sending end voltage is 400 kV. The receiving end voltage under no-load condition is
a) 400 kV b) 500 kV
c) 320 kV d) 417 kV

Q.22 In a short transmission line, voltage regulation is zero when the power factor angle of theload at the receiving end side is equal to
a) $\tan^{-1}\left(\frac{X}{R}\right)$ b) $\tan^{-1}\left(\frac{R}{X}\right)$
c) $\tan^{-1}\left(\frac{X}{Z}\right)$ d) $\tan^{-1}\left(\frac{R}{Z}\right)$

Q.23 The surge impedance of a 3-phase, 400 kV transmission line is 400Ω. The surge impedance loading (SIL) is
a) 400 MW b) 100 MW
c) 1600 MW d) 200 MW

Q.24 A 3-phase transmission line has its conductors at the corners of an equilateral triangle withside 3m. The diameter of each conductor is 1.63 cm. The inductance of the line per phase per km is
a) 1.232 mH b) 1.182 mH
c) 1.093 mH d) 1.043 mH

Q.25 A cable has inductance of 0.22 mH per km and capacitance of 0.202 μF per km. The surge impedance of the cable is
a) 28Ω b) 33Ω
c) 42Ω d) 50Ω

Q.26 A 100 km long transmission line is loaded at 110 kV. If the loss of line is 15 MW and the load is 150 MVA, the resistance of the line is
a) 8.06 ohms per phase
b) 0.806 ohms per phase
c) 0.0806 ohms per phase
d) 80.6 ohms per phase

Q.27 D_s is the GMR of each subconductor of a four subconductor bundle conductor and d is the bundle

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spacing. What of the equivalent single conductor?

a) $1.09\sqrt{D_s \times d^3}$ b) $1.09\sqrt{D_s^3 \times d^3}$

c) $1.09\sqrt[4]{D_s^3 \times d^3}$ d) $1.09\sqrt[4]{D_s \times d^3}$

Q.28 A string insulator has 4 units. The voltage across the bottom-most unit is 33.33% of thetotal voltage. Its string efficiency is

a) 25% b) 33.33%
c) 66.67% d) 75%

Q.29 To increase the visual critical voltage of corona for an overhead line, one solid phase-conductor is replaced by a "bundle" of four smaller conductors per phase, having an aggregate cross-sectional area equal to that of the solid conductor. If the radius of the solid conductor is 40 mm, then the radius of each of the bundle conductors would be

a) 10 mm b) 20 mm
c) 16.6 mm d) 30 mm

Q.30 A one kilometer long 11 kV 3-core three-phase metal sheathed cable gave the following test results:
i) Capacitance between2conductors joined to sheath and the third conductor: 0.6 μF
ii) Capacitance between all the three conductors bunched together and sheat : 0.96 μF
The effective capacitance of each core is

a) 0.12 μ b) 0.67 μF
c) 0.16 μF d) 0.32 μF

Q.31 The insulation resistance of a 20 km long underground cable is 8 mega ohm. Other things being the same, the insulation resistance of a 10 km long cable will be

a) 16 mega ohm b) 32 mega ohm
c) 4 mega ohm d) 2 mega ohm

Q.32 A suspension type insulator has three units with self-capacitance ground capacitance of 0.2 C having a string efficiency of

a) 78% b) 80%
c)82% d)84%

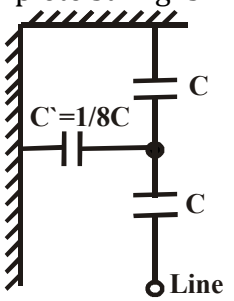
Q.33 A 66 kV system has string insulator having five discs and the earth to disco capacitance ratio of 0.10. The string efficiency will be

a) 89% b) 75%
c) 67% d) 55%

Q.34) The insulation resistance of a single-core cable is 200 MΩ/km. the insulation resistance for 5 km length is

a) 40 MΩ b) 1000 MΩ
c) 200 MΩ d) 8 MΩ

Q.35 The equivalent capacitor arrangement of a two –string insulator is shown in the above figure. The maximum voltage that each unit can withstand should not exceed 17.5 kV. The line-voltage of the complete string is



a) 17.5 kV b) 33 kV
c) 35 kV d) 37.3 kV

Q.36 In a three unit insulator string, voltage across the lowest unit is 17.5 kV and string efficiency is 84.28%. the total voltage across the string will be equal to

a) 8.825 kV b) 44.25 kV
c) 88.25 kV d) 442.5 kV

Q.37 Two insulator discs of identical capacitance value C make up a string

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for a 22 kV, 50 Hz, single-phase overhead line insulation system. If the pin to earth capacitance is also C, then the string efficiency is

a) 50% b) 75
c) 90% d) 86%

Q.38 In an unbalanced 3-phase system, the currents are measured as

I_a = zero, $I_b = 6\angle 60^\circ$ and $I_c = 6\angle -120^\circ$

The corresponding sequences components will be

	I_{a0}	Ia_1	Ia_2
a)	Zero	$3-j\sqrt{3}$	$-3+j\sqrt{3}$
b)	Zero	$-3+j\sqrt{3}$	$3-j\sqrt{3}$
c)	Zero	$-9+j3\sqrt{3}$	$9-j3\sqrt{3}$
d)	Zero	$9-j3\sqrt{3}$	$-9+j3\sqrt{3}$

Q.39 An equipment has 0.8 per unit impedance on a base of 66 KV, 100 MVA. It's per unit impedance on a base of 33 KV, 100 MVA will be

a) 0.4 b) 0.8
c) 1.6 d) 3.2

Q.40 A feeder with reactance of 0.2 p.u. has a sending end voltage 1.2p.u. If the reactive power supplied at the receiving end of the feeder is 0.3p.u.The approximate voltage drop in the feeder will be

a) 0.042 p.u. b)0.052p.u.
c) 0.60p.u. d) 0.070p.u.

Q.41 The reactance of a generator designed X" is given as 0.25 pu based on the generator's name plate rating of 18kV, 500MVA. If the base for calculations is changed to 20kV, 100MVA, the generator reactance X" on new base will be

a) 1.025 pu b) 0.05 pu
c) 0.0405 pu d)0.25 pu

Q.42 The severity of line to ground and three-phase faults at the terminals of an unloaded synchronous generator is to be same. If the terminals voltage is 1.0 pu, $Z_1 = Z_2$ = j 0.1pu and Z_0= j0.05 pu for the alternative, then the required inductance rectangle for neutral grounding is

a) 0.0166pu b) 0.05pu
c) 0.1pu d) 0.15pu

Q.43 Three singe –phase transformer with turn ratio 1 : 10 are connected in delta star to supply a 3- phase load. The supply voltage is 400V (line to line). The line voltage on the load side is

a) 400V b)400 $\sqrt{3}$ V
c) 4000V d) 4000 $\sqrt{3}$ V

Q.44 For a given base voltage and base voltamperes, The per unit impedance value of an element is x. The per unit impedance value of this element when the voltage and voltamperes bases are both doubled will be

a) 0.5 x b) x
c) 2x d) 4x

Q.45 Three single-phase transformers, each of 100 kVA rating are connected in delta, If one of the transformers is taken out of service, the capacity of the system will be

a) 200 kVA b) 173.2 kVA
c) 115.5 kVA d) 36.6 kVA

Q.46 There units of 1:5 transformers are connected in $\Delta - Y$ to supply a 3-Phase load from a 400 V, 3-phase. The line voltage on the load side is

a) 1000 V b) 80 V
c) 3464 V d) 803 V

Q.47 A 15 MVA, 33/11 kV, 3-phase transformer having an impedance of 16 Ω on the high tension side is supplied from a generator rated 30 MVA., 11 kV. The p.u. impedance of the transformer

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calculated on its own base and on the generator base will be in the ratio

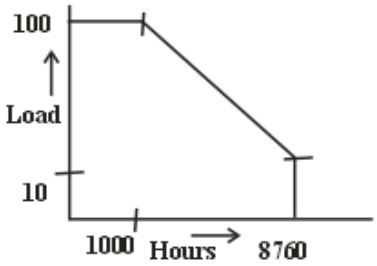
a) 1:1 b) 1 : 3
c) 1 : 9 d) 1: 18

Q.48 The following sequence currents were recorded in a power system under a fault condition:
$I_{positive}$ = j 1.653 p.u. $I_{negative}$ = -j 0.5 p.u. I_{zero} = - j 1.153 p.u.
The fault is
a)line to ground
b) three-phase
c) line to line to ground
d) line to line

Q.49 A single line to ground fault occurs on a three-phase isolated neutral system with a line to healthy phases rise to a value equal to

a) $\sqrt{2}$ V kV b) $\sqrt{3}$V k V
c) 3 V kV d) $\frac{1}{\sqrt{3}}$ V kV

Q.50 The load curve of a system is shown in the figure. The load factor of the system is:

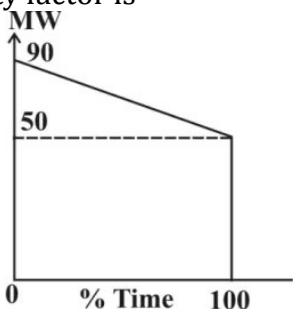


a) 1.66% b) 6.013%
c) 16.6% d) 60.13%

Q.51 A thermal generating station has an installed capacity of 15 MW and supplies a daily load of 10 MW for 12 hours and 5 MW for remaining 12 hours. The plant capacity factor for this station is

a) 1 b) 0.75
c) 0.67 d) 0.5

Q.52 The load duration curve for a power station is as shown in the figure. The reserve capacity in the plant at 70% capacity factor is



a) zero b) 10 MW
c) 30 MW d) 50 MW

Q.53 A generating station has a maximum demand of 30 MW, a load factor of 60% and a plant capacity factor of 50%. The reserve capacity of the plant is

a) 5 MW b) 4 MW
c) 6 MW d) 10 MW

Q.54 The per unit impedance of a circuit element is 0.15. If the base kV and base MVA are halved, then the new value of the per unit impedance of the circuit element will be

a) 0.075 b) 0.15
c) 0.30 d) 0.60

Q.55 A single line to ground fault occurs on an unloaded generator in phase a. If x_1 = x_2 = 0.25 p.u., x_o = 0.15 p.u. reactance connected in the neutral x_n = 0.05 p.u. and the initial prefault voltage is 1.0 p.u. then the magnitude of the fault current will be

a) 2.22 p.u b) 1.54 p.u.
c) 1.43 p.u. d) 1.25 p.u.

Q.56 A power system network with a capacity of 100 MVA has a source impedance of 10% at a point. The fault level at that point is

a) 10 MAV b) 30 MVA
c) 3000 MVA d) 1000 MVA

Q.57 The impedance value of a generator is 0.2 pu on a base value of 11KV, 50

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MVA. The impedance value for a base value of 22KV, 50MVA is
a) 0.05pu b) 0.2pu
c) 0.3pu d)2.4pu

Q.58 Four identical alternators each rated for 20MVA, 11KV having a sub transient reactance of 16% are working in parallel. The short – circuit level at the bus- bars is
a) 500 MVA b) 400MVA
c) 125MVA d) 80MVA

Q.59 In a power system with negligible resistance, the fault current at a point is 8.00 pu. The series reactance to be included at the fault point to limit the short – circuit current to 5.00 pu is
a) 3.000 pu b) 0.200 pu
c) 0.125 pu d) 0.075 pu

Q.60 The bus-bars of each of the two alternators of 15% reactance each are interconnected through tie- bar reactors of 15% each. The equivalent impedance to fault for a 3- phase fault in any alternative bus – bar will be
a) 7.5% b) 10%
c) 11.25% d)15%

Q.61 When a line-to-ground fault occurs, the current in a faulted phase is 100A.the zero sequence current in this case will be
a) Zero b) 33.3 A
c) 66.6A d) 100A

Q.62 When a 50 MVA, 11kV, 3-phase generator is subjected to a 3-phase fault, the fault current is –j5 pu (per unit). When it is subjected to a line-to-line fault, the positive sequence current is –j4 pu. The positive and negative sequence reactances are respectively
a) j0.2 and j0.05 pu
b) j0.2 and j0.25 pu
c) j0.25 and j0.25 pu
d) j0.05 and j0.05 pu

Q.63 The per unit impedance of asynchronous machine is 0.242. If the base voltage is increased by 1.1 times, the per unit value will be
a) 0.266 b) 0.242
c) 0.220 d) 0.200

Q.64 A 3-phase alternator rated at 50 MVA , 22 kV has a synchronous reactance per phase of 5 pu on its thermal rating. The pu value of this reactance on a base of 100 MVA and 220 kV is
a) 25 pu b) 12.5 pu
c) 1 pu d) 0.1 pu

Q.65 A star-connected 3-phase 11 kV, 25 MVA alternator with its neutral grounded through a 0.033 pu reactance (based on the alternator rating) has positive , negative and zero –sequence reactances of 0.2 pu, 0.1 pu and 0.1 pu respectively .a single line to ground fault on one of its terminals would result in a fault current of
a) 150 MVA b) 125 MVA
c) 100 MVA d) 50 MVA

Q.66 The impedance per phase of a 3-phase transmission line on a base of 100 MVA, 100kV is 2 pu. The value of this impedance on a base of 400 MVA and 400 kV would be
a) 1.5 pu b) 1.0 pu
c) 0.5 pu d) 0.25 pu

Q.67 An isolated synchronous generator with transient reactance equal to 0.1 pu on a 100 MVA base is connected to the high voltage bus through a step up transformer of reactance 0.1 pu on a 100 MVA base. The fault level at the bus is
a) 1000MVA b) 500 MVA
c) 50 MVA d) 10 MVA

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Q.68 If a 250 MVA, 11/400 kV three-phase power transformer has leakage reactance of 0.05 per unit on the base of 250 MVA and the primary voltage of 11 kV, then the actual leakage reactance of the transformer referred to the secondary side of 400 kV is

a) 0.8Ω b) 0.0032 Ω
c) 0.03125 Ω d) 32.0 Ω

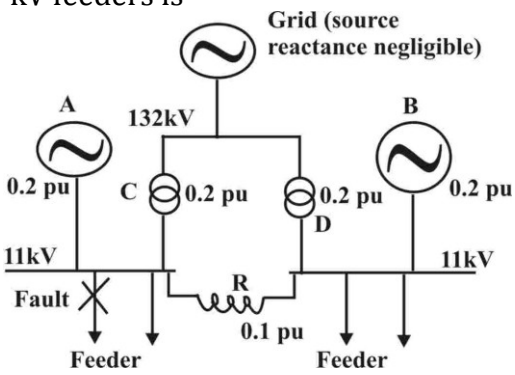
Q.69 Three generators rated 100 MVA, 11kV have an impedance of 0.15 pu each. If in the same plant, these generators are being replaced by a single equivalent generator, the effective impedance of equivalent generator will be

a) 0.05 pu b) 0.15 pu
c) 0.25 pu d) 0.45 pu

Q.70 The diagram shows the layout of a power station having two generators A and B, connected to the 11 kV buses which are also fed through two transformers C and D from a 132 kV grid. The 11 kV buses are interconnected through a reactor R.

