CLASS TEST

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Electrical Machines

(Synchronous Machine)

ELECTRICAL ENGINEERING

Date of Test : 30/06/2023

ANSWER KEY

1.	(b)	7.	(c)	13.	(a)	19.	(a)	25.	(b)
2.	(a)	8.	(b)	14.	(c)	20.	(d)	26.	(d)
3.	(b)	9.	(b)	15.	(a)	21.	(c)	27.	(c)
4.	(c)	10.	(d)	16.	(a)	22.	(a)	28.	(a)
5.	(c)	11.	(a)	17.	(c)	23.	(d)	28.	(d)
6.	(d)	12.	(b)	18.	(c)	24.	(c)	30.	(a)

DETAILED EXPLANATIONS

1. (b)

In a synchronous machine if the main field flux is ahead of armature field flux axis in the direction of rotation, the machine is acting like a synchronous generator.

2. (a)

Given,

$$V_{oc} = 2100 \text{ V}$$
$$I_{sc} = 425 \text{ A}$$

Then synchronous impedance,

$$X_s = \frac{2100}{425} = 4.94\ \Omega$$

Now internal voltage drop $= 4.94 \times 200$
$= 988.24$ V

3. (b)

Given, Load = 600 kW at 0.75 p.f. lagging

$$\text{Load kVA} = \frac{600}{0.75} = 800 \text{ kVA}$$

$$\text{Load kVAR} = \text{Load kVA} \times \sin\phi$$
$$= 800 \times \sqrt{1-(0.75)^2}$$
$$= 529.15 \text{ kVAR}$$

When a synchronous motor is connected to improve the power factor it is over excited. As there is reactive power required from motor so it will operate at zero power factor leading. Which supplied 529.15 kVAR to load.

4. (c)

$$\text{Power input to motor} = \frac{40 \text{ kW}}{\eta} = \frac{40 \times 10^3}{0.9} = 44.44 \text{ kW}$$

$$\text{Armature current, } I_a = \frac{\text{Power input}}{\sqrt{3} \times \text{supply voltage} \times \text{powe factor}}$$

$$= \frac{44.44 \times 10^3}{\sqrt{3} \times 415 \times 0.75} = 82.43 \text{ A}$$

5. (c)

According to power angle equation,

$$P_e = \frac{|E||V|}{|X|}\sin\delta$$

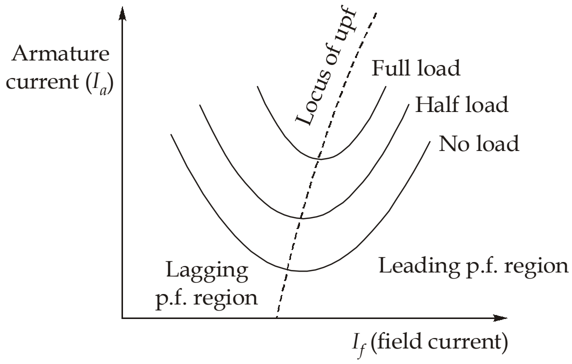
$$P_e = P_{max} \sin\delta$$

$$P_{max} = \frac{|E||V|}{|X|}$$

$$1.2 = \frac{|E| \cdot 1}{1.3 + 0.2}$$

$$E = 1.8 \text{ p.u.}$$

6. (d)



∴ As we go right of the unity power factor locus of V-curve we obtain over excitation and leading current input.

7. (c)

For short circuit current, $I_{sc} = \frac{E}{X_s}$

$$E \propto f\phi$$

$$X_s \propto f$$

So, $$I_{sc} \propto \phi$$

Hence short circuit current is only a function of excitation.

