EE3-13

Section A – Answer any 2 out of 3 questions in section A

Question 1

a) Explain how active and reactive power production are controlled by synchronous generation. [4]

b) A three-phase synchronous generator with negligible armature resistance has synchronous reactance Xd= 1.7241 p.u. and is connecting to very large system. The terminal voltage is 1.0 p.u. and the generator is supplying to the system a current of 0.8 p.u at 0.90 power-factor (reactive power is supplied to the system).

Find

(i) the magnitude and angle of the internal voltage Ei [4]

(ii) P and Q delivered to the system [4]

(iii) the angle δ between Ei and terminal voltage and the Q delivered to the system, if the real power output of the generator remains constant but excitation of the generator is

- (a) increased by 20 % and [4]
- (b) decreased by 20 % [4]

Solution

(a) The field current and mechanical torque on the shaft are controllable variables. The variations of the former (excitation system control), is used to supply or absorb a variable amount of reactive power. Synchronous generators runs at constant speed; therefore, the only way to vary the real power is through the control of the torque that is imposed on the shaft by the prime mover (in the case of a generator) or the mechanical load (in the case of a motor).

(b) 1. The power factor angle can be obtained by $\theta = \cos^{-1} 0.9 = 25.84$ lagging. So the synchronous internal voltage is: $E_i = |E_i|(cos\delta + jsin\delta) = V_t + jX_d I_a =$
$= 1 + j1.7241 \cdot 0.8(cos25.8419 - jsin25.8419) =$
$= 1.6012 + j1.2412 = 2.0261(cos37.7862 + jsin37.7862)$
2. The P, Q output of the generator are:

$$P = \frac{|V_t||E_i|}{X_d} sin\delta = \frac{1 \cdot 2.0261}{1.7241} sin37.7862 = 0.72pu$$

$$Q = \frac{|V_t|}{X_d}(|E_i|cos\delta - |V_t|) = \frac{1}{1.7241}(1.6012 - 1) = 0.3487pu$$

(c) Increasing excitation by 20% with P constant gives:

$$\frac{|V_t||E_i|}{X_d} sin\delta = \frac{1 \cdot 1.2 \cdot 2.0261}{1.7241} sin\delta = 0.72, so\ \delta = \sin^{-1}\frac{0.72 \cdot 1.7241}{1.2 \cdot 2.0261} = 30.7016$$

$$Q = \frac{1}{1.7241}(1.2 \cdot 2.0261 \cos(30.7016) - 1) = 0.6325pu$$

Reducing excitation by 20% we get:

$$\frac{|V_t||E_i|}{X_d} sin\delta = \frac{1 \cdot 0.8 \cdot 2.0261}{1.7241} sin\delta = 0.72, so\ \delta = \sin^{-1}\frac{0.72 \cdot 1.7241}{0.8 \cdot 2.0261} = 49.9827$$

$$Q = \frac{1}{1.7241}(0.8 \cdot 2.0261 \cos(49.9827) - 1) = 0.0245pu$$

Question 2

a) A 132/11kV 90MVA transformer has a per unit leakage reactance of 0.1 on rating.

(i) Calculate the actual impedances as seen at the HV and LV side of the transformer. [3]

(ii) What would the value of the per unit impedance of the transformer be, for a power base of 150MVA, base value of voltage at 11kV voltage level of 11.5kV (while base value of voltage at 132kV voltage level is 132kV). [2]

b) For a **transmission circuit given in Figure 1.1 and the corresponding phasor diagram below**, show:

(i) $$\overline{V}s = Vr + \left(\frac{RP_r + XQ_r}{Vr}\right) + j\left(\frac{XP_r - RQ_r}{Vr}\right)$$ [3]

(ii) Write an expression for the active and reactive power losses in the transmission circuit and then determine the active and reactive power generated by the source [3]

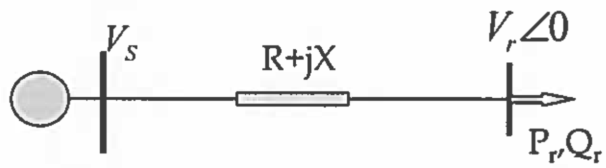

Figure 1.1 Transmission circuit with voltage and power specified at the receiving end

c)

Consider a high voltage transmission circuit with negligible resistance, as the one shown in figure 1.1. Assume that voltages (magnitudes and phase angles) are known at both sending and receiving ends.

