CLASS TEST

S.No.: 03SK_HIJKLMN_081024

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# Synchronous Machine

## ELECTRICAL ENGINEERING

**Date of Test : 08/10/2024**

## ANSWER KEY

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1. | (d) | 7. | (b) | 13. | (d) | 19. | (c) | 25. | (a) |
| 2. | (d) | 8. | (b) | 14. | (c) | 20. | (d) | 26. | (c) |
| 3. | (c) | 9. | (c) | 15. | (a) | 21. | (b) | 27. | (d) |
| 4. | (a) | 10. | (a) | 16. | (b) | 22. | (c) | 28. | (a) |
| 5. | (b) | 11. | (b) | 17. | (a) | 23. | (b) | 29. | (b) |
| 6. | (a) | 12. | (d) | 18. | (b) | 24. | (c) | 30. | (b) |

## DETAILED EXPLANATIONS

**1. (d)**

Total real power, $P = S_P\left(f_{nl} - f_{sys}\right)$

$$f_{sys} = f_{nl} - \frac{P}{S_P} = 61 - \frac{1800\text{ kW}}{1\text{ MW/Hz}}$$

Operating system frequency,

$$f_{sys} = 59.2\text{ Hz}$$

**2. (d)**

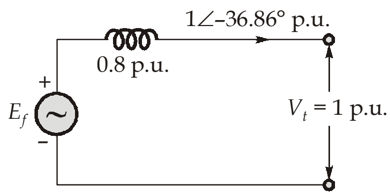
**3. (c)**

Reactive power output, $Q_{out} = \dfrac{EV}{X_d}\cos\delta - \dfrac{V^2}{X_d}$

The maximum reactive power occurs at $\delta = 0°$.

**4. (a)**

Consider the circuit diagram drawn below:




From circuit diagram we can write,

$$\vec{E}_f = 1 + j\,0.8\,(1\angle{-36.86°})$$

$$\vec{E}_f = 1.61\angle 23.4°\text{ p.u.}$$

Here, power angle, $\delta = 23.4°$

Real power; $P_e = \dfrac{V_t E_f}{X_s}\sin\delta$

Synchronizing power, $\dfrac{dP_e}{d\delta} = \dfrac{V_t E_f}{X_s}\cos\delta = \dfrac{1\times 1.61}{0.8}\cos(23.4°)$

$$\frac{dP_e}{d\delta} = 1.847\text{ p.u./electrical radian}$$

or, $\dfrac{dP_e}{d\delta} = 1.847\times 10^3 \times \dfrac{\pi}{180}$ kW/electrical degree

$= 32.236$ kW/electrical degree

or, 1 electrical degree $= \dfrac{P}{2}$ mechanical degree

then; $\dfrac{dP_e}{d\delta} = 32.236 \times 4$ kW/mechanical degree

$$\frac{dP_e}{d\delta} = 128.944\text{ kW/mechanical degree}$$

**5. (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.

**6. (a)**

On a per-phase basis :

$$\vec{E}_{a1} = 120\angle 10° \text{ V}$$

$$\vec{E}_{a2} = 120\angle 20° \text{ V}$$

$$\vec{Z}_{s1} = j5\ \Omega \quad ; \quad \vec{Z}_{s2} = j8\ \Omega$$

$$\vec{Z}_L = 4 + j3 = 5\angle 36.87°\ \Omega$$

$$\vec{V}_a = \vec{I}_L \vec{Z}_L$$

$$= \frac{\vec{E}_{a1}\vec{Z}_{s2} + \vec{E}_{a2}\vec{Z}_{s1}}{\vec{Z}_L(\vec{Z}_{s1}+\vec{Z}_{s2}) + \vec{Z}_{s1}\vec{Z}_{s2}}\vec{Z}_L$$

$$\Rightarrow \quad \vec{V}_a = \frac{(120\angle 10°)(j8) + (120\angle 20°)(j5)}{(4+j3)(j5+j8)+(j5)(j8)} \times (4+j3)$$

$$= 82.17\angle -5.93° \text{V}$$

**7. (b)**

Since there are as many coils as there are slots in the armature for a double layer winding, the number of coils in a phase group is

$$n = \frac{144}{16\times 3} = 3$$

The number of slots per pole:

$$S_p = \frac{144}{16} = 9$$

Thus, the slot span: $\gamma = \frac{180°}{9} = 20°$ electrical. Since there are 9 slots per pole and 3 coils in a phase group, each coil must span 7 slots. Hence, the coil pitch is 20 × 7 = 140° electrical