8. (b)

$$\text{Power (P)} = \frac{VE_f}{X_s}\sin\delta$$

$$0.75 = \frac{1 \times 1.25}{0.7}\sin\delta$$

$$\delta = 24.83°$$

Current is given by,

$$\vec{I} = \frac{\vec{E}_f - \vec{V}}{jX} = \frac{1.25\angle 24.83° - 1\angle 0°}{j0.7}$$

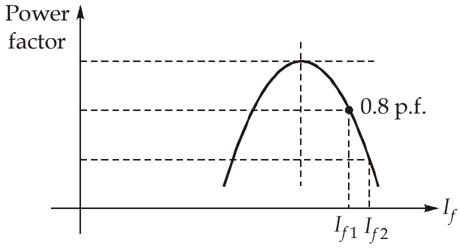
$$I = 0.77\angle -14.36°$$

$$\text{Phase angle, } \phi = 14.36°$$

$$\text{Power factor} = \cos\phi = 0.9688 \text{ (lagging)}$$

9. (b)

Inverted V curve is the curve between power factor and field current.



Power factor reduces. Thus it is obvious power factor angle will increase.

10. (d)

$$\text{Reluctance power, } P = V^2\left(\frac{X_d - X_q}{2X_dX_q}\right)\sin 2\delta$$

$$\text{Excitation emf, } \vec{E}_f = \vec{V} + j\vec{I}_a X_q$$

$$\text{Armature current, } \quad I_a = \frac{4\times 10^6}{\sqrt{3}\times 6600} \approx 350 \text{ A}$$

$$\vec{E}_f = \frac{6600}{\sqrt{3}} + j(350\angle -\cos^{-1}(0.8))\times 4$$

$$= 4783.48\angle 13.54° \text{ V}$$

$$\text{Load angle } \delta = 13.54°$$

$$\text{Reluctance power, } P = (6600)^2\left[\frac{10-4}{2\times 10\times 4}\right]\sin(2\times 13.54)$$

$$P = 1.487 \text{ MW}$$

11. (a)

For alternator, we can write,

$$E_f^2 = (V_t\cos\phi + I_a r_a)^2 + (V_t\sin\phi + I_a X_s)^2$$

For $\quad r_a = 0$

and $\quad X_s = 0.2$ p.u.

or $\quad E_f^2 = V_t^2\cos^2\phi + (V_t\sin\phi + I_aX_s)^2$

$$E_f^2 = V_t^2\left[\cos^2\phi + \left(\sin\phi + \frac{I_aX_s}{V_t}\right)^2\right]$$

$$\therefore \quad \frac{I_aX_s}{V_t} = X_{s\,(\text{p.u.})} = 0.2 \text{ p.u.}$$

$$E_f^2 = V_t^2\left[(0.8)^2 + (0.8)^2\right]$$

$$E_t = 1.131\ V_t \quad \text{...(i)}$$

$$\text{Voltage regulation; V.R.} = \frac{E_f - V_t}{V_t} = \frac{1.13\ V_t - V_t}{V_t}\times 100$$

$$= 13.1\%$$

12. (b)

$$\text{Frequency, } f = \frac{PN}{120} = \frac{6 \times 1000}{120} = 50 \text{ Hz}$$

$$\text{slots per pole} = m = 3$$

$$\text{No. of slots} = \frac{360°}{20} = 18$$

$$\text{No. of turns/phase} = \frac{18 \times 12}{2} = 108$$

$$\text{Slot angle, } \beta = 20°$$

$$\text{then, distribution factor, } K_d = \frac{\sin\frac{m\beta}{2}}{m \sin \beta/2}$$

$$K_d = \frac{\sin\frac{3 \times 20°}{2}}{3 \times \frac{\sin 20°}{2}} = 0.9598$$

$$\text{Emf generated per phase} = 4.44 f \phi N_{ph} \cdot K_d$$

$$= 4.44 \times 50 \times 3 \times 10^{-2} \times 108 \times 0.9598$$

$$E_p = 690.36 \text{ V}$$

13. (a)