(i) Write down the expressions for sending end active and reactive powers as functions of voltage magnitudes and phase angles. [3]

(ii) Based on these expressions, show that active power flow requires a difference in phase angle and that reactive power flow requires a difference in voltage magnitude. [3]

(iii) What is the maximum amount of active power that can be transported via this transmission line? [3]

Solution

a) 132/11 kV 90 MVA transformer has a per unit leakage reactance of 0.1 p.u. on rating.

(i) $$Z_{base\_hv} = \frac{U_{hv}^2}{S_b} = \frac{132^2 \cdot 10^6}{90 \cdot 10^6} = 193.6\Omega,\ X_{hv} = x \cdot Z_{base\_hv} = 0.1 \cdot 193.6 = 19.36\Omega$$

$$Z_{base\_lv} = \frac{U_{lv}^2}{S_b} = \frac{11^2 \cdot 10^6}{90 \cdot 10^6} = 1.34\Omega,\ X_{lv} = x \cdot Z_{base\_lv} = 0.1 \cdot 1.34 = 0.134\Omega$$

(ii) We use the formula $$Z^{pu}_{new} = Z^{pu}_{old} \frac{S_{B,new}}{S_{B,old}} \left(\frac{V_{B,old}}{V_{B,new}} \right)^2$$

If reactance is on the low-voltage side, then the value is:

x = 0.1 (150 / 90) (11 / 11.5)^2 = 0.152 p.u.

If reactance is on high voltage side then value is:

x = 0.1 (150 / 90) = 0.167 p.u.

b) For a transmission circuit given in Figure 1.1, we show:

$$\overline{S_r} = P_r + jQ_r = \overline{V_r} \cdot \overline{I^*}$$

$$\overline{I} = \frac{P_r - jQ_r}{\overline{V_r^*}}$$

$$\overline{V_s} = \overline{V_r} + (R + jX) \cdot \overline{I}$$

$$\overline{V_s} = \overline{V_r} + (R + jX) \cdot (\frac{P_r - jQ_r}{\overline{V_r^*}})$$

$$\overline{V_r} = \overline{V_r^*} = V_r \angle 0^0 = V_r$$

(i) $$\overline{V_s} = V_r + (\frac{RP_r + XQ_r}{V_r}) + j(\frac{XP_r - RQ_r}{V_r})$$

(ii) Active losses = $\left(\frac{S_r}{V_r} \right)^2 \cdot R = I^2 \cdot R$; Reactive losses = $\left(\frac{S_r}{V_r} \right)^2 \cdot X = I^2 \cdot X$

The active and reactive powers supplied by the source:

$$P_G = P_r + I^2 \cdot R \qquad Q_G = Q_r + I^2 \cdot X$$

c) For the network shown in Figure 1.1 we have:

$$\overline{I} = \frac{\overline{V_s} - \overline{V_r}}{jX}$$

(i) $$S = \overline{V_s} \cdot \overline{I}^* = \overline{V_s} \cdot \frac{\overline{V_s}^* - \overline{V_r}^*}{-jX} = \frac{V_s^2 - V_s V_r e^{j(\delta_s - \delta_r)}}{-jX} = \frac{jV_s^2 - V_s V_r e^{j(\delta_s - \delta_r + 90^\circ)}}{X}$$

$$= \frac{jV_s^2 - V_s V_r [(\cos(\delta_s - \delta_r + 90^\circ) + j\sin(\delta_s - \delta_r + 90^\circ)]}{X}$$

$$S = \frac{V_r \cdot V_s}{X}\sin(\delta_s - \delta_r) + j\frac{V_s^2 - V_r V_s \cos(\delta_s - \delta_r)}{X}$$

(ii) $$P = \frac{V_s \cdot V_r}{X}\sin(\delta_s - \delta_r)$$ P flow requires a difference in phase angle

$$Q = \frac{V_s^2 - V_s \cdot V_r \cos(\delta_s - \delta_r)}{X}$$ Q flows requires a difference in voltage magnitude

If both angles are the same then the sine will be zero, which implies that active power will be zero as well. For a small difference in angles the sine is the same as the difference (in radians), and therefore the active power is proportional to the difference in phase angles.