We can now compute the pitch factor, the distribution factor and the winding factor as

Pitch factor, $K_p = \sin\left(\frac{140°}{2}\right) = 0.94$

Distribution factor, $K_d = \dfrac{\sin\left(3\times\dfrac{20°}{2}\right)}{3\times\sin\left(\dfrac{20°}{2}\right)} = 0.96$

$K_w = 0.94 \times 0.96 = 0.902$

The effective turns per phase are

$$N_e = \frac{16\times3\times10\times0.902}{2} = 216.48$$

The frequency of generated voltage is

$$f = \frac{375\times16}{120} = 50 \text{ Hz}$$

RMS value of the generated voltage per phase is

$$E_a = 4.44 \times 50 \times 216.48 \times 0.025$$
$$= 1201.46 \text{ V}$$

RMS value of line voltage is

$$E_L = \sqrt{3}\times1201.46 = 2081 \text{ V}$$

**8. (b)**

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

$$0.75 = \frac{1\times1.25}{0.7}\sin\delta$$

$$\delta = 24.83°$$

Current is given by,

$$\vec{I} = \frac{\vec{E}_f - \vec{V}}{jX} = \frac{1.25\angle24.83° - 1\angle0°}{j0.7}$$

$$I = 0.77\angle-14.36°$$

Phase angle, $\phi = 14.36°$

Power factor $= \cos\phi = 0.9688$ (lagging)

**9. (c)**

Power angle can be calculated as,

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

As rated load is being supplied at unity power factor,

$\therefore$ $\vec{I}_a = 1\angle0°$ p.u.

$$\vec{E}'_f = 1.0\angle0° + j1.0\angle0°\ (0.8)$$
$$= 1.28\angle38.65° \text{ p.u.}$$

$\therefore$ Power angle, $\delta = 38.65°$

**10.** **(a)**

Let,synchronous speed of motor = $N_{sm}$

Also, $$N_{sm} = \frac{120 \times f_m}{P_m}$$

$\therefore$ $$N_{sm} = \frac{120 \times 60}{P_m}$$

Synchronous speed of alternator,

$$N_{sg} = \frac{120 \times f_g}{P_g} = \frac{120 \times 25}{20} = 150 \text{ rpm}$$

Since alternator and motor are directly coupled

$$N_{sg} = N_{sm}$$

(or) $$150 = \frac{120 \times 60}{P_m}$$

$\Rightarrow$ $$P_m = 48$$

**11.** **(b)**

Emf equation synchronous motor is given as

$$\vec{E} = \vec{V}_t - \vec{I}_a \vec{Z}_s$$

Given that, $$\vec{V}_t = 1\angle 0° \text{ p.u.}, \ \vec{I}_a = 1\angle 90° \text{ p.u.}, \ \vec{Z}_s = 0.5\angle 90° \text{ p.u.}$$

$$\vec{E} = 1\angle 0° - (1\angle 90°) \times (0.5\angle 90°)$$
$$= 1 - 0.5\angle 180°$$
$$\vec{E} = 1 + 0.5\angle 0° = 1.5 \text{ p.u.}$$