Given,

$$5 \text{ MVA, } 11 \text{ kV, } P = 6,$$

$$f = 50 \text{ Hz}$$

$$\text{Alternator rated current, } I_a = \frac{5 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 262.43 \text{ A}$$

$$\text{Base impedance} = \frac{V_{phase}}{I_a} = \frac{11 \times 10^3}{\sqrt{3} \times 262.43} = 24.2\,\Omega$$

$$\text{Synchronous reactance, } X_s = 0.4 \text{ p.u.} = 0.4 \times 24.2$$

$$= 9.68\ \Omega$$

$$\because \quad \text{Mechanical degree} = \text{Electrical radian} \times \frac{2}{P} \times \frac{180}{\pi}$$

$$= \text{Electrical radian} \times \frac{2}{6} \times \frac{180}{\pi}$$

$$= \frac{60}{\pi} \times \text{Electrical radian}$$

As we know;

$$P_{syn} = \frac{3 E_f V_t}{X_s} \cos\delta \quad \text{W/electrical radian}$$

or,

$$P_{syn} = \frac{\pi}{60} \times \frac{E'_f \cdot V'_t}{X_s} \cos\delta \quad \text{W/mech. degree}$$

[$\because$ Here E'_f and V'_t are line voltage]

$$P_{syn} = \frac{\pi}{60} \times \frac{11 \times 11 \times 10^6}{9.68} \cos\delta \;\; \text{W/mech. degree}$$

at no load, $\delta = 0°$

$$P_{syn} = 654.498 \text{ kW/mechanical degree}$$

14. (c)

Given;

$E_f = 1.5$ p.u. $\quad X_s = 1.3$ p.u.

∴ $P = 0.6$ p.u, $\quad V_t = 1.0$ p.u.

∵ Synchronous power; $P = \dfrac{E_f V_t}{X_s} \sin\delta$

$$0.60 = \frac{1.5 \times 1}{1.3} \sin\delta$$

$$\sin\delta = 0.52;$$

or, $\delta = 31.33°$

Considering the cylindrical rotor machine;
the reactive power is;

$$Q = \frac{E_f V_t}{X_s} \cos\delta - \frac{V_t^2}{X_s}$$

$$\frac{dQ}{d\delta} = \frac{-E_f \cdot V_t \sin\delta}{X_s} \quad \text{...(i)}$$

and $$\frac{dP}{d\delta} = \frac{E_f \cdot V_t}{X_s} \cos\delta \quad \text{...(ii)}$$

From equation (i) and (ii),

$$\frac{dQ}{dP} = -\tan\delta = -\tan 31.33°$$

$$= -0.6087$$

As given, with 2% increase in prime mover input; the active power is increased by 2%.

Then, $dQ = 2\% \times -0.6087$

$dQ = -1.2174\%$

15. (a)

As we know; $X_{s\,(adjusted)} = \dfrac{V_{rated}/\sqrt{3}}{I_{sc}}$ (At I_f corresponding to $V_{oc} = V_{rated}$)

Rated armature current; $I_{a\text{ rated}} = \dfrac{10 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 524.86$ A

At, $I_{f\,(rated)} = 812$ A,

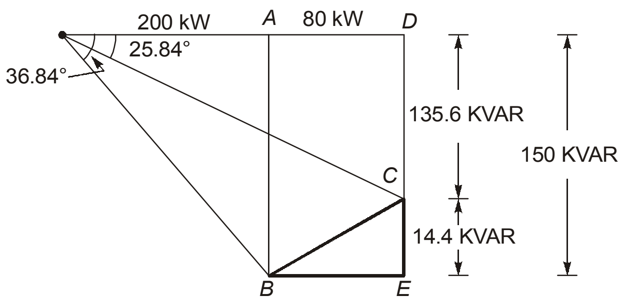
$$I_{sc} = \frac{524}{202} \times 812 = 2106.376 \text{ A}$$

$$X_{s\,(adjusted)} = \frac{11 \times 10^3 / \sqrt{3}}{2106.376} = 3.015\ \Omega$$

$$X_{s\,(p.u.)} = 3.015 \times \frac{10}{(11)^2} = 0.249 \text{ p.u.}$$

16. (a)