For a small difference in phase angles the cosine is close to one, and if voltage at the receiving end is the same as voltage at the sending end, the reactive power will be zero.

(iii) $$P = \frac{V_s \cdot V_r}{X}\sin(\delta_1 - \delta_2) = P_{max}\sin(\delta_1 - \delta_2)$$

For the angle difference of 90°, the sine becomes one.

Question 3

(a) A generator connected to a 33 kV circuit is connected through a 33 kV distribution line to a 3-phase load. The system is a balanced 3-phase system.

Distribution line details:

R = 0.3267 Ω/km, X = 0.4356 Ω/km, B = 0.0 S /km /phase ,

Length = 10 km

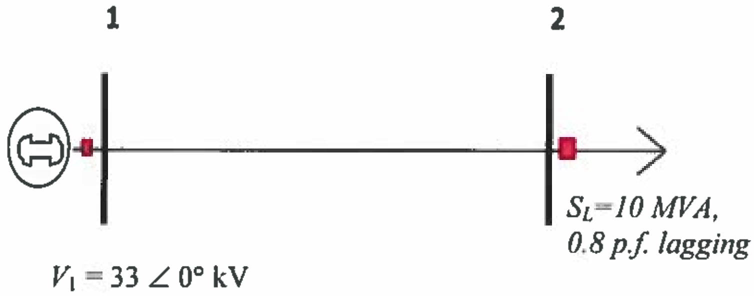

Figure 1.2. The simple power system

Frequency in the system is 50 Hz. Determine:

(i) The per unit value of distribution line impedance, voltage at generator terminal node and load. (Use 100 MVA base) and form Y bus matrix. [4]

(ii) Calculate the magnitude of the voltage at node 2 using Gauss Seidell load flow algorithm. Perform 3 iterations. [10]

(iii) Compute the losses and voltage drop across the distribution line. [6]

Solution

(i) Setting base voltage 33kV, and base Power 100MVA, we get base impedance as $\frac{33^2}{100} = 10.89\Omega$. The single-phase load is $\frac{8}{3}MW + j2MVAr$ and 0.026+j0.02 pu. The R for the line is 0.3267*10= 3.267Ω, while X= 4.356Ω, hence Zpu = 0.3+j0.4 pu yielding Ypu= 1.2-j1.6 pu. Thus, Ybus is : $\begin{bmatrix} 1.2 - j1.6 & -1.2 + j1.6 \\ -1.2 + j1.6 & 1.2 - j1.6 \end{bmatrix}$

(ii) Setting $P_2^{sch} = -0.026pu, Q_2^{sch} = -0.02pu, V_2^0 = 1pu, V_1^0 = 1pu$

$$\tilde{V}_2^{(1)} = \frac{\frac{P_2^{sch} - jQ_2^{sch}}{\tilde{V}_2^{(0)}} + y_{21}\tilde{V}_1^{(0)}}{y_{21}} = 0.9842 - j0.0044\,pu$$

$$\Delta V_2^1 = \left|V_2^{(1)} - V_2^{(0)}\right| = 0.0164$$

$$\tilde{V}_2^{(2)} = \frac{\dfrac{P_2^{sch} - jQ_2^{sch}}{\tilde{V}_2^{(1)}} + y_{21}\tilde{V}_1^{(0)}}{y_{21}} = 0.9839 - j0.0044\, pu$$

$$\Delta V_2^2 = \left|V_2^{(2)} - V_2^{(1)}\right| = 2.7332 \cdot 10^{-4}$$

$$\tilde{V}_2^{(3)} = \frac{\dfrac{P_2^{sch} - jQ_2^{sch}}{\tilde{V}_2^{(2)}} + y_{21}\tilde{V}_1^{(0)}}{y_{21}} = 0.9839 - j0.0044\, pu$$

$$\Delta V_2^3 = \left|V_2^{(3)} - V_2^{(2)}\right| = 4.629 \cdot 10^{-6}$$

$$P_1^{(3)} = Real\left(\tilde{V}_1^{(0)*}\left[\tilde{V}_1^{(0)}(y_{12}) - y_{12}\tilde{V}_2^{(3)}\right]\right) = 0.0263\, pu$$
$$Q_1^{(3)} = -Imag\left(\tilde{V}_1^{(0)*}\left[\tilde{V}_1^{(0)}(y_{12}) - y_{12}\tilde{V}_2^{(3)}\right]\right) = 0.0204\, pu$$