The reactances of A, B, C, D and R are in p.u. on a common MVA-and kV –base. All the generated voltages in A,B and grid are each 1.0 p.u. and assumed as in phase at the time of fault.

The steady state symmetrical fault-current for a 3-phase fault on the 11 kV feeders is



a) 10 p.u. b) 15 p.u.
c) 20 p.u. d) 25 p.u.

Q.71 A 4 KVA, 400/200V single-phase transformer has resistance of 0.02 p.u. and reactance of 0.06p.u. Its actual resistance and reactance referred to h.v. side are respectively.

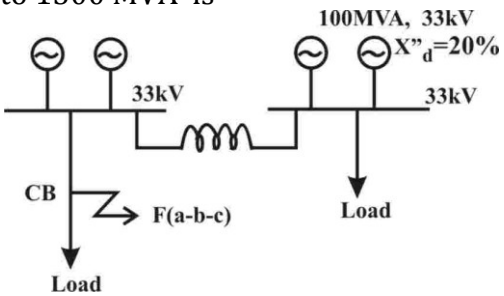
a) 0.2 ohm and 0.6 ohm
b) 0.8 ohm and 2.4 ohm
c) 0.08 ohm and 0.24 ohm
d) 2 ohm and 6 ohm

Q.72 The per unit impedance of an alternator corresponding to base values 13.2KV and 30 MVA is 0.2 p.u value of the impedance for base values 13.8 KV and 50 MVA in p.u. will be

a) 0.131 b) 0.226
c) 0.305 d) 0.364

Q.73 Four identical 100 MVA, 33 kV generators are operating in parallel, as shown above, in two bus-bar sections, interconnected through a current limiting reactor of x p. u. reactance on the generator-base. Each generator has a reactance of 0.2 p. u.

The value of the reactor x to limit a symmetrical short-circuit (a-b-c) current through the circuit breaker to 1500 MVA is



a) 0.05 p. u. b) 0.10 p. u.
c) 0.15 p. u. d) 0.20 p.u.

Q.74 The zero sequence current of a generator for line to ground fault is j 2.4 p. u. Then the current through the neutral during the fault is

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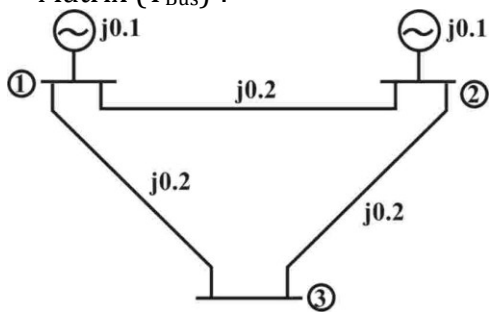
a) j 2.4 p. u. b) j 0.8 p. u.
c) j 7.2 p. u. d) j 0.24 p. u.

Q.75 A sample power system network is shown in the figure. The reactances marked are in pu. What is the pu value of Y_{22} of the Bus Admittance Matrix (Y_{Bus}) ?



a) j 10.0 b) j 0.5
c) – j 0.1 d) – j 20.0

Q.76 The direct axis reactance X_d of a synchronous generator is given as 0.4 pu based on the generator's name plate rating of 10 kV, 75 MVA. The base for calculation is 11 kV, 100 MVA. What is the pu value of X_d on the new base?
a) 0.279 b) 0.578
c) 0.412 d) 0.44

Q.77 Three identical impedances are connected in delta to a 3-phase supply of 400V. The line current is 34.65A and the total power taken is 14.4kW. The resistance of the load in each phase (in ohms) is
a) 20 b) 16
c) 12 d) 10

Q.78 An infinite bus of 1 pu is fed from a synchronous machine having E = 1.1 pu. If the transfer reactance between them is 0.5 pu, the steady state power limit will be
a) 1.1 pu b) 0.5 pu
c) 2.2 pu d) 1 pu

Q.79 The inertia constant of a 100 MVA , 50 Hz, 4-pole generator is 10 MJ/MVA. If the mechanical input to the machine is suddenly raised from 50 MW to 75 MW, the rotor acceleration will be equal to
a) 225 electrical degree/s^2
b) 22.5 electrical degree/s^2
c) 125 electrical degree/s^2
d) 12.5 electrical degree/s^2

Q.80 If a generator of 250 MVA rating has an inertia constant of 6 MJ/MVA, its inertia constant on 100 MVA base is
a) 15 MJ/MVA b) 10.5 MJ/MVA
c) 6 MJ/MVA d) 2.4 MJ/MVA

Q.81 Two 50 Hz generating units operate in parallel with in the same power plant and have the following ratings:
Unit1 : 500 MVA, 0.85 power factor, 20 kV, 3000 rpm, H_1=5 MJ/MVA
Unit 2 : 200 MVA, 0.9 power factor, 20 kV, 1500 rpm, H_2 = 5 MJ/MVA
The equivalent inertia constant H in MJ/MVA on 100 MVA base is
a) 2.5 b) 5.0
c) 0.0 d) 35.0

Q.82 A three-phase transmission line of negligible resistance and capacitance has an inductive reactance of 100 ohms per phase. When the sending-end and receiving-end voltages are maintained at 110 kV, the maximum power that can be transmitted will be
a) 121 MW b) $121\sqrt{3}$ MW
c) 363 MW d) 363 Kw

Q.83 A 3-phase line having neligible resistance and 22 ohm inductive reactance per phase operates with 110 kV sending-end voltages and 100 kV receiving-end voltage. The maximum power that this line can transmit as
a) $500\sqrt{3}$MW b) 500 MW
c) 1500 MW d) $\frac{500}{\sqrt{3}}$ MW

Q.84 If |Vs| = |Vr| = 38 KV for three – phase transmission and reactance is

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11 ohms/phase, then the maximum power transmission per phase would be

a) 132MW b) 396MW
c)66MW d)None of these

Q.85 For 800 MJ stored energy in the rotor at synchronous speed, what is the inertia constant H for a 50 Hz, four pole turbo-generator rated 100 MVA, 11 kV?

a) 2.0 MJ/MVA b) 4.0 MJ/MVA
c) 6.0 MJ/MVA d) 8.0 MJ/MVA

Q.86 A synchronous generator with a synchronous reactance of 1.3 pu is connected to an infinite bus whose voltage is 1pu, through an equivalent reactance of 0.2 pu. For maximum output 1.2 pu, the alternator emf must be

a) 1.5 pu b) 1.56pu
c) 1.8 pu d)2.5 pu

Q.87 The power angle characteristics of machine-infinite bus system is $P_e = 2 \sin \delta$ pu. It is operating at $\delta = 30^o$. Which one of the following is the synchronizing power coefficient at the operating point?

a) 1.0 b) $\sqrt{3}$
c) 2.0 d) $\frac{1}{\sqrt{3}}$

Q.88 A 100 km transmission line is designed for a nominal voltage of 132 kV and consists of one conductor per phase. The line reactance is 0.726 ohm/km. The static transmission capacity of the line, in Megawatts, would be

a) 132 b) 240
c) 416 d) 720

Q.89 The inertia constant of a 100 MVA, 11 kV water-wheel generators is 4. The energy stored in the rotor at the synchronous speed is

a) 400 MJ b) 400 kJ
c) 25 MJ d) 25 kJ

Q.90 If a 500 MVA, 11 kV three-phase generator at 50 Hz feeds, through a transfer impedance of (0.0+J0.605)Ω per phase, an infinite bus also at 11 kV; then the maximum steady state power transfer on the base of 500 MVA and 11 kV is

a) 1.0 pu b) 0.8 pu
c) 0.5 pu d) 0.4 pu

Q.91 The incremental cost characteristics of the two units in plant are given by:
$IC_1 = Rs\ (0.1P_1 + 8.0)$ per MWh(c)
$IC_2 = Rs\ (0.15P_2 + 3.0)$ per MWh
The optimum sharing of load when the total load is 100 MW is

a) $P_1 = 60$ MW and $P_2 = 40$ MW
b) $P_1 = 33.3$ MW and $P_2 = 66.7$ MW
c) $P_1 = 40$ MW and $P_2 = 60$ MW
d) $P_1 = 66.7$ MW and $P_2 = 33.3$ MW

Q.92 A two –bus system is shown in the given figure. when 100MW is transmitted from plant 1 to the load, the transmission loss 10MW. The incremental fuel costs of the two plants are

$\frac{dc_1}{dp_1} = 0.02P_1 + 16$ and $\frac{dc_2}{dp_2} = 0.04P_2 + 20$

The optimum distribution of total load of 260 MW between the two plants when losses are included but not coordinated is P_1

(a) 300MW (b) 240MW
(c) 130MW (d) 220MW

Q.93 The equivalent Thevenin`s bus admittance matrix of a two-bus system with identical generators on both buses is

$$\begin{bmatrix} -j30 & +j10 \\ +j10 & -j30 \end{bmatrix}$$

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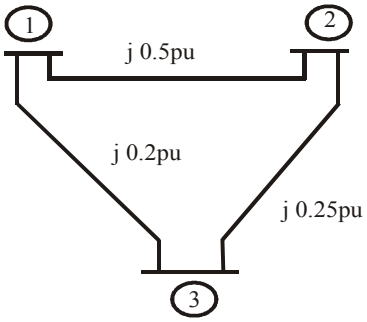
The generator reactance and interconnecting line reactance will be respectively

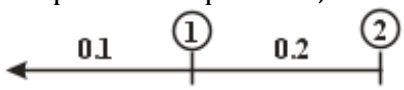
a) j0.05 and j 0.1 b) –j30 and j0.1
c) –j30 and –j0.1 d) j0.1 and j0.05

Q.94 A single line diagram of a power system is shown in the given figure. The diagonal elements of the Y_{BUS} matrix is



a) j0.7 pu, j0.75pu, j0.45
b)-j 0.7pu, - j 0.75pu,
c) –j7.0pu, -j6.0pu, - j 9.0 pu
d) j 7.0 pu, -j6.0 pu, j9.0 pu

Q.95 The bus admittance matrix of the network shown in the given figure, for which the marked parameters are per unit impedance, is



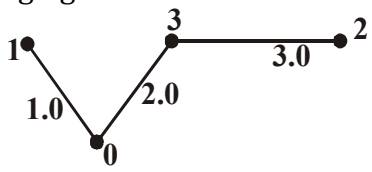
a) $\begin{bmatrix} 0.3 & -0.2 \\ -0.2 & 0.2 \end{bmatrix}^{-1}$ b) $\begin{bmatrix} 0.3 & 0.2 \\ 0.2 & 0.2 \end{bmatrix}$

c) $\begin{bmatrix} 0.3 & -0.2 \\ -0.2 & 0.2 \end{bmatrix}$ d) $\begin{bmatrix} 15 & 5 \\ 5 & -5 \end{bmatrix}$

Q.96 The incremental fuel cost for two generating units are given by
$I C_1 = 25 + 0.2 PG_1$
$I C_2 = 32 + 0.2 PG_2$, where PG_1 and PG_2 are real power generated by the units.
The economic allocation for a total load of 250 MW, neglecting transmission loss is given by

a) PG_1= 142.5 MW, PG_2 = 107.5 MW
b) PG_1=109.75MW,PG_2=140.25 MW
c) $PG_1 = PG_2$ = 125 MW
d) PG_1 = 100 MW, PG_2 = 150 MW

Q.97 Consider the network shown in the following figure:



The bus numbers and impedances are marked. The bus impedance matrix of this network is

a) $\begin{matrix} & 1 & 2 & 3 \\ 1 & 1.0 & 0 & 0 \\ 2 & 0 & 2.0 & 0 \\ 3 & 0 & 0 & 5.0 \end{matrix}$

b) $\begin{matrix} & 1 & 2 & 3 \\ 1 & 1.0 & 0 & 0 \\ 2 & 0 & 2.0 & 0 \\ 3 & 0 & 0 & 3.0 \end{matrix}$

c) $\begin{matrix} & 1 & 2 & 3 \\ 1 & 1.0 & 0.0 & 0.0 \\ 2 & 0 & 5.0 & 2.0 \\ 3 & 0 & 2.0 & 2.0 \end{matrix}$

d) $\begin{matrix} & 1 & 2 & 3 \\ 1 & 1.0 & 0.0 & 0.0 \\ 2 & 0.0 & 2.0 & 2.0 \\ 3 & 0.0 & 2.0 & 5.0 \end{matrix}$

Q.98 The incremental cost characteristic of the two units in a plant are
$IC_1 = 0.1 P + 8.0$ Rs./MWh
$IC_2 = 0.15 P + 3.0$ Rs./MWh
When the total load is 100 MW, the optimum sharing of load is

	P_1	P_2
a)	40MW	60MW
b)	33.3MW	66.7MW
c)	60MW	40MW
d)	66.7 MW	33.3MW

Q.99 The incremental generating costs of two generating units are given by
IC_1=0.1X+20Rs./MWhr.
IC_2=0.15Y+18 Rs./MWhr.
Where X and Y are power (in MW) generated by the two units. For a total demand of 300 MW, the values