**12.** **(d)**

The flux in this machine is given by,

$$\phi = dlB$$ [where $d$ is diameter and $l$ is length of the coil]

$$\phi = (0.5)\ (0.3)\ (0.2)$$
$$= 0.03 \text{ Wb}$$

speed of the rotor is given by,

$$\omega = 3600 \times \frac{2\pi}{60} = 377 \text{ rad/sec}$$

The magnitude of peak phase voltage,

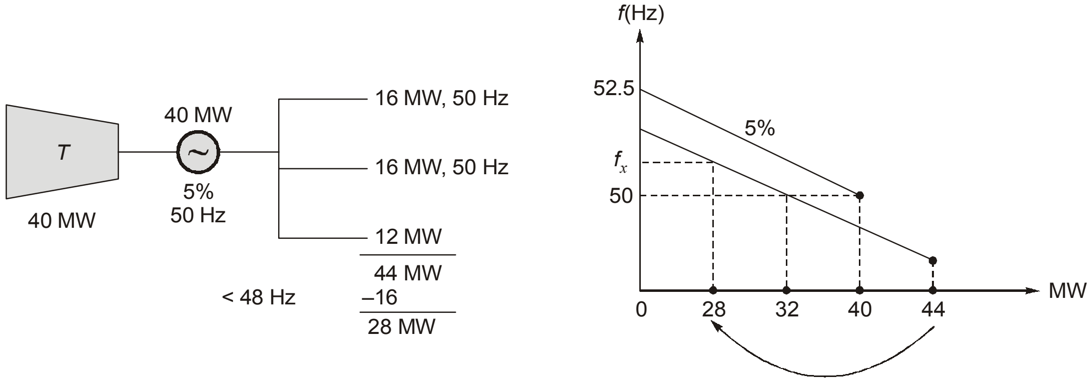
$$E_{max} = N_c\, \phi\, \omega$$
$$= 15 \times 0.03 \times 377$$
$$= 169.65 \text{ V}$$

Rms phase voltage, $$E_{rms} = \frac{E_{max}}{\sqrt{2}} = \frac{169.65}{\sqrt{2}} = 120 \text{ V}$$

Since generator is Y-connected,

$$V_{terminal} = \sqrt{3}(120) = 208 \text{ V}$$

**13. (d)**




From drop characteristics,

$$\frac{\Delta f_1}{\Delta P_1} = \frac{\Delta f_2}{\Delta P_2}$$

$$\frac{2.5}{40} = \frac{\Delta f_2}{4}$$

$$\Delta f_2 = \frac{2.5 \times 4}{40} = 0.25$$

$\therefore$ $$f_x = 50 + 0.25 = 50.25 \text{ Hz}$$

**14. (c)**

Power equation for salient pole alternator is,

$$P = \frac{E_f \cdot V_t}{X_d}\sin\delta + \frac{V_t^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

Putting values in power equations,

$$P = \frac{1.12 \times 1.0}{0.5}\sin\delta + \frac{(1.0)^2}{2}\left(\frac{1}{0.25} - \frac{1}{0.5}\right)\sin 2\delta$$

$$= 1.12 \times 2\sin\delta + 0.5\left(\frac{1}{0.5}\right)\sin 2\delta$$

$$P = 2.24 \sin\delta + \sin 2\delta$$

For, $P_{max}$ $$\frac{dP}{d\delta} = 0;$$

$$\frac{dP}{d\delta} = 2.24\cos\delta + 2\cos 2\delta = 0$$

or, $2.24\cos\delta + 2(2\cos^2\delta - 1) = 0$

or, $2.24\cos\delta + 4\cos^2\delta - 2 = 0$

or, $2\cos^2\delta + 1.12\cos\delta - 1 = 0$

Solving we get;

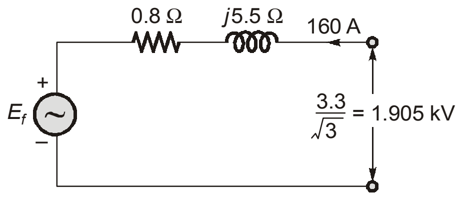
$$\cos\delta = 0.48; -1.04 \text{ (invalid)}$$

or, $\cos\delta = 0.48$

or, $\delta = \cos^{-1}(0.48) = 61.32°$

**15.** **(a)**

Consider the following circuit;




$$\text{Full load current} = 160\angle{-36.86^\circ}\ \text{A}$$

$$\text{Synchronous impedance; } Z_s = (0.8 + j\,5.5)\ \Omega = 5.56\angle 81.724^\circ\ \Omega$$