(iii)

$I_{12} = y_{12}\left(\tilde{V}_1^{(0)} - \tilde{V}_2^{(3)}\right) = -I_{21}$ with $I_{21} = -0.0263 + j0.0204pu$

We can find the voltage drop by $I_{12}(\ 0.3 + j0.4) =\ 0.0161\ +\ j0.0044\, pu$

$S_{12} = \tilde{V}_1^{(0)} \cdot I_{12}^* = 0.0263 + j0.0204pu$

$S_{21} = \tilde{V}_2^{(3)} \cdot I_{21}^* = -0.026 - j0.02pu$

$S_{loss} = S_{12} + S_{21} = 3.3343 \cdot 10^{-4} + j4.4457 \cdot 10^{-4}pu$

Section B – Answer any 2 out of 3 questions in section B

Question 4

a) Explain the role of power-flow analysis, Thevenin theorem and superposition theorem in fault current calculation.

[5]

- Pre-fault steady state voltages and currents are obtained from power flow analysis
- Thevenin equivalent voltage and impedance are calculated at the fault point. Then voltage and currents at points of interest in the network are computed by exciting the network at the fault point with negative of the Thevenin equivalent voltage in series with fault impedance.
- Fault current (and voltage) is obtained by adding the results of step 1 (pre-fault) and 3 according to the superposition theorem

b) Show how the fault current and voltage at the faulted bus *i* can be calculated using the appropriate element of the bus impedance matrix. Consider a fault impedance Z_f

[4]

Change in bus voltages due to fault current can be expressed in terms of bus impedance matrix as

$$\Delta V = Z_{\text{bus}}(-I_f)$$

Voltage at faulted bus *i* is

$$V_i^f = V_i^0 + \Delta V_i = V_i^0 - Z_{ii} I_f = Z_f I_f$$

$$I_f = \frac{V_i^0}{Z_{ii} + Z_f}$$

c) Four identical 13 kV, 60 MVA three-phase generators, G1, G2, G3 and G4 are connected to a bus bar A and bus bar B as shown in Figure 4.1. The sub-transient reactance of each generator is 0.15 p.u. (with respect to their respective base). Bus bar A is connected to bus bar B through a reactor *X*. A feeder is supplied from bus bar A through a 240 MVA step-up transformer, T with 0.2 p.u. (with respect to its own base) leakage reactance. Choose 60 MVA base for the calculations. Neglect pre-fault loading and assume zero fault impedance.

(i) Determine the reactance *X* in ohms, if the fault level due to a three-phase fault at point F on the feeder side of the transformer, T is to be limited to 600 MVA.

[5]

(ii) Calculate the voltage (in kV) at bus bar A during the three-phase fault at point F in part (i) if the generator is operating at 13 kV (line).

[3]

(iii) For the three phase fault at point F, how much fault current (in kA) would be contributed by the generator G4?

[3]