$$\theta_1 = \cos^{-1}(0.8) = 36.87°$$
$$\theta_2 = \cos^{-1}(0.9) = 25.84°$$



Leading kVAR taken by motor= CE

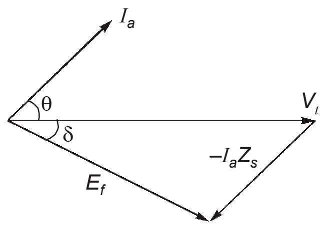
$$CE = AB - DC$$
$$= 200\tan(36.87°) - 280\tan(25.84°)$$
$$CE = 14.4 \text{ kVAR}$$

17. (c)

Consider the below circuit diagram for synchronous motor,

We are given;

$$V_t = 11 \text{ kV line to line}$$



$$V_{t\text{ phase}} = \frac{11}{\sqrt{3}} \text{KV}$$

$$I_a \text{ (rated armature current)} = \frac{1000}{\sqrt{3}\times 11} = 52.486 \text{ A}$$

$\therefore$ Power factor = 0.8 leading

therefore power factor angle, ϕ = 36.86°

or $I_a = 52.486\angle 36.86°$ A

Now; for synchronous motor; $\vec{V}_t = \vec{E}_f + \vec{I}_a Z_s$

Where; $Z_s = (3.5 + j\,40)\ \Omega$

$$\vec{E}_f = \vec{V}_t - \vec{I}_a Z_s$$

$$= \frac{11}{\sqrt{3}} \times 10^3 \angle 0° - 52.486\angle 36.86°(3.5 + j40)$$

$$\vec{E}_{f\text{phase}} = 7674.89\angle{-13.486°} \text{ V}$$

18. (c)

Given, pole, P = 12,

flux per pole, ϕ = 0.05 Wb/pole

$$\text{Slots per pole per phase} = \frac{12}{3} = 4 = \text{m}$$

$$\text{Slot angle, } \gamma = \frac{180° \times P}{s} \qquad [\because \text{s= no. of slots}]$$

$$= \frac{180°}{12} = 15°$$

Distribution factor; $K_d = \dfrac{\sin\left(\dfrac{m\gamma}{2}\right)}{m\sin\left(\dfrac{\gamma}{2}\right)} = \dfrac{\sin\left(4\times\dfrac{15°}{2}\right)}{4\sin\left(\dfrac{15°}{2}\right)}$

$K_d = \dfrac{0.5}{0.5221} = 0.9576$

$E_{\text{line}} = \sqrt{3}\times 4.44\times N_{ph}\times f\times\phi_m\times K_d$

Here, N_{ph} = No. of conductors in series per phase

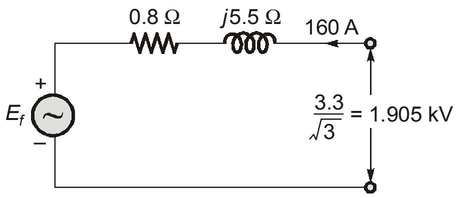
$= \dfrac{144\times 12}{3\times 2} = 288$

$E_{\text{line}} = \sqrt{3}\times 4.44\times 288\times 50\times 0.05\times 0.9576$

E_{line} = 5302.25 Volts

19. (a)

Consider the following circuit;



Full load current = $160\angle{-36.86°}$ A

Synchronous impedance; Z_s = $(0.8 + j\,5.5)$ Ω

$= 5.56\angle 81.724°$ Ω

From circuit diagram we can write;

$\vec{E}_f = 1.905\times 10^3\angle 0° - 5.56\angle 81.724° \times 160\angle{-36.86°}$

$E_f = 1.42\angle{-26.22°}$ kV

Now $P_{\text{mech (dev)}} = 3\times 1.42\times 160\cos(-36.86° + 26.22°)$

= 669.88 kW

shaft output = 669.88 – 30 = 639.88 kW

Power input = $\sqrt{3}\times 3.3\times 160\times 0.8$

= 731.62 kW

$\eta_{\text{full load}} = \dfrac{\text{Output}}{\text{Input}}\times 100 = \dfrac{639.88}{731.62}\times 100$

= 87.46%

20. (d)

The power taken by driving motor without excitation is corresponding to friction and windage loss:

therefore, $P_{w\&f}$ = 900 W

When armature is short circuited, the power corresponds to the copper losses at full load.