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(in MW) of X and Y will be respectively
a) 172 and 128 b) 128 and 172
c) 175 and 125 d) 200 and 100

Q.100 A power system network consists of three elements 0-1,1-2 and 2-0 of per unit impedances 0.2,0.4 and 0.4 respectively . Its bus impedance matrix is given by

a) $\begin{matrix} & 1 & 2 \\ 1 & 7.5 & -2.5 \\ 2 & -2.5 & 5.0 \end{matrix}$

b) $\begin{matrix} & 1 & 2 \\ 1 & 0.16 & 0.08 \\ 2 & 0.08 & 0.24 \end{matrix}$

c) $\begin{matrix} & 1 & 2 \\ 1 & 0.16 & -0.08 \\ 2 & -0.08 & 0.24 \end{matrix}$

d) $\begin{matrix} & 1 & 2 \\ 1 & 0.6 & 0.4 \\ 2 & 0.4 & 0.8 \end{matrix}$

Q.101 The powers generated by two plants are:
P_1=50 MW, P_2=40 MW. If the loss coefficients are B_{11}=0.001, B_{22} =0.0025 and B_{12}= - 0.0005, then the power loss will be
a) 5.5 MW b) 6.5 MW
c) 4.5 MW d) 8.5 MW

Q.102 The following data pertain to two alternators working in parallel and supplying a total load of 80 MW:
Machine 1: 40 MVA with 5% speed regulation
Machine 2: 60 MVA with 5% speed regulation.
The load sharing between machines 1 and 2 will be:

	$\frac{P_1}{48\,MW}$	$\frac{P_2}{32\,MW}$
a)		
b)	40 MW	40 MW
c)	30 MW	50 MW
d)	32 MW	48 MW

Q.103 The combined frequency regulation of machines in area of capacity 1500 MW and operating at a nominal frequency of 60 kHz is 0.1 pu on its own base capacity. The regulation in Hz/MW will be
a) 0.1/1500 b) 60/1500
c) 6/1500 d) 60/150

Q.104 With the usual notation, the impedance matrix for the system shown in the above figure is

a) $\begin{bmatrix} 3 & 1 \\ 1 & 3 \end{bmatrix}$ b) $\begin{bmatrix} \frac{3}{8} & -\frac{1}{8} \\ -\frac{1}{8} & \frac{3}{8} \end{bmatrix}$

c) $\begin{bmatrix} \frac{6}{5} & \frac{4}{5} \\ \frac{4}{5} & \frac{6}{5} \end{bmatrix}$ d) $\begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix}$

Q.105 Four alternators, each rated at 5 MVA, 11 kV with 20% reactance are working in parallel. The short – circuit level at bus bars is
a) 6.25 MVA b) 20 MVA
c) 25 MVA d) 100 MVA

Q.106 If, for a given alternator in economic operation mode, the incremental cost is given by (0.012P+8)Rs./mwh, $\frac{dP_L}{dP} = 0.2$ and plant λ = 25, then the power generation is
a) 1000 MW b) 1250 MW
c) 750 MW d) 1500 MW

Q.107 Two generators rated at 200 MW and 400MW are operating in parallel. both the governors have a drop of 4%, when the total load is 300 MW. They share the load as (suffix '1' is used for generator 200 MW and suffix '2' is used for generator400MW)
a) P_1= 100 MW and P_2 = 200 MW
b) P_1= 150 MW and P_2= 150 MW
c) P_1= 200 MW and P_2 = 100 MW
d) P_1= 100 MW and P_2= 400 MW

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Q.108 A 12-bus power system has 3 voltage controlled buses. The dimensions of the jacobian matrix will be

a) 21 x 21 b) 21 x 19
c) 19 x 19 d) 19 x 21

Q.109 Two alternators each having 4% speed regulation are working in parallel. alternator 'I' is rated for 12 MW and alternator '2' is rated for 8 MW. When the total load is 10 MW., the loads shared by alternators 1 and 2 would be respectively

a) 4 MW and 6 MW
b) 6 MW and 4MW
c) 5 MW and 5 MW
d) 10 MW and zero

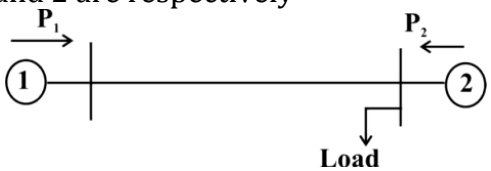
Q.110 The cost function of a 50 MW generator is given by (P_i is the generator loading)

$F(P_i) = 225+53P_i +0.02\ P_i^2$

When 100% loading is applied, the incremental fuel cost (IFC) will be

a) Rs. 55 per MWh b) Rs. 55 per MW
c) Rs. 33 per MWh d) Rs. 33 per MW

Q.111 The power plants interconnected by a tieline as shown in the above figure have loss formula coefficient $B_{11}=10^{-3}MW^{-1}$. power is being dispatched economically with plant '1' as 100 MW and plant '2' as 125 MW. The penalty factorsfor plants 1 and 2 are respectively



a) 1 and 1.25 b) 1.25 and 1
c) 1 and zero d) zero and 1

Q.112 The speed regulation parameter R of a control area is 0.025 Hz/MW and load frequency constant D is 2 MW/Hz. The area frequency response characteristic (AFRC)

a) 42.0 MW/Hz b) 40.0 MW/Hz
c) 20 MW/Hz d) 2 MW/Hz

Q.113 The Y_{BUS} matrix of a 100-bus interconnects system is 90% sparse. Hence the number transmission lines in the system must be

a) 450 b) 500
c) 900 d) 1000

Q.114 Two generators rated 200 MW and 400 MW having governor droop characteristics of 4% and 5% respectively are operating in parallel. If the generators operate on noload at 50 Hz, the frequency at which they would operate with a total load of 600 MW is

a) 48.50 Hz b) 47.69 Hz
c) 46.82 Hz d) 49.04 Hz

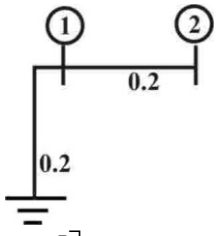
Q.115 The bus admittance of a power system is given as

$$\begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}\begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} -j50 & +j10 & +j5 \\ +j10 & -j30 & +J10 \\ +j5 & +j10 & -j25 \end{bmatrix} \end{array}$$

The impedance of line between bys 2 and 3 will equal to

a) + j 0.1 b) – j 0.1
c) + j 0.2 d) – j 0.2

Q.116 In the network as shown above, the marked parameters are p. u. impedances. The Bus-admittance matrix of the network is



a) $\begin{bmatrix} 10 & -5 \\ -5 & 5 \end{bmatrix}$ b) $\begin{bmatrix} 5 & -5 \\ -5 & 10 \end{bmatrix}$

c) $\begin{bmatrix} -10 & 5 \\ 5 & -5 \end{bmatrix}$ d) $\begin{bmatrix} -5 & 5 \\ 5 & -10 \end{bmatrix}$

Q.117 Incremental fuel costs in Rs / MWh for a plant consisting of two units

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are given by $\frac{dF_1}{dP_1} = 0.4P_1 + 400$ & $\frac{dF_2}{dP_2} = 0.48P_2 + 320$ The allocation of loads P_1 and P_2 between the units 1 and 2 respectively for minimum cost of generation for a total load of 900 MW is

a) 200MW and 700MW
b) 300MW and 600MW
c) 400MW and 500MW
d) 500MW and 400MW

Q.118 The time taken for a surge to travel a 600 km long overhead transmission line is

a) 6 s b) 1 s
c) 0.02 s d) 0.002 s

Q.119 A three-phase 50 Hz transmission line has a capacitance of line to neutral C_n= 0.01μF/km. The voltage of the line is 100 kV. The charging current per kilometer of line is

a) $\frac{314}{\sqrt{3}}$ A / km b) $\frac{314}{\sqrt{3}\times10^3}$ A / km
c) $\frac{\sqrt{3}\times10^3}{314}$ A / km d) $\sqrt{3}\times10^3$ A / km

Q.120 The velocity of travelling wave through a cable of relative permittivity 9 is

a) 9×10^8 m/s b) 3×10^8 m/s
c) 10^8 m/s d) 2×10^8 m/s

Q.121 The propagation constant of a transmission line is:
$0.15\times10^{-3} + j1.5\times10^{-3}$.
The wavelength of the travelling wave is

a) $\frac{1.5\times10^{-3}}{2\pi}$ b) $\frac{2\pi}{1.5\times10^{-3}}$.
c) $\frac{1.5\times10^{-3}}{\pi}$ d) $\frac{\pi}{1.5\times10^{-3}}$.

Q.122 A surge of 260 kV travelling in a line of natural impedance of 500 Ω arrives at a junction with two lines of natural impedance of 250 Ω and 50 Ω respectively the voltage transmitted in the branch lines is

a) 400 kV b) 260 kV
c) 80 kV d) 40 kV

Q.123 An overhead line with surge impedance of 400Ω is terminated through a resistance 'R'.A surge travelling over the line will not suffer any reflection at the junction, if the value of R is

a) 100 Ω b) 200 Ω
c) 400 Ω d) 800 Ω

Q.124 An overhead line with a surge impedance of 400Ω is connected to a transformer by a short length of cable of surge impedance 100Ω.if a rectangular surge wave of 40 kV travels along the line towards the cable, then the voltage of the wave travelling from the junction of the overhead line through the cable towards the transformer would be

a) 16 kV b) 24 kV
c) 32 kV d) 36 kV

Q.125 In a certain single phase a.c. circuit the instantaneous voltage is given by v = V sin (ωt+30°) p.u. and the instantaneous current is given by i =I sin (ωt – 30°) p.u. Hence the per unit value of reactive power is

a) $\frac{1}{4}$ b) $\frac{1}{2}$
c) $\frac{\sqrt{3}}{4}$ d) $\frac{\sqrt{3}}{2}$

Q.126 A surge of 100 kV travels along an overhead line towards its junction with a cable.

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The surge impedances for the overhead line and cable are 400 ohms and 50 ohms
respectively. The magnitude of the surge transmitted through the cable is
a) 11.11 KV b) 22.22 KV
c) 12.50 KV d) 88.89 KV

Q.127 The charging reactance of 50 km length of the line is 1500 Ω. What is the charging reactance for 100 km length of the line ?
a) 1500 Ω b) 3000Ω
c) 750 Ω d) 600Ω

Q.128 If the fault current is 2 kA, relay setting is 50% and the CT ratio is 400/5, then setting multiplier will be
a) 25 b) 15
c) 10 d) 12.5

Q.129 A three-phase 11/66 kV, delta /star transformer, protected by merz-price scheme has CT ratio of 400 /5 on L.T. side . ratio of C.T. on H.T. side will be equal to
a) 1:23 b) 23:1
c) 23: $\sqrt{3}$ d) $\sqrt{3}$: 23

Q.130 An over-current relay, having a current setting of 125% is connected to a supply circuit through a current transformer of ratio 400/5. the pick-up value is
a) 6.25 A b) 10 A
c) 12.5 A d) 15 A

Q.131 In a 400 kV power network, 360 kV is recorded at a 400 kV bus. The reactive powerabsorbed by a shunt reactor rated for 50 MVAR, 400 kV connected at the bus is
a) 61.73 MVAR b) 55.56 MVAR
c) 45.0 MVAR d) 40.5 MVAR

Q.132 A power plant has a maximum demand of 15MW. The load factor is 50% and the plant factor is 40%. The operating reserve is
a) 3.0MW b) 3.75MW
c) 6.0MW d) 7.5MW

Q.133 If the current is 3000 A, for an I.D.M.T. relay with a plug setting of 50% and C. T. ratio of 400/5, the plug setting multiplier would be
a) 7.5 b) 15.0
c) 18.75 d) 37.5

Q.134 If the fault current is 3000 A for a relay with a plug setting of 50% and CT ratio of 1000/ 1, the plug setting multiplier would be
a) 1.5 b) 3
c) 4.5 d) 6

Q.135 For a 15-bus power system with 3 voltages controlled bus, the size of Jacobian matrix is
a) 11×11 b) 12×12
c) 24×24 d) 25×25

Q.136 A 50 Hz 3-phase transmission line of length 100 km has a capacitance of 0.03/μ F per km. It is represented as a π mc. The shunt admittance at each of the transmission line will be
a) $150\times10^{-6}\angle90^{o}$ mho
b) $100\times10^{-6}\angle90^{o}$ mho
c) $471\times10^{-6}\angle90^{o}$ mho
d) $\frac{10^{6}}{150}\times10^{-6}\angle90^{o}$ mho

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ANSWER KEY:

1	2	3	4	5	6	7	8	9	10	11	12	13	14
(b)	(b)	(c)	(a)	(b)	(c)	(b)	(c)	(c)	(d)	(d)	(c)	*	(d)
15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
(a)	(d)	(d)	(c)	(a)	(b)	(b)	(b)	(a)	(a)	(b)	(a)	(d)	(d)
29	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**
(c)	(b)	(a)	(a)	(c)	(a)	(b)	(b)	(b)	(c)	(d)	(b)	(c)	(a)
43	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**
(d)	(a)	(b)	(c)	(d)	(c)	(b)	(d)	(d)	(b)	(c)	(c)	(d)	(d)
57	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
(a)	(a)	(d)	(b)	(b)	(b)	(d)	(d)	(a)	(c)	(b)	(d)	(a)	(b)
71	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**	**80**	**81**	**82**	**83**	**84**
(b)	(c)	(b)	(c)	(d)	(d)	(c)	(c)	(a)	(a)	(d)	(a)	(b)	(a)
85	**86**	**87**	**88**	**89**	**90**	**91**	**92**	**93**	**94**	**95**	**96**	**97**	**98**
(d)	(b)	(b)	(b)	(a)	(d)	(c)	(b)	(b)	(c)	(d)	(a)	(c)	(a)
99	**100**	**101**	**102**	**103**	**104**	**105**	**106**	**107**	**108**	**109**	**110**	**111**	**112**
(a)	(b)	(a)	(d)	(c)	(c)	(d)	(a)	(a)	(c)	(b)	(a)	(b)	(b)
113	**114**	**115**	**116**	**117**	**118**	**119**	**120**	**121**	**122**	**123**	**124**	**125**	**126**
(a)	(b)	(b)	(c)	(c)	(d)	(b)	(c)	(b)	(d)	(c)	(a)	(d)	(b)
127	**128**	**129**	**130**	**131**	**132**	**133**	**134**	**135**	**136**				
(c)	(c)	(b)	(a)	(d)	(b)	(b)	(d)	(d)	(c)				