From circuit diagram we can write;

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

$$E_f = 1.42\angle{-26.22^\circ}\ \text{kV}$$

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

$$= 669.88\ \text{kW}$$

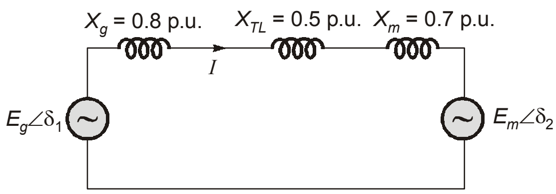
$$\text{shaft output} = 669.88 - 30 = 639.88\ \text{kW}$$

$$\text{Power input} = \sqrt{3}\times 3.3\times 160\times 0.8 = 731.62\ \text{kW}$$

$$\eta_{\text{full load}} = \frac{\text{Output}}{\text{Input}}\times 100 = \frac{639.88}{731.62}\times 100 = 87.46\%$$

**16.** **(b)**

Consider the following circuit diagram:




from the +ve sequence circuit, we can write

$$X_{eq} = X_g + X_{TL} + X_m = 0.8 + 0.5 + 0.7 = 2.0\ \text{p.u.}$$

As $E_g = 1.5$ p.u.

and $E_m = 1.1$ p.u.

Power transferred from generator to motor,

$$P = \frac{E_g \times E_m}{X_{eq}}\sin(\delta')$$

Where, $\delta' = \delta_1 - \delta_2$

then; $$0.6 = \frac{1.5\times 1.1}{2.0}\sin(\delta_1 - \delta_2)$$

$$\sin(\delta_1 - \delta_2) = \frac{1.2}{1.5 \times 1.1} = 0.7272$$

$$(\delta_1 - \delta_2) = 46.66° \text{ (electrical)}$$

**17. (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,

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

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

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

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

**18. (b)**

Synchronous impedance, $Z_s$ $=(0.5 + j5)\Omega = 5.025\angle 84.29° \ \Omega$

$$I_a = \frac{V\angle 0° - E\angle -\delta}{Z_s\angle\theta}$$

$$S = VI_0^* = V\angle 0\left[\frac{V\angle 0 - E\angle -\delta}{Z_s\angle\theta}\right]^*$$

$$S = \frac{V^2}{Z_s}\angle\theta - \frac{EV}{Z_s}\angle\theta + \delta$$

So from above equation,

$$P = \frac{V^2}{Z_s}\cos\theta - \frac{EV}{Z_s}\cos(\theta + \delta)$$

$$900 \times 10^3 = \frac{2000^2}{5.025}(\cos 84.29°) - \frac{2000 \times 3000}{5.025}\cos(84.29° + \delta)$$

$$84.29° + \delta = 133.426°$$

$$\text{Power angle, } \delta = 49.13°$$

**19. (c)**

Take, $V_t = 1\angle 0°$ p.u.

So, $I_a = 1\angle{-\cos^{-1}(0.8)}$ p.u.

Alternator excitation emf, $\vec{E}_f = \vec{V}_t + \vec{I}_a\vec{Z}_s$

$$\vec{E}_f = 1\angle 0° + [1\angle -\cos^{-1}(0.8)] \times 1.25\angle 90°$$

$$\vec{E}_f = 1 + 1.25\angle 53.13°$$

$$\left|\vec{E}_f\right| = \sqrt{(1 + 1.25\cos 53.13°)^2 + (1.25\sin 53.13°)^2}$$