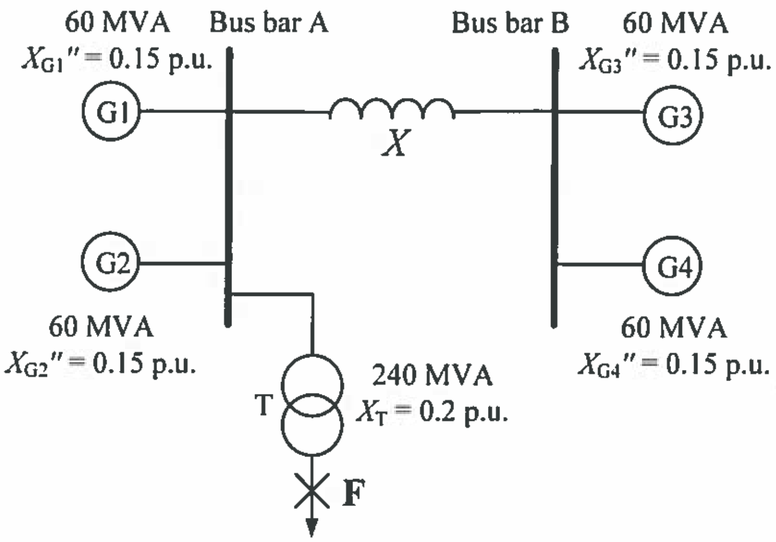

Figure 4.1: Single-line diagram of the generator arrangement for Question 4(b)

(i) Choose $S_{base} = 60$ MVA

Fault level at P should be limited to $^{600}/_{60} = 10$ p.u.

Therefore, Z_{eq} should be $Z_{eq} = {}^{1}/_{10} = 0.1$ p.u.

Reactance of transformer on 60 MVA base is $0.2 \times {}^{60}/_{240} = 0.05$ p.u.

From the circuit,

$$Z_{eq} = \left[\left(\frac{0.15}{2}\right) \parallel \left(\frac{0.15}{2} + X\right)\right] + 0.05$$

$$= \frac{0.0056 + 0.075X}{0.15 + X} + 0.05$$

By equating Z_{eq},

$$Z_{eq} = \frac{0.0056 + 0.075X}{0.15 + X} + 0.05 = 0.1$$

$$\Rightarrow X = 0.076 \text{ p.u.}$$

Reactance X in ohms is

$0.076 \times \frac{(13\ \text{kV})^2}{60\ \text{MVA}} = 0.214$ ohms

(ii) Voltage at bus bar A $= 10 \times 0.05 = 0.5$ p.u.

$= 13 \times 0.5 = 6.5$ kV

(iii) Total fault current I_F = Fault MVA (in p.u.) = 10 p.u.

Fault current contributed by G4

$$I_{F-G4} = \frac{1}{2} \times 10 \times \frac{0.15/_2}{0.15/_2 + 0.076 + 0.15/_2} = 0.997 \text{ p.u}$$

$$= 0.997 \times \frac{60}{\sqrt{3} \times 13} = 2.66 \text{ kA}$$

Question 5

a) Derive an expression for the minimum value of the neutral grounding reactor (X_n) of a star-connected generator so that the line-to-ground fault current at the generator terminal is limited to the corresponding three-phase fault current level. Assume identical values for positive (X_1) and negative (X_2) sequence reactance of the generator. Neglect resistance and derive the expression for X_n in terms of positive (X_1) and zero (X_0) sequence reactance of the generator.

[5]

$$I_{f\text{-}LG} = \frac{3E_a}{X_1 + X_2 + X_0 + 3X_n} = \frac{3E_a}{2X_1 + X_0 + 3X_n}$$

$$I_{f\text{-}3p} = \frac{E_a}{X_1}$$

$$I_{f-LG} \leq I_{f-3p}$$

$$\frac{3E_a}{2X_1 + X_0 + 3X_n} \leq \frac{3E_a}{3X_1} \rightarrow X_n \geq \frac{1}{3}(X_1 - X_0)$$

b) A 3-phase line is supplying a star connected balanced 3-phase load with its neutral grounded. After a sudden disconnection of supply to phase B, the line currents in phase A and phase B are $I_A = 10\angle 0°$ A and $I_B = 10\angle 120°$ A. Calculate the magnitude and phase angles of the B-phase component of the positive, negative and zero sequence currents.