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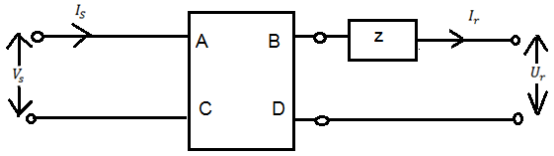
EXPLANATIONS

Q.1 **(b)**

$$\begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} A & AZ+B \\ C & CZ+D \end{bmatrix}$$



Q.2 **(b)**

Lint = KH/m

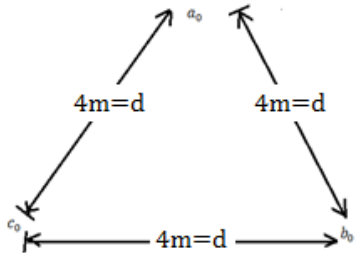
If the diameter of the conductor is doubled

$$\text{Lint} = \frac{\mu_o\mu_r}{8\pi} \rightarrow \text{Independent of length}$$

and diameter of the conductor

Lint = KH/m

Q.3 (c)



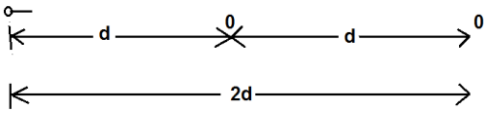
$\text{GMD} = \sqrt[3]{d.d.d}$

$= d$

GMR = selfGMD = r′

L/ph ∝ GMD

$$C/ph \propto \frac{1}{GMD}$$



$\text{GMD}_1 = \sqrt[3]{d.d.(2d)}$

$= d.2^{1/3}$

$\text{GMD}_1 > \text{GMD}$

$$L_1/ph = 2\times10^{-7}\ln\left(\frac{GMD}{GMR}\right)$$

$$C_1/ph = \frac{2\pi\in_0\in_r}{\ln\left(\frac{GMD_0}{GMR}\right)}$$

$C_{n1} < C_{n2}$

$L_2 > L_1$

Q.4 **(a)**

Because of Bundle conductor

Self GMD(= GMR) will increase

$$C/ph = \frac{2\pi\in_0}{\ln\left(\frac{GMD}{GMR}\right)}$$ will increase

$$L/ph = 2\times10^{-7}\ln\left(\frac{GMD}{GMR}\right)$$ will decrease

C/ph ↑ and L/ph ↓

Q.5 **(b)**

$L = 1.2mh/\text{phase}$

$$= 2\times10^{-7}\ln\left(\frac{GMD}{GMR}\right) \text{ or}$$

$$= 2\times10^{-7}\ln\left(\frac{d}{r'}\right)$$

$d_1 = d \Rightarrow d_2 = 2d$

$r'_1 = 0.7788r \Rightarrow r'_2 = 0.7788\times2r$

$$L_2 = 2\times10^{-7}\ln\left(\frac{d_2}{r'_2}\right)$$

$$= 2\times10^{-7}\ln\left(\frac{d}{r'}\right)$$

= 1.2mH/phase

Q.6 **(c)**

$$\%\text{Regulation} = \frac{IR\cos\phi_r \pm I\ x\ \text{Sin}\phi_r}{V_R}$$

$$= \frac{I_R}{V_R}\cos\Phi_r \pm \frac{I_x}{V_R}\sin\phi_r$$

$\frac{I_R}{V_R} = V_r = \text{per unit resistance drop}$

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$\frac{I_x}{V_R} = V_x = $ per unit reactance drop

%per unit regulation

$= V_r\cos\Phi_r \pm V_x\sin\Phi_r$

Q.7 (b)

Surge Impedance

$z_c = 50\Omega$ for 100km line

40kms line =?

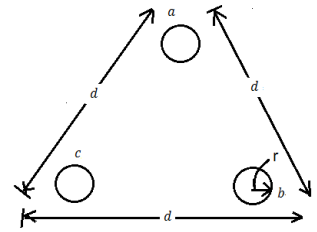
$$z_c = \sqrt{\frac{r + j\omega L}{g + \omega c}}$$

$$= \sqrt{\frac{z}{y}} \rightarrow \text{for lossy line}$$

$$= \sqrt{\frac{L/km}{C/km}} \rightarrow \text{Loss} - \text{less Line}$$

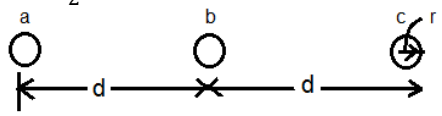
Surge impedance z_c for a loss- less line is independent of length of the line.

Q.8 (c)



$GMD_2 = \sqrt[3]{d.d.d} = d$

$GMR_2 = r'$



$GMD_1 = \sqrt[3]{d \times d \times 2d} = d.2^{1/3}$

$GMR_1 = r'$

$GMR_1 = GMR_2 = GMR$

$GMD_1 > GMD_2$

$$L_1 = 2\times10^{-7}\ln\left(\frac{GMD_1}{GMR_1}\right) \& L_2$$

$$= 2\times10^{-7}\ln\left(\frac{GMD_2}{GMR}\right)$$

$L/ph \propto GMD \Rightarrow L_2 < L_1$

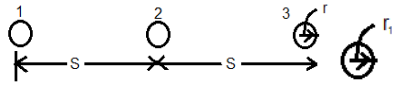
$$C_1 = \frac{2\pi\in_0}{\ln\left(\frac{GMD_1}{GMR}\right)} \& C_2 = \frac{2\pi\in_0}{\ln\left(\frac{GMD_2}{GMR}\right)}$$

$$\frac{C}{ph} \propto \frac{1}{GMD} C_2 > C_1$$

Average capacitance will increase but the average inductance will decrease.

Q.9 (c)

Bundle conductor



$GMR_1 = \sqrt{r' \times S \times 25}$

Single conductor

$GMR_2 = r'_1$

$r' = 0.7788r'_1$

Self GMD or GMR will increase for Bundle conductor

GMD is almost same

$(\because s \ll d \,\&\, r \ll s)$

$$L/ph = 2\times10^{-7}\ln\left(\frac{GMD}{\text{self GMD}}\right)$$

L/ph will decrease because self GMD is more 15.

Q.10 (d)

$3-\Phi$ circuit breaker

s.c MVA =2000

$V_L = 33kV$

$$I_{sc} = \frac{2000\times10^6}{\sqrt{3}\times33\times10^3} 35kA$$

making current $= 2.55 \times I_{sc}$

$= 2.55\times35KA = 89.22KA$

Q.11 (d)

$L = 1H$

$c = 0.01\mu F$

Current interrupted $= 10A = I$

Voltage across the breaker contact is

$$v = I\sqrt{\frac{L}{C}}$$

$$= 10\sqrt{\frac{1}{0.01\times10^{-6}}} = 100\times10^3 v$$

$= 100KV$

Q.12 (c)

220KV system

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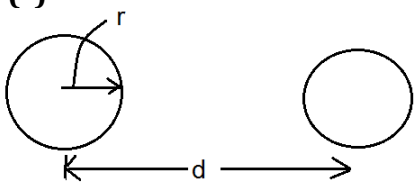
L = 25mH
C = 0.025μF

No transient oscillations $R = \frac{1}{2}\sqrt{\frac{L}{C}}$

$$R = 0.5\sqrt{\frac{L}{C}} = 0.5\sqrt{\frac{25\times10^{-3}}{0.025\times10^{-6}}}$$

$= 500\Omega$

Q.13 (*)



$L_2 = 2L_1$

$$L_1 = 2\times10^{-7}\ln\left(\frac{d}{r'}\right)r' = 0.7788r$$

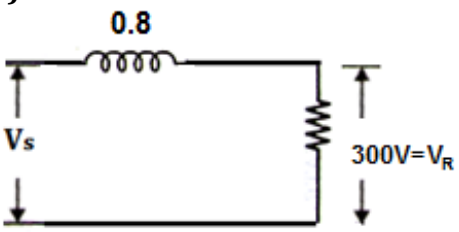
$$L_2 = 2\times2\times10^{-7}\ln\left(\frac{d_1}{r'}\right)$$

$$\frac{L_1}{L_2} = \frac{2\times10^{-7}\ln\left(\frac{d}{r'}\right)}{2\times10^{-7}\ln\left(\frac{d_1}{r'}\right)} = \frac{L_1}{L_2}$$

$$\ln\left(\frac{d_1}{r'}\right) = \ln\left(\frac{d}{r'}\right)^2$$

$$\left(\frac{d_1}{r'}\right) = \left(\frac{d}{r'}\right)^2$$

Q.14 (d)



$V_s = V_R + I_x$
$= 300 + j500 \times 0.8$
$= 300 + j400$
$= 500\lfloor -53.13°$
Power factor $= \cos\Phi_2 = \cos53.13$
$= 0.6$lag

Q.15 (a)

$z_c = 500\Omega$

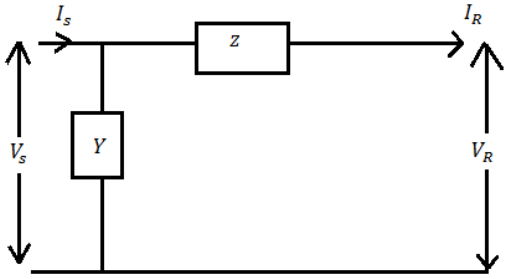
$V_{surge} = 1000$KV
Surge Impedance Loading (SIL)

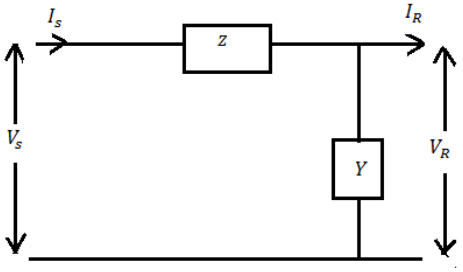
$$= \frac{V_{surge}^2}{z_c}$$

$$= \frac{1000\times1000\times10^6}{500}$$

$= 2000$MW

Q.16 (d)





$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix}\begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix}\begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ Y & 1 \end{bmatrix}\begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$$= \begin{bmatrix} 1 & z \\ Y & 1+Yz \end{bmatrix}\begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$$= \begin{bmatrix} 1+Yz & z \\ Y & 1 \end{bmatrix}\begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

Q.17 (d)

$$\frac{x}{R} = 1$$

$$\%\text{Regulation} = \frac{IR\cos\Phi_r - IX\sin\Phi_r}{V_R}$$

$\Phi_r + \theta = 90°$

$$\Phi_r = 90 - \theta = 90 - \text{Tan}^{-1}\left(\frac{x}{R}\right)$$

$= 45°$lead
$\cos\Phi_r = 0.707$(Lead)

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Q.18 (c)

$R = 2\Omega, x = 3\Omega$

$I = 125A, \cos\phi = 0.8$

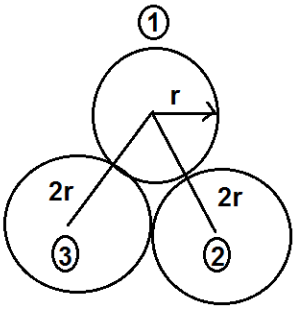
$v = 11.1kV$(per phase)

$$\%Regulation = \frac{125(2\times0.8+3\times0.6)}{11.1\times10^3}\times100$$

$$= \frac{I(R\cos\phi + X\sin\phi)}{v}\times100$$

$$= 3.8\%$$

Q.19 (a)

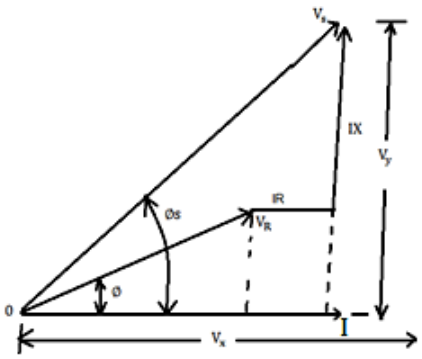


$$\text{Self GMD} = \sqrt[3]{r'\times d_{12}\times d_{13}}$$

$$= [0.7788\times r\times 2r\times 2r]^{1/3}$$

$$= r[0.7788\times2\times2]^{1/3}$$

Q.20(b)



$V_x = V_R\cos\phi + IR$

$V_y = V_R\sin\phi + IX$

$$V_s = \sqrt{V_x^2 + V_y^2}$$

$$\cos\phi_s = \frac{V_x}{V_s}$$

$$= \frac{V_R\cos\phi + IR}{V_s}$$

Q.21 (b)

$A = D = 0.81°, B = 17085°\Omega$

$C = 0.00290.4°\mho$

$V_s = 400KV$

$V_s = AV_R + BI_R$

at no-load $I_r = 0 \Rightarrow V_s = AV_{ro}$

$$V_{ro} = \frac{V_s}{A} = \frac{400}{0.8}kV$$

$$= 500kV$$

Q.22 (b)

%Regulation = 0(only for leading pf)

$$0 = \frac{I_rR\cos\phi_r - I_r\times\sin\phi_r}{V_r}$$

$I_rR\cos\phi_r = I_r \times \sin\phi_r$

$$\frac{\cos\phi_r}{\sin\phi_r} = \frac{x}{R}$$

$$\text{Tan}\phi_r = \frac{R}{x}$$

$$\phi_r = \text{Tan}^{-1}\left(\frac{R}{x}\right)$$

Q.23 (a)