Therefore, $P_{cu\,(fl)}$ = 3000 – 900 = 2100 W

Half load copper loss,

$$P_{cu}'_{(Hl)} = \frac{1}{4}P_{cu(fl)} = \frac{1}{4}\times 2100 = 525 \text{ W}$$

Now when armature is open circuited;

$$I_a = 0$$

or $$P_{cu} = 0$$

then only iron losses and rotational losses will be present;

Now, $$P_{iron} = 2000 - 900$$
$$= 1100 \text{ W}$$

Total losses at half load (50%)

$$= 900 + 525 + 1100 = 2525 \text{ W}$$

Efficiency at 50% load

$$\%\eta = \frac{\text{Output}}{\text{Output + losses}}$$

$$\%\eta = \frac{30000\times 100}{30000+2525} = 92.24\%$$

21. (c)

Given,

$$V_t = 6.6 \text{ kV (line)} = 3810.6 \text{ V (phase)}$$

$$\text{Rated load} = 1000 \text{ kVA}$$

$$I_{a\,(\text{rated})} = \frac{1000}{\sqrt{3}\times 6.6} = 87.48\angle -36.86° \text{ A}$$

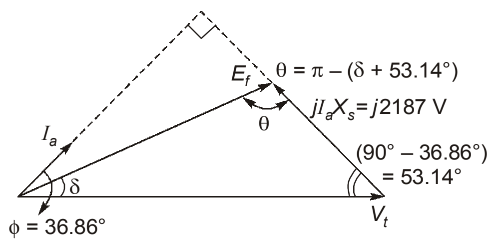
Operation at 0.8 lagging p.f. at rated terminal voltage

$$\vec{E}_f = \vec{V}_t + j\vec{I}_a X_s$$

$$= 3.8106 \times 10^3\angle 0° + j\,87.48\angle{-36.86°} \times (25)$$

$$\vec{E}_f = 5413.12\angle 18.86° \text{ V}$$

Operation at 0.8 leading p.f. excitation remaining unchanged. Consider the phasor diagram shown below.



From diagram; we can write

$$\frac{5413.12}{\sin 53.14°} = \frac{2187}{\sin\delta}$$

Solving we get; $$\sin\delta = 0.323$$
$$\delta = 18.84°$$

Here, $$\theta = \pi - (\delta + 53.14)$$
$$= 108.02°$$

Again, we can write,

$$\frac{V_t}{\sin 108.02°} = \frac{2187.5}{0.323}$$

or, V_t = 6438.77 V (phase)

or, $V_{t\text{ (line)}}$ = 11.15 kV

22. (a)

Given,

V_t = 1.0 p.u.

I_a = 1.0 p.u. at 0.8 p.f. lagging

$\phi = \cos^{-1} 0.8 = 36.86°$

X_d = 0.8 p.u.

X_q = 0.5 p.u.

As we can use the relation,

$$\tan \psi = \frac{V_t \sin\phi + I_a X_q}{V_t \cos\phi + I_a r_a} \qquad [\because \text{ Here } r_a = 0]$$

$$\tan \psi = \frac{1\times 0.6 + 1\times 0.5}{1\times 0.8 + 0}$$

or $\tan \psi = 1.375$

$\psi = 53.97°$

$\because$ Power angle; $\delta = \psi - \phi$ [for generator]

$= 53.97° - 36.86°$

$= 17.11°$

We can write,

No load voltage; $E_f = V_t \cos \delta + I_d X_d$

$= V_t \cos \delta + (I_a \sin \psi)X_d$

$= 1 \times \cos 17.11° + (1 \times \sin 53.97°) \times 0.8$

$= 1.602$ p.u. ≈ 1.60 p.u.