$$= 2.01 \text{ p.u.}$$

When motor just fall out of step,

$$\delta \approx 90$$

Now for same excitation,

$$2.01\angle 90° = 1\angle 0° + I_a \times 1.25\angle 90°$$

$$\vec{I}_a = \frac{j2.01 - 1}{j1.25} = 1.608 + j0.8$$

$$\vec{I}_a = 1.8\angle 26.45° \text{ p.u.}$$

$$\text{Power factor} = \cos(26.45°) = 0.895 \text{ leading}$$

**20. (d)**

$$S_{\text{load}} = 1200\angle -\cos^{-1}(0.8) = 960 - j720$$

$$S_A = 750\angle -\cos^{-1}(0.9) = 675 - j326.9$$

Now, $$S_A + S_B = S_{\text{load}}$$

$\therefore$ $$S_B = S_{\text{load}} - S_A$$

$$= 960 - j720 - 675 + j326.9$$

$$= 285 - j393.1$$

$$S_B = 485.54\angle -54.05°$$

$$\cos\phi_B = \cos(-54.05) = 0.587 \text{ (lagging)}$$

**21. (b)**

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{10}{2 \times 25} = 0.2\ \Omega$$

Internal generated voltage,

$$E_A = V_{\text{ph O.C.}} = \frac{V_T}{\sqrt{3}}$$

$$E_A = \frac{540}{\sqrt{3}} = 311.77 \text{ V}$$

The short circuit is equal to line current, since generator is Y-connected,

$$I_{A,\text{ SC}} = I_L = 300 \text{ A}$$

$$\frac{E_A}{I_A} = \sqrt{R^2 + X_S^2}$$

$$X_S = \sqrt{\left(\frac{311.77}{300}\right)^2 - (0.2)^2}$$

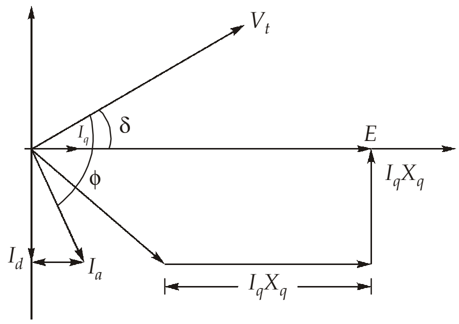
$$X_S = 1.02\ \Omega$$

**22. (c)**

With no field excitation,

$$P_{in} = \frac{V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\delta$$

For maximum $P_{in}$ $\quad \delta = 45°$




$$|I_dX_d| = |I_qX_q| = V_t \cos 45°$$

$$I_d = \frac{1}{\sqrt{2}} \times \frac{1}{1.2} = 0.589 \text{ p.u.}$$

$$I_q = \frac{1}{\sqrt{2}} \times \frac{1}{0.6} = 1.178 \text{ p.u.}$$

$$\psi = \tan^{-1}\left(\frac{I_d}{I_q}\right) = \tan^{-1}\left(\frac{0.589}{1.178}\right) = 26.56°$$

$$\text{power factor} = \cos\phi = \cos(26.56° + 45°) = 0.316 \text{ (lagging)}$$

**23. (b)**

$$P_{in} = \sqrt{3} \times VI_a$$

$$P_{in} = \sqrt{3} \times 460 \times I_a$$

$$P_{in} = P_{out} + P_{loss}$$

$$= 125 \times 746 + 3 \times I_a^2 \times 0.078$$

$$\sqrt{3} \times 460 \times I_a = 93250 + 0.234\, I_a^2$$

$$0.234\, I_a^2 - 796.74\, I_a + 93250 = 0$$

$$I_a = 121.4 \text{ A}$$

**24. (c)**

Connected load, $P_1 + P_2 = 50$ MW

No load frequency, $f_0 = 50$ Hz

drop in frequency for a drop of 50 MW

$$= 3\% \text{ of } f_0$$
$$= 0.03 \times 50 = 1.5 \text{ Hz}$$

For load of $P_1$ MW $= \frac{1.5}{50} \times P_1$

Operating frequency of generator $A$,

$$f_A = \left(50 - \frac{1.5}{50} P_1\right)$$

Operating frequency of generator $B$,

$$f_B = f_0 - \left(\frac{3.5}{100} \times 50\right)\frac{P_2}{25} = \left(50 - \frac{3.5}{50} P_2\right)$$