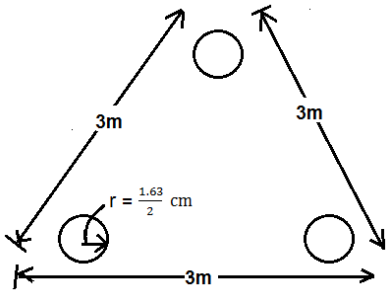
$3-\phi$, 400kVTransmission line

$z_c = 400\Omega$

$$SIL = \frac{V^2}{Z_c}MW = \frac{400^2}{400}Mw$$

$= 400Mw$

Q.24 (a)



3-ph transmission line

$$GMD = \sqrt[3]{3\times3\times3} = 3$$

$= 300cm$

$GMR = 0.7788 \times r$

$$= 0.7788\times\frac{1.63}{2}$$

$= 0.6347cm$

$$L_{ph} = 0.2\times\ln\left(\frac{GMD}{GMR}\right)mH/km$$

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$$= 0.2 \ln\left(\frac{300}{0.6347}\right) = \frac{1.232\text{mH}}{\text{km}}$$

Q.25 (b)

Underground cable

L = 0.22mH/km

c = 0.202μF/km

$$\text{surgeimpedance, } z = \sqrt{\frac{L}{c}} = \sqrt{\frac{0.22\times10^{-3}}{0.202\times10^{-6}}}$$

= 33Ω

Q.26 (a)

100km long transmission line

v = 110Kv

loss of line= 15Mw

S = 150MVA

$$I = \frac{s}{\sqrt{3}.V} = \frac{150\times10^{6}}{\sqrt{3}\times110\times10^{3}}$$

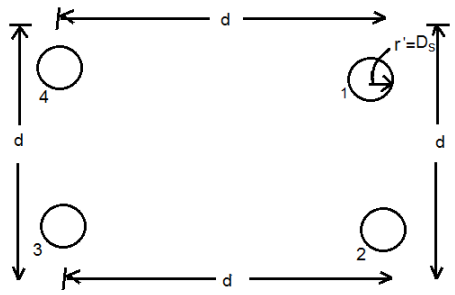
= 787.3A

Loss = $3I^2R$

$$R = \frac{15\times10^{6}}{3\times(787.3)^{2}}$$

= 8.066Ω per phase

Q.27 (d)



$$\text{GMR} = \sqrt[4]{r' \times d_{12} \times d_{13} \times d_{14}}$$

$$= \sqrt[4]{D_s \times d \times \sqrt{2}d \times d}$$

$$= 2^{\frac{1}{8}} \sqrt[4]{D_s \times d^3}$$

$$= 1.09 D_s^{\frac{1}{4}} d^{3/4}$$

Q.28 (d)

String insulator has 4 units =n

The voltage across the bottom most unit = V_b = 33.33% of total voltage

$$\eta_{string} = \frac{\text{total voltage}}{n \times \text{voltage across the bottom unit}}$$

$$= \frac{1}{4\times0.3333} = 0.75 \text{or} 75\%$$

Q.29 (c)

Diameter of a bundle conductor

$$= \frac{\text{Dia of solid conductor}}{\text{No of sub conductors}}$$

$$= \frac{40}{3} = 16.6$$

Q.30 (b)

C_x = 0.96μF

C_y = 0.6μF

$$2C = \frac{3}{2}C_x - \frac{1}{6}C_y$$

$$= \frac{3}{2}\times0.96 - \frac{1}{6}\times0.6$$

= 1.44 – 0.1 = 1.34

$$C = \frac{1.34}{2} = 0.67$$

Q.31 (a)

R_{ins} = 8MΩ for 20km long

R_{ins} for 10kms

$$R_{ins} \propto \frac{1}{\ell}$$

$$\frac{R_{ins1}}{R_{ins2}} = \frac{\ell_2}{\ell_1}$$

$$R_{ins2} = \frac{R_{ins1} \times \ell_1}{\ell_2}$$

$$= \frac{8M\times20}{10} = 16M\Omega$$

Q.32 (a)

$$n = 3, m = \frac{1}{0.2} = 5$$

V_1 = Voltage from top insulator

V_3 = Voltage near the conductor

$$V_2 = \frac{m+1}{m}V_1 = \frac{6}{5}V_1$$

$$V_3 = \frac{m^2+3m+1}{m^2}V_1 = \frac{25+15+1}{25}V_1$$

$$= \frac{41}{25}V_1 = 1.64V_1$$

$V_{string} = V_1 + V_2 + V_3$

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$= [1 + 1.2 + 1.64]V_1 = 3.84V_1$

$$\eta_{string} = \frac{\text{voltage of string}}{\text{no. of units} \times \text{voltage near the conductors}}$$

$$\eta_{string} = \frac{\text{voltage of string}}{\text{no. of units} \times \text{voltage near the conductors}} = \frac{3.84V_1}{3 \times 1.64V_1} = 78.04\%$$

Q.33 (c)

$\eta = 5m = 10 \quad v = 66kv$

$$V_2 = \frac{m+1}{m}V_1 = \frac{11}{10}V_1 = 1.1V_1,$$

$$V_3 = \frac{V_1 + 1.1V_1}{10} + 1.1V_1$$

$$= \frac{13.1}{10}V_1 = 1.31V_1$$

$$V_4 = \frac{V_1 + 1.1V_1 + 1.31V_1}{10} + 1.31V_1$$

$$= 1.651V_1$$

$$V_5 = \frac{V_1 + 1.1V_1 + 1.31V_1 + 1.651V_1}{10} + 1.651V_1$$

$= 2.1571V_1$

$$\eta = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{n \times V_5} = \frac{7.2181 \times 1}{5 \times 2.157}$$

$= 66.92\% = 67\%$

Q.34 (a)

$R_{ins1} = 200M\Omega/km$

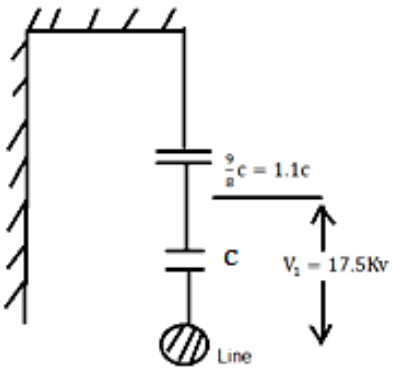
R_{ins2} for 5km

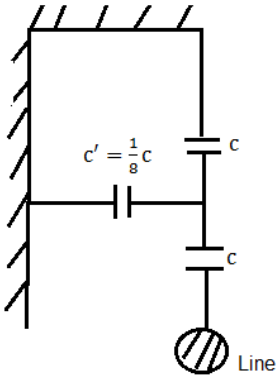
$$\frac{R_{ins2}}{R_{ins1}} = \frac{l_1}{l_2}$$

$$R_{ins2} = \frac{1}{5} \times 200 \times 10^6$$

$= 40M\Omega$

Q.35 (b)





$$V_1 = v\frac{1.1C}{1.0C + 1.1C}$$

$$v = v\frac{2.1}{1.1} = 33.5kv$$

Q.36 (b)

$\eta = 3$

Voltage across the lowest unit, $V_b = 17.5kv$

$\eta_{string} = 84.28\%$

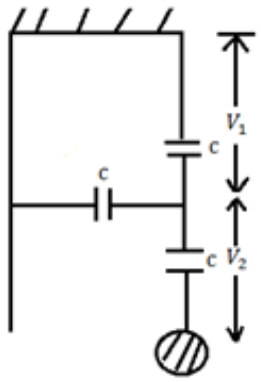
$$\eta_{string} = \frac{V}{n \times V_b}$$

$$0.8428 = \frac{V}{3 \times 17.5 \times 10^3}$$

$V = 0.8428 \times 3 \times 17.5 \times 10^3$

$= 44.25kv$

Q.37 (b)



$v = 22kv$

$c' = c$

$m = 1$

$n = 2$

$V_{sh} = V_1 + V_2$

$$V_2 = \left(\frac{m+1}{m}\right)V_1$$

$V_{sh} = 3V$

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$$\eta_{string} = \frac{V_{string}}{n \times V_2} = \frac{3V}{2 \times 2V} = \frac{3}{4}$$

= 75%

Q.38 (c)

3 – Ø Unbalanced system

$I_a = 0 \quad I_b = 660°, I_c = 6-120°$

$$I_{a0} = \frac{1}{3}\left(I_a + I_b + I_c\right)$$

$$= \frac{1}{3}\left(6\cos 60 + j6\sin 60 + 6\cos(-120) - j\,6\sin 120\right)$$

$$= 0$$

$$I_{a1} = \left(I_a + KI_b + K^2 I_c\right)$$

$$= \left(1120 \times 660 + 1240 \times 6 - 120°\right)$$

$= -9 + j3\sqrt{3} = -9 + j5.2$

$$I_{a2} = \left(I_a + K^2 I_b + KI_c\right)$$

$$= \left(1240 \times 660 + 1120 \times 6 - 120°\right)$$

$= 9 - j3\sqrt{3} = 9 - j5.2$

Q.39 (d)

$Z_{pu(old)} = 0.8$

$kv_{(old)} = 66kv, MVA_{(old)} = 100MVA$

$kv_{(new)} = 33kv, MVA_{(new)} = 100MVA$

$$Z_{pu(new)} = Z_{pu(old)} \times \frac{kv^2_{(old)} \times MVA_{(new)}}{kv^2_{(new)} \times MVA_{(old)}}$$

$$= 0.8\frac{66^2 \times 100}{33^2 \times 100} = 0.8 \times 4$$

= 3.2pu

Q.40 (b)

$X_{pu} = 0.2$

$V_{s(pu)} = 1.2$

$Q_{(pu)} = 0.3$

$$\Delta V = \frac{Q_x}{V_s} = \frac{0.3 \times 0.2}{1.2}$$

= 0.05pu

Q.41 (c)

$X_{pu(old)} = 0.25$

$kv_{(old)} = 18kv \; MVA_{(old)} = 500MVA$

$kv_{(new)} = 20kv \; MVA_{(new)} = 100MVA$

$$X_{pu(new)} = X_{pu(old)} \times \frac{kv^2_{(old)} \times MVA_{(new)}}{kv^2_{(new)} \times MVA_{(old)}}$$

$$= 0.25 \times \frac{18^2 \times 100}{20^2 \times 500}$$

= 0.0405pu

Q.42 (a)

$V_{pre-fault} = 1.0pu$

$z_1 = z_2 = j0.1pu$

$z_0 = j0.05pu$

Line-to-ground fault current = Three phase fault current

$$\frac{3V_{pre-fault}}{z_1 + z_2 + z_0 + 3z_n} = \frac{V_{pre-fault}}{z_1}$$

$$\frac{3 \times 1.0}{z_1 + z_2 + z_0 + 3z_n} = \frac{1}{z_1}$$

$Z_1 + z_2 + z_0 + 3z_n = 3z_1$

$\Rightarrow 3z_n = 0.3 - 0.1 - 0.1 - 0.05 = 0.05$

$$z_n = \frac{0.05}{3} 0.0166pu$$

Q.43 (d)

1 – Ø transformer, $N_1 : N_2 = 1 : 10$

Delta/star Δ Y

$V_L = V_{ph} = 400V = V_1$

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

$$\Rightarrow \frac{V_2}{400} = \frac{10}{1}$$

$$\Rightarrow V_2 = 4000$$

V_2 is the phase voltage in star connection

$V_2(\text{Line} - \text{Line}) = 4000 \times \sqrt{3}$

Q.44 (a)

$z_{old(pu)} = x$

$MVA_{(new)} = 2 \times MVA_{(old)}$

$KV_{(new)} = 2 \times KV_{(old)}$

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)} \times MVA_{(new)}}{KV^2_{(new)} \times MVA_{(old)}}$$

$$= x \times \frac{KV^2_{(old)} \times MVA_{(old)}}{\left(2KV^2_{(old)}\right) \times MVA_{(old)}}$$

$$= \frac{x}{4} \times 2 = \frac{x}{2}$$

Q.45 (b)

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3; 1 – Ø Transformers in Delta
Rating of T.F =100 KVA
One transformer is out of service ⇒ Open delta
Rating of T.F in open Delta = $\sqrt{3}$ ×Rating of each transformer
= $\sqrt{3}$ × 100KVA=173.2KVA

Q.46 (c)

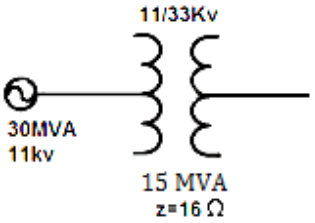
Three units of 1 – Ø T.Fs
Δ – Y $N_1 : N_2 = 1:5$
$V_L = V_{ph} = 400 = V_1$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \Rightarrow V_2 = \frac{N_2}{N_1} V_1$$

$$= 5 \times 400 = 2000V$$

Line voltage on load side
= $\sqrt{3}V_2$ = $\sqrt{3}$ × 2000
= 3464.1V

Q.47 (d)



$$\frac{Z_{pu}(trans)}{Z_{pu}(Gen)} = \frac{z \times MVA(trans)}{kv^2_{(trans)}} \times \frac{kv^2_{(Gen)}}{z \times MVA_{(Gen)}}$$

$$= \frac{16 \times 15}{(33)^2} \times \frac{(11)^2}{16 \times 30} = \frac{1}{18}$$

Q.48 (c)

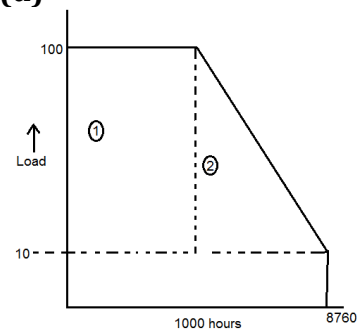
$I_{positive}$ = j1.653pu
$I_{negative}$ = –j0.5pu
I_{zero} = –j1.153pu
$I_{positive} + I_{negative} + I_{zero} = 0$
$I_{a1} = (I_{a2} + I_{a0})$ For line to line ground fault (or) Double Line ground Fault

Q.49 (b)

Single line to ground Fault (isolated neutral)
The voltage of healthy phase will increase to $\sqrt{3}$V the fault current is zero.