[5]

$$I_{B0} = I_{B0} = \frac{1}{3}[10\angle 0° + 0 + 10\angle 120°] = 3.33\angle 60°\text{A}$$

$$I_{A1} = \frac{1}{3}[10\angle 0° + 0 + 10\angle(120 + 240°)] = 6.67\angle 0°\text{A}$$

$$I_{B1} = 6.67\angle -120°\ A$$

$$I_{A2} = \frac{1}{3}[10\angle 0° + 0 + 10\angle(120 + 120°)] = 3.33\angle -60°\text{A}$$

$$I_{B2} = 3.33\angle(-60° + 120°)\ A = 3.33\angle 60°\text{A}$$

c) Two 30 MVA, 6.6 kV three-phase star-connected synchronous generators are connected in parallel to supply a 6.6 kV feeder. One generator has its star point grounded through a 0.4 Ω resistor and the other has its star point isolated. The sequence reactance for the generator are $X_{g1} = 0.2$ p.u.; $X_{g2} = 0.16$ p.u. and $X_{g0} = 0.06$ p.u. and for the feeder are $X_{f1} = X_{f2} = 0.6\ \Omega$ per phase and $X_{f0} = 0.4\ \Omega$ per phase. For a line-to-ground fault on phase A at the far end (opposite to the generator) of the feeder calculate the following considering 30 MVA base:

(i) the fault current in kA

[5]

(ii) the power dissipated (in MW) in the generator grounding resistor

[2]

(iii) what value of neutral grounding resistor (in ohms) would be required to limit the line-to-ground fault current to 2 kA

[3]

(i) For $S_{base} = 30$ MVA

$$Z_{base} = \frac{6.6\ \mathrm{kV}^2}{30\ \mathrm{MVA}} = 1.452\ \Omega$$

Sequence reactance of the feeder in p.u.

$$X_{f1} = X_{f2} = \frac{0.6}{1.452} = 0.413\ \text{p.u.};\ X_{f0} = \frac{0.4}{1.452} = 0.275\ \text{p.u.}$$

Grounding resistor in p.u.

$$R_n = \frac{0.4}{1.452} = 0.275\ \text{p.u.}$$

Line-to-ground fault current is

$$I_{f\text{-LG}} = \frac{3}{(jX_{g1} + jX_{f1}) + (jX_{g2} + jX_{f2}) + (jX_{g0} + jX_{f0} + 3R_n)}$$
$$= \frac{3}{(j0.2 + j0.413) + (j0.16 + j0.413) + (j0.06 + j0.275 + 3 \times 0.275)}\ \text{p.u.}$$
$$= 1.904 \angle -58.45°\ \text{p.u.}$$

Base current is

$$I_{base} = \frac{30}{\sqrt{3} \times 6.6} = 2.62\ \mathrm{kA}$$

Fault current $I_{f\text{-LG}} = 1.904 \times 2.62 = 4.98$ kA

(ii) LG fault current flows through the neutral grounding resistor.
Power dissipated is

$$P_{Rn} = I_{f\text{-LG}}^2 \times R_n = 9.92\ \mathrm{MW}$$

(iii) LG fault current to be limited to

$$I_{f\text{-LG}} < 2\ \mathrm{kA} = \frac{2}{2.62} = 0.76\ \text{p.u.}$$

$$I_{\text{f-LG}} = \frac{3}{(j0.2 + j0.413) + (j0.16 + j0.413) + (j0.06 + j0.275 + 3R_{\text{n}})}$$

$$|I_{\text{f-LG}}| = \frac{3}{\sqrt{1.52^2 + 9R_{\text{n}}^2}} < 0.76 \text{ p.u.}$$

$$R_{\text{n}} > 1.2 \text{ p.u.}=1.2\times1.452=1.76\ \Omega$$

Question 6

a) Explain physically (not analytically) why the steady-state stability limit for a round rotor synchronous generator corresponds to a power angle of 90 degrees if resistances are neglected.

[4]

If the generator operates at a power angle of below 90 degrees in steady state, any increase in mechanical input leads to acceleration of the rotor resulting in increase in load angle and hence electrical power output. Thus increase (decrease) in mechanical power input implies corresponding increase (decrease) of electrical power output which helps maintain stability. On the other hand, if the operating point is at a power angle larger than 90 degrees any increase in mechanical input results in increase in load angle as before, but on this occasion increase in load angle leads to reduction in electrical power output because of the negative slope of power angle curve. This is a runway situation with increase in mechanical input causing reduction in electrical power output and hence, the situation is unstable.

b) A 50 Hz, 4-pole synchronous generator is rated 500 MVA, 22 kV and has an inertia constant of 7.5 s. Assume that the generator is synchronized with a large power system and has a zero accelerating power while delivering a power of 400 MW. Suddenly its input power is increased to 500 MW. Calculate speed of the generator in revolutions per minute (rpm) after 10 cycles. Neglect rotational losses and any change in electrical power output of the generator during this period.