For parallel operation,

$$f_A = f_B$$
$$50 - \frac{1.5}{50} P_1 = 50 - \frac{3.5}{50} P_2$$
$$1.5\ P_1 = (3.5)\ (50 - P_1)$$
$$P_1 = 35 \text{ MW}$$

**25. (a)**

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

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

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

$= 628.318$ kW/mech degree

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

**26. (c)**

Power angle can be calculated as,

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

As rated load is being supplied at unity power factor,

$\therefore$ $\vec{I}_a = 1\angle 0°$ p.u.

$$\vec{E}'_f = 1.0\angle 0° + j1.0\angle 0°\ (0.8)$$
$$= 1.28\angle 38.65° \text{ p.u.}$$

$\therefore$ Power angle, $\delta = 38.65°$

**27. (d)**

$$N_{ph} = \frac{4 \times 54}{2 \times 3} = 36$$

$$m = \frac{54}{2 \times 3} = 9$$

$$\beta = \frac{180°}{\left(\frac{54}{2}\right)} = \frac{20°}{3}$$

$$K_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}} = \frac{\sin(30°)}{9\sin\frac{10}{3}} = 0.955$$

$$\text{coil span} = 180° - 2 \times \frac{20°}{3} = 166.67°$$

$$\alpha = 2 \times \frac{20°}{3} = \frac{40°}{3}$$

$$K_C = \cos\frac{\alpha}{2} = \cos\frac{20°}{3} = 0.993$$

$$E_{ph} = \frac{3300}{\sqrt{3}} = \sqrt{2}\pi f \times 0.993 \times 0.955 \times 36 \times \phi$$

$$\phi = 0.2512 \text{ Wb}$$

**28. (a)**

Given, efficiency, $\eta = 0.95$

$$\text{Input} = \frac{800 \text{ kW}}{0.95} = 842.10 \text{ kW}$$

$$I_a = \frac{842.10}{\sqrt{3} \times 11 \times 0.8} = 55.25 \text{ A at 0.8 p.f. leading}$$

$$V_t = \frac{11000}{\sqrt{3}} = 6351 \text{ V}$$

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

$$= 6351 - j35 \times 55.25\angle\cos^{-1} 0.8$$

$$= 7668.90\angle{-11.637}$$

$$|E_f| = 7.668 \text{ kV}$$

**29. (b)**

$$\text{Load kVA} = \frac{1280 \times 1000}{0.8} = 1600 \text{ kVA}$$

$$I_L = \frac{\text{kVA}}{\sqrt{3}V_L} = \frac{1600 \times 1000}{\sqrt{3} \times 13500} = 68.43 \text{ A}$$

$$V_{ph} = \frac{V_t}{\sqrt{3}} = \frac{13500 \text{ V}}{\sqrt{3}} = 7794.23 \text{ V}$$

$$E_{ph}^2 = (V_{ph}\cos\phi + I_a r_a)^2 + (V_{ph}\sin\phi - I_a X_s)^2$$

$$E_{ph}^2 = (7794.23 \times 0.8 + 68.43 \times 1.5)^2 + (7794.23 \times 0.6 - 68.43 \times 30)^2$$

$$E_{\text{ph}} = 6859.63 \text{ V}$$

$$\% VR = \frac{E_{\text{ph}} - V_{\text{ph}}}{V_{\text{ph}}} \times 100 = \frac{6859.63 - 7794.23}{7794.23} \times 100 = -11.99\%$$

**30. (b)**

The generator described above is Y-connected, so the direct current in the resistance test flows through two windings

$$2R_A = \frac{V_{DC}}{I_{DC}}$$

$$R_A = \frac{10}{2 \times 25} = 0.2\ \Omega$$

Internal generated voltage,

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$$I_{A,\,SC} = I_L = 300 \text{ A}$$

$$\frac{E_A}{I_A} = \sqrt{R^2 + X_S^2}$$

$$X_S = \sqrt{\left(\frac{311.77}{300}\right)^2 - (0.2)^2}$$

$$X_S = 1.02\ \Omega$$

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