This phenomenon is called Arcing ground.

Q.50 (d)



$$Area = 100 \times 1000 + \frac{1}{2} \times 7760 \times 90 + 10 \times 7760 = 526800$$

$$AverageLoad = \frac{Area}{No.of\ Hours}$$

$$= \frac{526800}{8760}$$

= 60.13Mw
Max. demand = 100Mw

$$Load\ factor = \frac{AverageLoad}{Max.demand} = \frac{60.13}{100}$$

= 60.13%

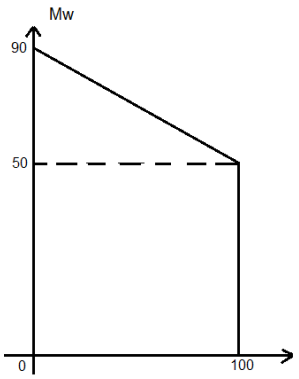
Q.51 (d)

Installed Capacity,IC = 15Mw
10Mw For 12 hours
and 5Mw for 12 hours
Plant capacity factor

$$= \frac{No.of\ units\ generated}{Installed\ capaicty \times Max.possible\ hours\ perday}$$

$$= \frac{12 \times 10 + 5 \times 12}{15 \times 24} = 0.5$$

Q.52 (b)



Capacity Factor

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$$= \frac{\text{AverageLoad}}{\text{Installed capacity(IC)}}$$

$$\text{Average Load} = \frac{90+50}{2} = 70$$

$$(\text{IC}) = \frac{70}{0.7} = 100\text{Mw}$$

Maxdemand = M.D = 90Mw

Reserve capacity = IC – MD

$= 100 - 90 = 10\text{Mw}$

Q.53 (c)

Maxdemand = M.D = 30Mw

Load factor = 60% = LF

Plantcapacity Factor(PCF) = 50%

$$\frac{\text{PCF}}{\text{LF}} = \frac{\text{AverageLoad}}{\text{Installed capacity}} \times \frac{\text{Maxdemand}}{\text{AverageLoad}}$$

$$\frac{50}{60} = \frac{30}{\text{IC}}$$

$$\text{IC} = \frac{30 \times 6}{5} = 36\text{Mw}$$

$$\text{Reservecapacity} = \text{IC} - \text{MD} = 36 - 30$$

= 6Mw

Q.54 (c)

$z_{pu(old)}$ = 0.15

$KV_{(new)} = 0.5 \times KV_{(old)}$

$MVA_{(new)} = 0.5 \times MVA_{(old)}$

$$z_{pu(new)} = z_{pu(old)} \cdot \frac{KV^2_{(old)} \times MVA_{(new)}}{KV^2_{new} \times MVA_{(old)}}$$

$$= 0.15 \frac{KV^2_{old} \times 0.5 \times MVA_{(old)}}{\left(0.5 \times KV_{(old)}\right)^2 \times MVA_{(old)}}$$

= 0.3pu

Q.55 (d)

Single line to ground fault

$x_1 = x_2 = 0.25$pu, $x_0 = 0.15$pu

$x_n = 0.05$pu

$V_{prefault} = 1.0$pu

$$I_f = \frac{V_{prefault}}{x_1 + x_2 + x_6 + 3x_n} =$$

$$\frac{1}{0.25+0.25+0.15+3\times 0.05} = 1.25\text{pu}$$

Q.56 (d)

$$\text{Basecapacity} = \text{BaseMVA} = 100\text{MVA}$$

%z = 10%

$$\text{Fault level} = \frac{\text{BaseMVA}}{\%\text{Impedance}(\text{or})\text{Reactance}}$$

$$= \frac{100}{0.1} = 1000\text{MVA}$$

Q.57 (a)

$z_{pu(old)}$ = 0.2

$KV_{(old)}$ = 11KV, $MVA_{(old)}$ = 50MVA

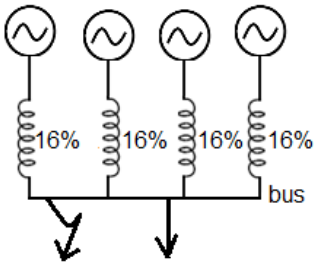
$KV_{(new)}$ = 22KV, $MVA_{(new)}$ = 50MVA

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)} \times MVA_{(new)}}{KV^2_{(new)} \times MVA_{(old)}}$$

$$= 0.2 \frac{11^2 \times 50}{22^2 \times 50}$$

= 0.05pu

Q.58 (a)



Base MVA = 20MVA

$$Z_T = \frac{16}{4} = 4\% = 16161616$$

Base voltage = Base KV = 11KV

Short- circuit level = fault level

$$= \frac{\text{Base MVA}}{Z_T} = \frac{20}{0.04} = 500\text{MVA}$$

Q.59 (d)

Fault current, I_{f1} = 8.0pu

I_{f2} = 5.0pu v = 1.0pu

$$z_{f1} = \frac{v}{I_{f1}} = \frac{1}{8} = 0.125$$

$$z_{f2} = \frac{v}{I_{f2}} = \frac{1}{5} = 0.2$$

$Z_{f2} = z_{f1} + x \Rightarrow x = 0.2 - 0.125$

$= 0.075$pu

Q.60 (b)

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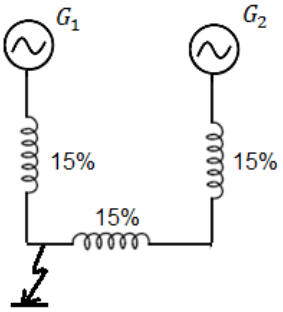


3 – ϕ Fault

$$Z_f = x_f = \frac{0.15\times0.3}{0.15+0.3}$$

= 0.1

$\%z_f = \%x_f = 10\%$

Q.61 (b)

Line –to –ground fault

Fault current, I_f = 100A

$I_f = I_{a1} + I_{a2} + I_{a0}$

$I_{a1} = I_{a2} = I_{a0}$

$$3I_{a0} = I_f \Rightarrow I_{a0} = \frac{I_f}{3} = \frac{100}{3} = 33.3A$$

Q.62 (b)

50MVA,11KV, 3 – ϕ Generator

3 – ϕ Fault current = –j5 pu = I_{f1}

Positive sequence current

$I_{a1} = -j4pu = I_{f2}$

Pre- fault voltage = 1.0p. u = $V_{pre-fault}$

$$I_{f1} = \frac{V_{pre-fault}}{z_1} \Rightarrow z_1 = \frac{1}{-j5} = j0.2pu$$

$$I_{f2} = \frac{V_{pre-fault}}{z_1+z_2} \Rightarrow z_1 + z_2$$

$$= \frac{1}{-j4} = +j0.25pu$$

z_2 = j0.25 – j0.2 = j0.05pu

Q.63 (d)

$z_{pu(old)}$ = 0.242

$KV_{(new)} = 1.1KV_{(old)}$

$MVA_{(new)} = MVA_{(old)}$

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)}}{KV^2_{(new)}}$$

$$= 0.242\frac{KV^2_{(old)}}{(1.1V)^2_{old}} = \frac{0.242}{(1.1)^2} = 0.2pu$$

Q.64 (d)

3 – ϕAltemator

$Z_{pu(old)}$ = 5, $MVA_{(old)}$ = 50MVA, $KV_{(old)}$ = 22KV

$MVA_{(new)} = 100MVA, KV_{(new)} = 220KV$

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)}MVA_{(new)}}{KV^2_{(new)}MVA_{(old)}}$$

$$= 5\frac{22^2\times100}{220^2\times50} = 0.1p.u$$

Q.65 (a)

11Kv, 25MVA, alternator with reactance grounding

z_1 = 0.2pu, z_2 = 0.1pu, z_0 = 0.1pu

z_n = 0.033pu$V_{pre-fault}$ = 1.0pu

Single line to ground Fault

$$I_a\,(\text{Fault current})\,I_f = \frac{3V_{pre-fault}}{z_1+z_2+z_0+3z_n}$$

$$I_f = \frac{3\times1.0}{0.2+0.1+0.1+3\times0.033} = 6pu$$

Fault level = 25 × 6 = 150MVA

Q.66 (c)

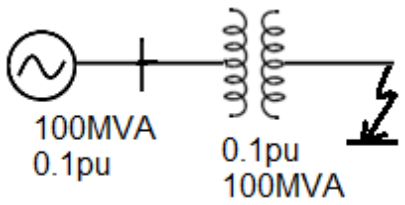
$z_{pu(old)} = 2pu, MVA_{(old)} =$ 100MVA, $KV_{(old)} = 100KV$

$MVA_{(new)}$ = 400MVA, $KV_{(new)}$ = 400KV

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)}\times MVA_{(new)}}{KV^2_{(new)}\times MVA_{(old)}}$$

$$= 2\times\frac{100^2\times400}{400^2\times100} = 0.5p.u$$

Q.67) (b)



$$\text{Fault level} = \frac{\text{Base MVA}}{\text{Impedance}} = \frac{100}{0.1+0.1}$$

= 500MVA

Q.68 (d)

z_{pu} = 0.05 250MVA, 11/400kv

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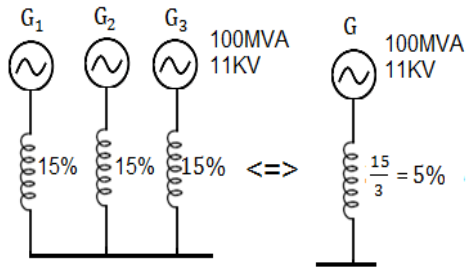
$$z_{pu} = z(\Omega).\frac{MVA}{(kv)^2}$$

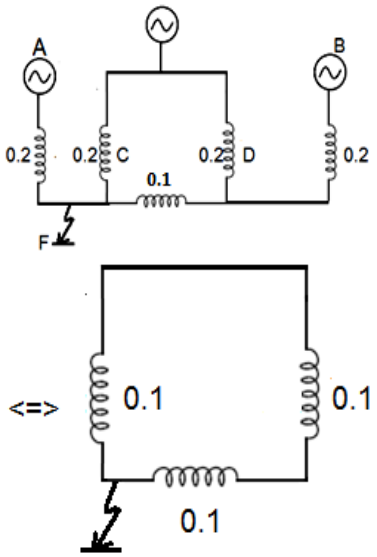
$$z(\Omega) = \text{secondary side}$$

$$= \frac{0.05 \times 400^2}{250} = 32\Omega$$

Q.69 (a)



Q.70 (b)



$$z_{eq} = \frac{0.1 \times 0.2}{0.3} = \frac{0.2}{3}$$

$$I_f = \frac{V_{pre-fault}}{z_{eq}} = \frac{3}{0.2} = 15pu$$

Q.71 (b)

4KVA, 400/200 v 1 – ϕ Transfomer

R_{pu} = 0.02

X_{pu} = 0.06

$$R_{(\Omega)} = R_{pu} \times \frac{KV^2}{MVA} = 0.02 \times \frac{0.4 \times 0.4}{4 \times 10^{-3}}$$

= 0.8Ω

$$X_{(\Omega)} = X_{pu} \times \frac{KV^2}{MVA} = 0.06 \times \frac{0.4 \times 0.4}{4 \times 10^{-8}}$$

= 2.4Ω

Q.72 (c)

$Z_{pu(old)}$ = 0.2 $KV_{(old)}$

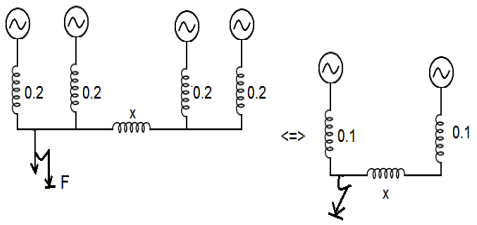
= 13.2KV, $MVA_{(old)}$ = 30MVA

$Kv_{(new)}$ = 13.8KV, $MVA_{(new)}$ = 50MVA

$$z_{pu(new)} = z_{pu(old)} \frac{KV^2_{(old)} \times MVA_{(new)}}{KV^2_{(new)} \times MVA_{(old)}}$$

$$= 0.2 \frac{13.2^2 \times 50}{13.8^2 \times 30} = 0.305\,pu$$

Q.73 (b)



Base MVA = 100MVA

s. c MVA = 1500MVA

$$\%z = \frac{\text{base MVA}}{\text{s.c MVA}} = \frac{100}{1500} = \frac{1}{15}$$

$$z = \frac{0.1 \times (0.1 + x)}{0.1 + 0.1 + x} = \frac{1}{15}$$

0.2 + x = 1.5x(0.1 + x)

$$0.05 = 0.5x \Rightarrow x = \frac{0.05}{0.5} = 0.1pu$$

Q.74 (c)

I_{a0} (Line –to–ground fault)=j2.4pu

I_n (Current through neutral)=?