[5]

Rotational acceleration

$$\alpha = \frac{d^2\delta}{dt} = \frac{\omega_s}{2H}(P_m - P_e) = \frac{100\pi}{2 \times 7.5} \times \frac{(500-400)}{500} = 4.19 \text{ elect-rad/s}^2$$

The generator has 4 poles, so rotational acceleration in mechanical terms is

$$\alpha = \frac{d^2\delta}{dt} = \frac{4.19}{2} = 2.1 \text{ mech-rad/s}^2 = 2.1 \times \frac{60}{2\pi} = 20 \text{ rpm/s}$$

Initial speed $\omega_0 = \frac{50\times60}{2} = 1500$ rpm

Acceleration time $t = 10$ cycles $= \frac{10}{50}$s=0.2 s

Speed after 10 cycles

$$\omega_1 = \omega_0 + \alpha t = 1504 \text{ rpm}$$

c) A round-rotor synchronous generator is connected to an infinite busbar via a generator transformer and a double-circuit overhead line. The leakage reactance of the transformer is 0.15 p.u. The reactance of each circuit of the double-circuit overhead line is 0.4 p.u. The generator has a transient reactance of 0.2 p.u and is supplying 0.8 p.u. active power at a terminal voltage of 1 p.u. All impedance values are based on the generator rating and the voltage of the infinite busbar is 1 p.u. Neglect generator resistance and assume constant mechanical input to the generator.

(i) Calculate the power angle (in degrees) across the double circuit corridor under pre-fault condition.

[3]

(ii) A three-phase solid fault occurs at the sending (generator) end of one of the transmission line circuits and is cleared by disconnecting the faulted line. Calculate the maximum allowable power angle (in degrees) across the double circuit corridor under the post-fault condition without losing stability.

[3]

(iii) Use equal area criteria to determine the critical clearing angle (in degrees) for the three-phase s fault mentioned in part 6(c)(ii). Assume zero power output from the generator during the fault.

[5]

(i) Reactance between the generator terminal and the infinite bus bar is

$$X = 0.15 + {}^{0.4}/_{2} = 0.35 \text{ p.u.}$$

$$P = \frac{V_G V_{\text{inf}}}{X} \sin \delta_0 \rightarrow \delta_0 = \sin^{-1}\left(\frac{0.8 \times 0.35}{1}\right) = 16.26°$$

(ii) During post-fault condition, reactance between the generator terminal and the infinite bus bar is

$$X = 0.15 + 0.4 = 0.55 \text{ p.u.}$$

$$P_{\max} = \frac{V_G V_{\text{inf}}}{X} = \frac{1}{0.55} = 1.82 \text{ p.u.}$$

Maximum allowable power angle is

$$\delta_{\max} = 180° - \sin^{-1}\left(\frac{P}{P_{\max}}\right) = 180° - 26.08° = 153.92°$$

(iii) Accelerating area is

$$\int_{\delta_0}^{\delta_{\text{cl}}} (P - 0) d\delta = 0.8 \times (\delta_{\text{cl}} - 16.26°) \text{ p.u.-deg}$$

Decelerating area is

$$\int_{\delta_{\text{cl}}}^{\delta_{\max}} (P_{\max} \sin \delta - P) d\delta$$

$$= 1.82 \times (\cos \delta_{\text{cl}} - \cos 153.92°) + 0.8 \times (\delta_{\text{cl}} - 153.92°) \text{ p.u.-deg}$$

Using equal-area criteria

$$\delta_{cl} = \cos^{-1}\left(\frac{1.82\cos 153.92° + 0.8 \times 153.92 \times {}^{\pi}/_{180} - 0.8 \times 16.26 \times {}^{\pi}/_{180}}{1.82}\right)$$

$$= 80.9°$$