23. (d)

Synchronous speed, $N_s = \frac{120\times 50}{8} = 750$ rpm

Synchronizing power, $$P_{syn} = \frac{3V_P E_f}{X_s}\cos\delta \times \frac{\pi}{180}\times\frac{P}{2}$$

$$= 3\times\left(\frac{6000}{\sqrt{3}}\right)\times\frac{6000}{\sqrt{3}}\times\frac{1}{4}\times 1\times\frac{\pi}{180}\times\frac{8}{2}$$

= 628.318 kW/mech degree

Synchronizing torque, $$T_{syn} = \frac{628.318\times 10^3}{2\pi\times 750}\times 60 = 8000 \text{ Nm/mech degree}$$

24. (c)

$$\vec{E}' = \vec{V_t} - j\vec{I_a}X_q$$

$$X_q = 7\ \Omega$$

$$\text{p.u. value of } X_q = \frac{\text{ohmic value}}{\text{base value}}$$

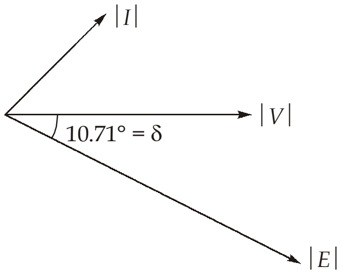
$$\text{Base ohms} = \frac{\left(\frac{440}{\sqrt{3}}\right)}{10} = 25.4\ \Omega$$

$$\text{p.u. value of } X_q = \frac{7}{25.4} = 0.2756 \text{ p.u.}$$

$$\vec{E} = 1 - ((j0.2756) \times 1\angle\cos^{-1}(0.8))$$

$$= 1.18\angle{-10.71°} \text{ p.u.}$$

$$\therefore \quad \text{Torque angle, } \delta = 10.71°$$



Alternative method:

$$\text{Torque angle, } \delta = \tan^{-1}\left[\frac{IX_q\cos\theta}{V + IX_q\sin\theta}\right]$$

$$= \tan^{-1}\left[\frac{10\times7\times\cos(36.87°)}{254+(10\times7\sin(36.87°))}\right]$$

$$\delta = 10.71°$$

25. (b)

$$\vec{E} = \vec{V} + j\vec{I}\vec{X}_s$$

$$= 1 + (j0.8 \times 1\angle{-\cos^{-1}(0.8)})$$

$$= 1.61\angle 23.4° \text{ p.u.}$$

$$\left(\frac{\partial P_e}{\partial \delta}\right)_{\delta=\delta_0} = \frac{EV}{X_s}\cos\delta$$

$$= \frac{1.61\times1}{0.8}\cos(23.4°) = 1.847 \text{ p.u./elec. rad}$$

$$1 \text{ p.u.} = 1000 \text{ kVA}$$

$$\text{Synchronizing coefficient} = \frac{1847}{\left(\frac{180}{\pi}\right)} = 32.23 \text{ kW/elec. degree}$$

26. (d)

$$P_m = \frac{V_t E_f}{X_d}\sin\delta = \frac{V_t E_f}{X_d}\sin 30°$$

$$T_m = \frac{V_t E_f}{\omega_s X_d}\sin 30°$$

$$T_m = \frac{V_t \times 1.1 E_f}{1.1\omega_s \times 1.1 X_d}\sin\delta = \frac{V_t E_f}{\omega_s X_d}\sin 30°$$

$$\sin\delta = 1.1 \sin 30°$$

$$\delta = \sin^{-1}(0.55)$$

$$\delta = 33.36°$$

27. (c)

$$\text{Excitation emf, } \left(\vec{E}_f\right) = \vec{V} + \vec{I}_a Z_s$$

$$\text{Armature current, } I_a = \frac{20 \times 10^3}{\sqrt{3} \times 400} = 28.87 \text{ A}$$

$$\vec{E}_f = \frac{400}{\sqrt{3}} + (28.87\angle 36.87°) \times (0.5 + j3)$$

$$\vec{E}_f = 205.85\angle 22.25° \text{ V}$$

$$\text{Voltage regulation} = \frac{|E_f| - |V|}{|V|} \times 100$$

$$= \frac{205.85 - \left(\frac{400}{\sqrt{3}}\right)}{\left(\frac{400}{\sqrt{3}}\right)} \times 100 = -10.86\%$$