Line–to–ground Fault

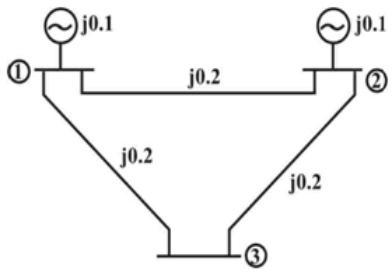
$I_{a1} = I_{a2} = I_{a0}$

$I_f = I_{a1} + I_{a2} + I_{a0} = 3I_{a0} = 3 \times j2.4$

= jf. 2pu

$I_n = I_f$ = j7.2pu

Q.75 (d)



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$$Y_{22} = \frac{1}{Z_{22}} + \frac{1}{Z_{23}} + \frac{1}{Z_{21}}$$
$$= \frac{1}{j0.1} + \frac{1}{j0.2} + \frac{1}{j0.2} = -j10 - j5 - j5$$
$$= -j20$$

Q.76 (d)

$X_d = 0.4pu$ 10KV, 75MVA
11KV, 100MVA

$$X_{d(new)} = X_d \times \frac{KV^2_{(old)} \times MVA_{(new)}}{KV^2_{(new)} \times MVA_{(old)}}$$
$$= 0.4 \times \frac{10^2 \times 100}{11^2 \times 75} = 0.44$$

Q.77 (c)

Three Identical Impedances are connected in Delta
$V_L = 400V$
$I_L = I_{ph} = 34.65A$
$P_{Load} = 14.4kw$
$= I_L{}^2 R$
$$R = \frac{14.4 \times 10^3}{(34.65)^2}$$
$= 11.99 \simeq 12\Omega$

Q.78 (c)

$V = 1.0pu$
$E = 1.1pu$
$X = 0.5pu$
$$P = \frac{EV}{x} = \frac{1.0 \times 1.1}{0.5} = 2.2pu$$

Q.79 (a)

$S = 100MVA$, $H = 10MJ/MVA$
4pole, 50Hz,
Mechanical power raised from 50Mw to 75 Mw
$P_a = P_s - P_e = 75 - 50 = 25Mw$
$$M\frac{d^2\delta}{dt^2} = P_a \Rightarrow \frac{5H}{\pi f}\frac{d^2\delta}{dt^2} = 25$$
$$\frac{d^2\delta}{dt^2} = \frac{25 \times 180 \times 50}{100 \times 10}$$
$= 225 elect.degrees/s^2$

Q.80 (a)

250MVA, $H = 6MJ/MVA$
100MVA
$S_1H_1 = S_2H_2$
$S_{(old)}H_{(old)} = S_{(New)}H_{(New)}$
$250 \times 6 = 100 \times H_{(New)}$
$$H_{(New)} = \frac{1500}{100} = 15MJ/MVA$$

Q.81 (d)

$S_1 = 500$ $H_1 = 5MJ/MVA$
$S_2 = 200$ $H_2 = 5MJ/MVA$
$S_bH_b = (S_1H_1 + S_2H_2)$
$$H_b = \frac{500 \times 5 + 200 \times 5}{100} = 35MJ/MVA$$

Q.82 (a)

$x = 100\Omega$ per phase
$V_s = V_r = 110KV$
$$S.S.L = \frac{V_s.V_r}{x} = \frac{110^2}{100}$$
$= 121Mw$

Q.83 (b)

$V_s = 110KV, V_r = 100KV$
$x = 22\Omega$
$$S.S.L = \frac{110 \times 100}{22} = \frac{V_sV_r}{x}$$
$= 500Mw$

Q.84 (a)

$|V_s| = |V_r| = 38KV$
$x = 11\Omega$/phase
$$S.S.L = \frac{|V_s||V_r|}{x} = \frac{38 \times 38}{11}$$
$= 131.28Mw$

Q.85 (d)

KineticEnergy $= K.E = 800MJ$
50Hz, Four pole, 100MVA, 11Kv?
$SH = K.E$
$$H = \frac{800}{100} = 8MJ/MVA$$

Q.86 (b)

$X_s = 1.3pu$
$v = 1.0pu$

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$S.S.L = 1.2pu$
E?

$$S.S.L = \frac{EV}{X_s} \Rightarrow E = \frac{1.2\times1.3}{1.0} = 1.56pu$$

Q.87 (b)

$P_e = 2\sin\delta$ pu
$\delta = 30°$
Synchronizing power co-efficient

$$\frac{\partial P_e}{\partial S} = 2cos\delta$$

$$= 2\cos 30 = 2\times\frac{\sqrt{3}}{2} = \sqrt{3}$$

Q.88 (b)

Length of line $= 100km$
$V = 132KV = V_s = V_r$

$$x = \frac{0.726\Omega}{km} \Rightarrow X_L$$

$$= 100\times0.726 = 72.6\Omega$$

$$S.S.L = \frac{132\times132}{72.6} = \frac{|V_s||V_r|}{x_l}$$

$$= 240Mw$$

Q.89 (a)

$S = 100MVA, V_L = 11Kv$
$H = 4MJ/MVA$
nergy stored in rotor = 5H
$= 100 \times 4 = 400MJ$

Q.90 (d)

$|V_s| = |V_R| = 11KV$
$x = 0.605\Omega$
$S_b = 500MVA$

$$P_{max} = \frac{|V_s||V_R|}{x} = \frac{11\times11}{0.605} = 200$$

On 500MVA base

$$P_b = \frac{200}{500} = 0.4pu$$

Q.91 (c)

$I_{C_1} = 0.1P_1 + 8.0\ R_s/MWh$
$I_{C_2} = 0.15P_2 + 3.0\ R_s/MWh$
$P_1 + P_2 = 100Mw$
$I_{C_1} = I_{C_2}$ For Economic operation
$0.1P_1 + 8 = 0.15P_2 + 3.0$

$$0.1P_1 = 0.15P_2 = -5$$

$$\underline{0.1P_1 \pm 0.1P_2 = _10}$$

$$0.25P_2 = -15 \Rightarrow P_2 = \frac{15}{0.25} = 60Mw$$

$P_1 = 100 - 60 = 40Mw$

Q.92 (b)

$$\frac{dc_1}{dP_1} = 0.02P_1 + 16$$

$$\frac{dc_2}{dP_2} = 0.04P_2 + 20$$

$P_1 + P_2 = 260Mw$
$P_L = 10Mw$
Losses are included not coordinated

$$\frac{dc_1}{dP_1} = \frac{dc_2}{dP_2}$$

$0.02P_1 + 16 = 0.04P_2 + 20$

$$0.02P_1 - 0.04P_2 = 4$$

$$\underline{0.04P_1 + 0.04P_2 = 10.4}$$

$0.06P_1 = 14.4$

$$P_1 = \frac{14.4}{0.06} = 240Mw$$

Q.93 (b)

Two bus system

$$Y_{BUS} = \begin{bmatrix} -j30 & +j10 \\ +j10 & -j30 \end{bmatrix}$$

$$Y_{12} = -y_{12} = -\frac{1}{Z_{12}} \Rightarrow Z_{12} = \frac{-1}{j10} = j0.1$$

$Y_{11} = y_{11} + y_{12} = y_{11} = -30$

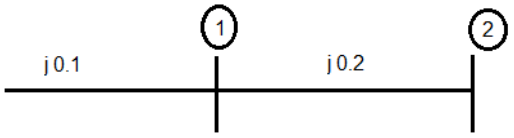
Q.94 (c)

$$Y_{11} = \frac{1}{j0.5} + \frac{1}{j0.2} = -j2 - j5 = -j7pu$$

$$Y_{22} = \frac{1}{j0.5} + \frac{1}{j0.25} = -j2 - j4 = -j6pu$$

$$Y_{33} = \frac{1}{j0.25} + \frac{1}{j0.2} = -j4 - j5 = -j9pu$$

Q.95 (d)



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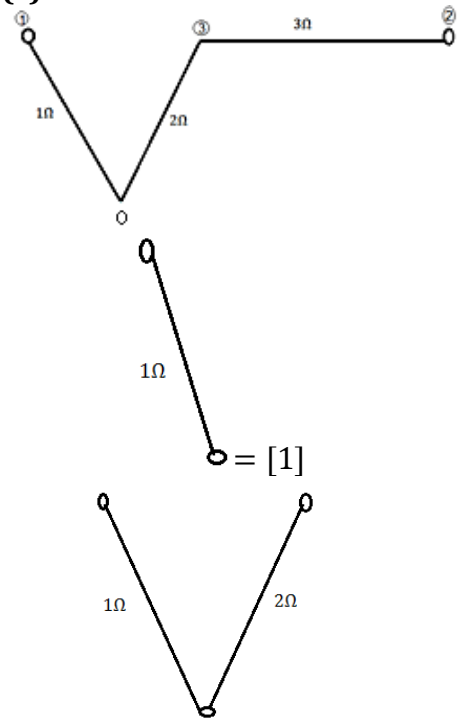
$$Y_{11} = \frac{1}{j0.1} + \frac{1}{j0.2}$$
$$= -j10 - j5 = -j15$$
$$Y_{12} = -\frac{1}{j0.2} = j5, Y_{21} = j5$$
$$Y_{22} = \frac{1}{j0.2} = -j5$$
$$Y = \begin{bmatrix} -j15 & j5 \\ j5 & -j5 \end{bmatrix}$$

Q.96 (a)

$IC_1 = 25 + 0.2P_{G_1}$
$IC_2 = 32 + 0.2P_{G_2} P_1 + P_2 = 250Mw$
$IC_1 = IC_2$
$25 + 0.2P_{G_1} = 32 + 0.2P_{G_2}$
$0.2P_{G_1} - 0.2P_{G_2} = 7 \Rightarrow P_{G_1} - P_{G_2} = 35$
$P_{G_1} + P_{G_2} = 250$
$$P_{G_1} = \frac{285}{2} = 142.5Mw$$
$P_{G_2} = 250 - 142.5 = 107.5Mw$

Q.97 (c)



$= [1]$

$$= \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

$$= \begin{matrix} ① \\ ③ \\ ② \end{matrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 2 \\ 0 & 2 & 5 \end{bmatrix}$$
$$\begin{matrix} & ① & ② & ③ \end{matrix}$$
$$= \begin{matrix} ① \\ ② \\ ③ \end{matrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 5 & 2 \\ 0 & 2 & 2 \end{bmatrix}$$

Q.98 (a)

$IC_1 = 0.1P_1 + 8R_s/Mwh$
$IC_2 = 0.15P_2 + 3R_s/Mwh,$
$P_1 + P_2 = 100Mw$
$IC_1 = IC_2$
$0.1P_1 + 8 = 0.15P_2 + 3$
$0.1P_1 - 0.15P_2 = -5$
$0.1P_1 \pm 0.1P_2 = _10$

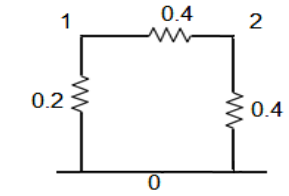
$$-0.25P_2 = -15 \Rightarrow P_2 = \frac{15}{0.25} = 60Mw$$
$P_1 = 100 - 60 = 40Mw$

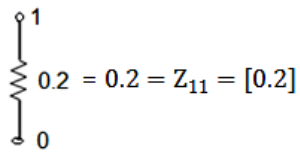
Q.99 (a)

$IC_1 = 0.1x + 20R_s/Mwhr$
$IC_2 = 0.15y + 18R_s/Mwhr$
$x + y = 300$
$IC_1 = IC_2$
$0.1x + 20 = 0.15y + 18$
$0.1x - 0.15y = -2$
$0.15x + 0.15y = 45$

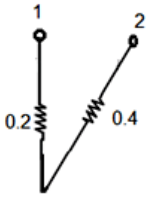
$$0.25x = 43 \Rightarrow x = \frac{43}{0.25} = 172Mw$$
$y = 300 - 172 = 128Mw$

Q.100 (b)





$= 0.2 = Z_{11} = [0.2]$



$$= \begin{bmatrix} 0.2 & 0 \\ 0 & 0.4 \end{bmatrix}$$

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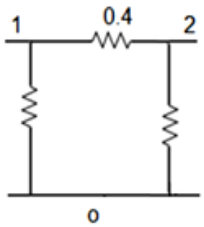


$$=\begin{bmatrix}0.2 & 0\\ 0 & 0.4\end{bmatrix}-\frac{1}{0.2+0.4+0.4}\begin{bmatrix}0.2\\ -0.4\end{bmatrix}[0.2-0.4]$$

$$=\begin{bmatrix}0.2 & 0\\ 0 & 0.4\end{bmatrix}-\begin{bmatrix}0.04 & -0.08\\ -0.08 & 0.16\end{bmatrix}=\begin{bmatrix}0.16 & 0.08\\ 0.08 & 0.24\end{bmatrix}$$

Q.101 (a)

$P_1 = 50Mw, P_2 = 40Mw$
$B_{11} = 0.001, B_{22} = 0.0025, B_{12} = -0.0005$
Assume $B_{21} = 0$
$P_L = B_{11}P_1^2 + B_{22}P_2^2 + P_1B_{12}P_2$
$= 0.001 \times 50^2 + 0.0025 \times 40^2 - 0.0005 \times 50 \times 40$
$= 5.5Mw$

Q.102 (d)

Two alternators are working in parallel
$P_1 + P_2 = 80Mw$
achine 1 : 40MVA,5%regular
Machine 2:60mVA, 5% regular
Speed regulation is same, therefore, load is shared based on MVA rating.

$$P_1 = \frac{40}{40+60}\times 80 = 32Mw$$

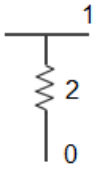
$$P_2 = \frac{60}{40+60}\times 80 = 48Mw$$

Q.103 (c)

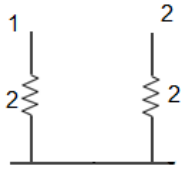
$P = 1500Mw$
$f = 60Hz$
Frequency regulation =0.1pu=reg
$\Delta f = veg \times f = 0.1 \times 60 = 6$

$$\text{regulation} = \frac{6}{1500}\text{Hz/Mw}$$

Q.104 (c)

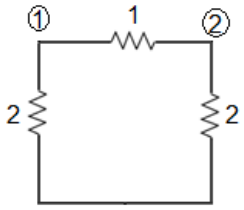


$$[Z_{11}] = [2]$$



$$=\begin{bmatrix}2 & 0\\ 0 & 2\end{bmatrix}$$

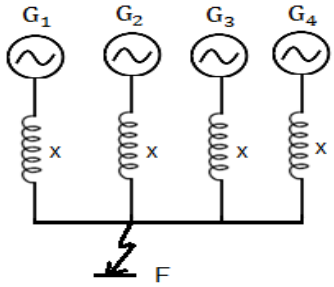
$Z_{link} = 1\Omega$



$$=\begin{bmatrix}2 & 0\\ 0 & 2\end{bmatrix}-\frac{1}{Z_{11}+Z_{22}+Z_{link}}\begin{bmatrix}2\\ -2\end{bmatrix}[2 \quad -2]$$

$$=\begin{bmatrix}2 & 0\\ 0 & 2\end{bmatrix}-\frac{1}{5}\begin{bmatrix}4 & -4\\ -4 & 4\end{bmatrix}=\begin{bmatrix}\frac{6}{5} & \frac{4}{5}\\ \frac{4}{5} & \frac{6}{5}\end{bmatrix}$$