28. (a)

For double layer winding,

No. of slots = No. of coils

Total number of turns = 60 × 10 = 600

$$\text{Turns per phase} = \frac{600}{3} = 200$$

$$\text{Pitch factor } (K_c) = \cos 18° = 0.951$$

$$\text{Distribution factor } (K_d) = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$

$$m = \frac{60}{4} \times \frac{1}{3} = 5$$

$$\beta = \frac{180}{60/4} = 12°$$

$$K_d = \frac{\sin\frac{5\times 12}{2}}{5\sin\frac{12}{2}} = 0.9567$$

$$\text{Induced emf, } E_{ph} = \sqrt{2}\pi K_w \phi f T_{ph}$$

$$E_{ph} = \sqrt{2}\pi \times 0.9567 \times 0.95 \times 0.015 \times 50 \times 200$$

$$E_{ph} = 606.33 \text{ V}$$

$$E_{L\text{-}L} = 1.05 \text{ kV}$$

28. (d)

$$\text{Base impedance } (Z_B) = \frac{V_B^2}{S_B} = \frac{400^2}{50000} = 3.2\ \Omega$$

Synchrnous reactance,

$$(X_s)_{pu} = \frac{7.5}{3.2} = 2.34375 \text{ p.u.}$$

When motor is operating at 75% load with 0.8 p.f. leading

$$\vec{E}_{f1} = \vec{V} - j\vec{I}_{a1}X$$

$$= 1\angle 0° - j(0.75\angle\cos^{-1}(0.8)) \times (2.34375)$$

$$= 2.49\angle{-34.4°} \text{ p.u.}$$

Now excitation emf is decreased by 5%

$$E_f \sin\delta = \text{constant}$$

$$E_{f1}\sin\delta_1 = E_{f2}\sin\delta_2$$

$$E_{f2} = 0.95 \times 2.49 = 2.37$$

$$\delta_2 = \sin^{-1}\left(\frac{E_{f1}}{E_{f2}} \times \sin\delta_1\right)$$

$$\delta_2 = \sin^{-1}(0.594)$$

$$\delta_2 = 36.44°$$

$$\text{Current, } \vec{I}_{a2} = \frac{\vec{V} - \vec{E}_{f2}}{jX_s} = \frac{1 - 2.37\angle -36.44°}{j2.34375}$$

$$\vec{I}_a = 0.7144\angle 32.78°$$

$$\text{Power factor} = \cos 32.78° = 0.8407 \text{ lagging}$$

30. (a)

$$\text{Full load current} = \frac{25 \times 10^3}{\sqrt{3} \times 400 \times 0.8} = 45.11 \text{ A}$$

$$\text{Excitation emf } \vec{E}_f = \vec{V} - j\vec{I}_a X$$

$$= \frac{400}{\sqrt{3}} - (45.11\angle 36.87°)(j7)$$

$$= 490.5\angle{-31°} \text{ V}$$

Rotor angle slip by 0.25 mechanical degree,

$$\theta_e = \frac{P}{2}\theta_m$$

$$\Delta\delta = \frac{4}{2} \times 0.25 = 0.5°$$

$$\text{Synchronizing emf} = 2E_f \sin\frac{\Delta\delta}{2}$$

$$= 2 \times 490.5 \sin\left(\frac{0.5}{2}\right) = 4.28 \text{ V}$$

$$\text{Synchronizing current} = \frac{4.28}{7} = 0.611 \text{ A}$$

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