Q.105 (d)



$s = 5MVA, V = 11Kv\, x = 20\%$

$$x_{eq} = \frac{20}{4} = 5\%$$

$$S\,C\,MVA = \frac{\text{Base MVA}}{x_{eq}}$$

$$= \frac{5}{5/100} = 100MVA$$

Q.106 (a)

$IC = (0.012P + 8)R_s/Mwh$

$$\frac{dP_L}{dP} = 0.2\lambda = 25$$

$$\lambda = \frac{IC}{1-\frac{\partial P_L}{\partial P}} = \frac{0.012P+8}{(1-0.2)}$$

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$0.012P + 8 = 25 \times 0.8$

$$P = \frac{12}{0.012} = 1000\text{Mw}$$

Q.107 (a)

$P_{G1} = 200\text{Mw}, P_{G2} = 400\text{Mw}$

%droop = 4% $P_{G1} + P_{G2}$

$= P_{load} = 300\text{Mw}$

$$P_1 = \frac{P_{G1}}{P_{G1}+P_{G2}} \times P_{load} = \frac{200}{200+400} \times 300$$

$= 100\text{Mw}$

$$P_2 = \frac{P_{G2}}{P_{G1}+P_{G2}} \times P_{load} = \frac{400}{200+400} \times 300$$

$= 200\text{Mw}$

Q.108 (c)

No. of buses N = 12

Voltage controlled buses, $N_g = 3$

$$\text{Jocobian} = [2N - N_g - 2] \times [2N - N_g - 2]$$

$$= [2\times12 - 3 - 2] \times [2\times12 - 3 - 2]$$

$= 19 \times 19$

Q.109 (b)

%regulation =4%

$P_{1\text{rated}} = 12\text{Mw}$ $P_{2\text{rated}} = 8\text{Mw}$

$P_{load} = 10\text{Mw}$

$$P_1 = \frac{12}{12+8} \times 10 = 6\text{Mw}$$

$$P_2 = \frac{8}{12+8} \times 10 = 4\text{Mw}$$

Q.110 (a)

$$P = 50\text{Mw}\ F(P_i) = 225 + 53P_i + 0.02P_i^2$$

$$\text{IFC} = \frac{dFP_i}{dP_i} = 0.04P_i + 53$$

$= 0.04 \times 50 + 53 = 55R_s/\text{Mwh}$

Q.111 (b)

$B_{11} = 10^{-3}\text{Mw}^{-1}$

$P_1 = 100\text{Mw}$ & $P_2 = 125\text{Mw}$

$P_L = B_{11}P_1^{\ 2}$

$$\frac{\partial P_L}{\partial P_1} = 2 \times B_{11} \times P_1 = 2 \times 10^{-3} \times 100$$

$= 0.2$

$$L_1 = \frac{1}{1 - \frac{\partial P_L}{\partial P_1}} = \frac{1}{1-0.2} = 1.25$$

$$\frac{\partial P_L}{\partial P_2} = 0 \Rightarrow L_2 = \frac{1}{1-0} = 1$$

Q.112 (b)

R = 0.025Hz/Mw

D = 2Mw/Hz

rea frequency characteristic

$$\text{AFRC} = \frac{1}{R}$$

$$\text{AFRC} = \frac{1}{0.025} = 40\text{Mw/Hz}$$

Q.113 (a)

Y_{Bus} order = 100 × 100 = 10,000

No. of zeros = 0.9 × 10.000 = 9,000

Non zero elements = 1000

Non − diagonal elements

= 1000 − 100 = 900

$$\text{No.of transmission Lines} = \frac{900}{2} = 450$$

Q.114 (b)

x = Load on 200Mw generator

$$\frac{\Delta f}{x} = \frac{0.04\times50}{200} = \frac{1}{100} \Rightarrow \Delta f = \frac{1}{100}x$$

$$\frac{f}{600-x} = \frac{0.05\times50}{400} = \frac{1}{160}$$

$$\Rightarrow f = \frac{1}{160}(600-x)$$

$$f = f \Rightarrow \frac{1}{100}x = \frac{1}{160}(600-x)$$

$$x = \frac{600\times160\times100}{160\times260} = 230.8 \simeq 231\text{Mw}$$

$$\Delta f = \frac{1}{100} \times 231 = 2.31\text{Hz}$$

Frequency of operation

= 50 − 2.31 = 47.69Hz

Q.115 (b)

$$Y = \begin{matrix} \\ ① \\ ② \\ ③ \end{matrix} \begin{matrix} \begin{matrix} ① & ② & ③ \end{matrix} \\ \begin{bmatrix} -j50 & j10 & j5 \\ j10 & -j30 & j10 \\ +j5 & j10 & -j25 \end{bmatrix} \end{matrix}$$

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$$Y_{23} = -Y_{23} = -\frac{1}{Z_{23}}$$

$$\Rightarrow Z_{23} = -\frac{1}{Y_{23}} = -\frac{1}{j10}$$

$$Z_{23} = -j0.1\Omega$$

Q.116 (c)

$$Y_{11} = \frac{1}{j0.2} + \frac{1}{j0.2}$$

$$= -j5 - j5 = -j10\mho$$

$$Y_{12} = -\frac{1}{j0.2} = j5, Y_{21} = -\frac{1}{j0.2} = j5\mho$$

$$Y_{22} = \frac{1}{j0.2} = -j5$$

$$Y = \begin{bmatrix} -j10 & j5 \\ j5 & -j5 \end{bmatrix}$$

Q.117 (c)

$$\frac{DF_1}{dP_1} = 0.4P_1 + 400 \frac{dF_2}{dP_2} = 0.48P_2 + 320$$

$$P_1 + P_2 = 900Mw$$

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2}$$

$$0.4P_1 + 400 = 0.48P_2 + 320$$

$$0.4P_1 - 0.48P_2 = -80$$

$$\underline{0.4P_1 \pm 0.4P_2 = 360}$$

$$0.88P_2 = 440 \Rightarrow P_2 = \frac{440}{0.88} = 500Mw$$

$$P_1 = 900 - 500 = 400Mw$$

Q.118 (d)

$$\ell = 600km$$

$$v = 3 \times 10^5 km/sec$$

$$v = \frac{\ell}{t} \Rightarrow t = \frac{600}{3\times10^5} = 2ms$$

$$= 0.002s$$

Q.119 (b)

$$C_n = 0.01\mu F/km$$

$$V_L = 100Kv$$

$$I_c = WCV_{ph}$$

$$= \frac{314\times0.01\times10^{-6}\times100\times10^3}{\sqrt{3}}$$

$$= 0.1812A = \frac{314}{\sqrt{3}\times10^3} A$$

Q.120 (c)

$$\epsilon_r = 9$$

$$v = \frac{3\times10^8}{\sqrt{\epsilon_r}} = \frac{3\times10^8}{\sqrt{9}}$$

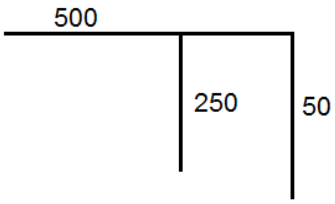
$$= 1 \times 10^8 m/s$$

Q.121 (b)

$$r = 0.15\times10^{-3} + j1.5\times10^{-3} = \alpha + j\beta$$

$$\text{Wave length} = \frac{2\pi}{\beta} = \frac{2\pi}{1.5\times10^{-3}}$$

Q.122(d)



$$V = 260KV$$

$$Z_c = 500\Omega$$

$$Z_{eff} = \frac{250\times50}{250+50} = \frac{250}{6}$$

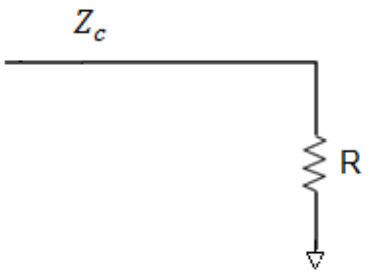
$$= 41.66\Omega$$

$$V_2 = 2V\frac{Z_{eff}}{Z_{eff} + Z_c}$$

$$= 2\times260\times10^3 \times \frac{41.66}{41.66+500}$$

$$= 39.99Kv \simeq 40Kv$$

Q.123 (c)



$$Z_c = 400\Omega$$

No reflection means $V_1 = 0$

$$V_1 = \frac{R - Z_c}{R + Z_c}.V = 0$$

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$$\frac{R-Z_c}{R+Z_c}=0\Rightarrow R-Z_c=0$$

$$R=Z_C=400\Omega$$

Q.124 (a)

$Z_C = 400\Omega$

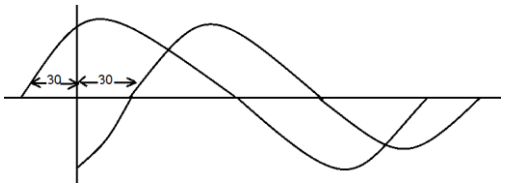
$Z_L = 100\Omega$

$V = 40Kv$

$$V_t=2v\frac{Z_L}{Z_L+Z_C}=2\times40\times\frac{100}{100+400}$$

$= 16KV$

Q.125 (d)



$$V = V\sin(wt+30)pu$$

$$i = I\sin(wt-30)pu$$

$$pf=\cos(30+30)=\frac{1}{2}$$

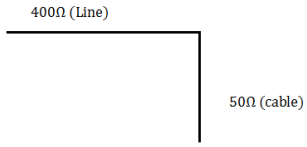
$\phi = 30 + 30 = 60°$

Pu reactive power Q

$$=\frac{\frac{V_mI_m}{2}\sin\phi}{\frac{V_mI_m}{2}}$$

$$=\sin 60=\frac{\sqrt{3}}{2}pu$$

Q.126 (b)



$V = 100KV$

$$V_t=2V\frac{Z_{cable}}{Z_{cable}+Z_{line}}$$

$$=2\times100.\frac{50}{400+50}=22.22KV$$

Q.127 (c)

$\ell_1 = 50km$

$x_{c1} = 1500\Omega$

$\ell_2 = 100km$

$\Rightarrow x_{c2} = ?$

$$x_c=\frac{1}{2\pi fc.l}\Rightarrow x_c\propto\frac{1}{\ell}$$

$$\frac{x_{c1}}{x_{c2}}=\frac{\ell_2}{\ell_1}\Rightarrow\frac{1500}{x_{c2}}=\frac{100}{50}$$

$$x_{c2}=\frac{1500}{2}=750\Omega$$

Q.128 (c)

Fault current =2000A

Relay setting =50%

CT ratio =400/5

Plug setting multiplier (PSM)

$$=\frac{\text{Fault current}}{\text{CT ratio}\times\text{Relay setting}\times\text{CTsecondary current}}$$

$$=\frac{2000}{0.5\times5\times\frac{400}{5}}=10$$

Q.129 (b)

$3-\phi$ 11kv / 66KV Delta / star transformer

$$\text{CTratio}=\frac{400}{5}\text{ on LT side}$$

Line current on star current

$$=400\times\frac{11}{66}=\frac{200}{3}$$

CT on star side is Delta side then line current of Delta Side is

$$5A\Rightarrow\text{phase current}\frac{5}{\sqrt{3}}$$

$$\frac{200}{3}:\frac{5}{\sqrt{3}}\Rightarrow23.1:1$$

Q.130 (a)

Current setting =125%

$$\text{CT ratio}=\frac{400}{5}$$

Pick –up value = 5 × 1.25 = 6.25A

Q.131 (d)

$V_r = 360KV$

$V_s = 400KV$

Shunt reactor: 50MVAR, 400KV

Reactive Power $\propto V^2$

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$$\frac{MVA_{r1}}{MVA_{r2}} = \frac{V_1^2}{V_2^2}$$

$$\Rightarrow MVA_{r2} = \left(\frac{360}{400}\right)^2 \times 50$$

$= 40.5MVAR$

Q.132 (b)

$$LoadFactor = \frac{Averge\ load}{Max.demand}$$

$$Averge\ load = 0.5 \times 15Mw = 7.5Mw$$

$$Plant\ factor = \frac{Averge\ load}{Plant\ capacity}$$

$$0.4 = \frac{7.5Mw}{Plant\ capacity} \Rightarrow Plant\ capacity$$

$$= \frac{7.5}{0.4} = 18.75$$

Reserve capacity

$= 18.75 - 15 = 3.75Mw$

Q.133 (b)

Fault current =3000A

Plug setting =50%

$$Ratio = \frac{400}{5}$$

Plug setting multiplier

$$PSM = \frac{Fault\ current}{Plug\ setting \times CT secondary\ current \times CT\ ratio}$$

$$= \frac{3000}{0.5 \times 5 \times \frac{400}{5}} = 15$$

Q.134 (d)

Fault current =3000A,CT ratio

$$= \frac{1000}{1}$$

Plug setting=50%

$$PSM = \frac{Fault\ current}{Plug\ setting \times CT secondary\ current \times CT\ ratio}$$

$$= \frac{3000}{0.5 \times 1 \times 1000} = 6$$

Q.135 (d)

No. of buses $= 15 = N$

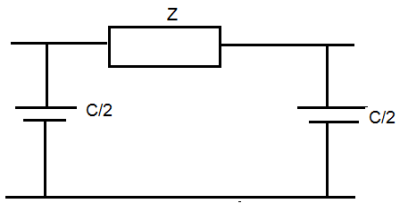
voltage controlled buses $= 3 = N_g$

Jocobian matrix $= [2N - N_g - 2]$

$= [2 \times 15 - 3 - 2] = 25$

order $= 25 \times 25$

Q.136 (c)



$3 - \Phi, 50Hz$

transmission line of 100km Length.

(Nominal π model)

$c = 0.03\mu F/km$

$Y = j\omega c$

$= j314 \times 0.03 \times 10^{-6} \times 100 \times \frac{1}{2}$

$= 471 \times 10^{-6} \angle 90\ \mho$

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