استاد جناب آقای ... تمرین سری 6 ماشین‌های الکتریکی مصطفی محسنی کیمی

(9910 23 96)

1 (الف)

$n_m = 1440\ rpm < n_{sync} \Rightarrow n_{sync} = \dfrac{120 \times 50}{P} > 1440 \Rightarrow P = 4$

$n_{sync} = 1500\ rpm$

(ب)

$S = \dfrac{n_{sync} - n_m}{n_{sync}} (\times 100) \Rightarrow S = \dfrac{1500 - 1440}{1500} \times 100 = 4\ \%$

$f_{re} = S f_{se} \Rightarrow f_{re} = 0.04 \times 25 = 1\ Hz$

(ج)

سرعت میدان استاتور نسبت به استاتور : $n_{sync} = \dfrac{120 \times 50}{4} = 1500\ rpm$

سرعت میدان استاتور نسبت به روتور : $n_{slip} = 1500 - 1440 = 60\ rpm$

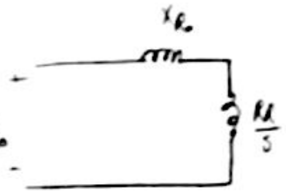
(د)

سرعت میدان روتور نسبت به روتور : $1440 - 1500 = -60\ rpm$

استاتور " " " " " : $1440\ rpm$

میدان استاتور " " " " " : صفر

2 (الف)



$n_{sync} = \dfrac{120 f_e}{P} = \dfrac{120 \times 50}{4} = 1500\ rpm \qquad \omega_{sync} = \dfrac{4 \pi f_e}{P} = 157$

$S_{fl} = \dfrac{n_{sync} - n_m}{n_{sync}} = \dfrac{1500 - 1440}{1500} = 0.04$

در حالت راه اندازی $S = 1 \Rightarrow I_R = \dfrac{E_{R0}}{jX_{R0} + R_R} = 117.7 \angle -78.7^\circ$

$\cos\varphi = \cos(\angle E_{R0} - \angle I_R) = \cos(78.7) \Rightarrow PF = 0.196$ پس‌فاز

$\tau_{ind} = \dfrac{P_{AG}}{\omega_s} = \dfrac{3 E_{R0} I_R \cos\varphi}{\omega_{sync}} = \dfrac{3 \times 120 \times 117.7 \times 0.196}{157} = 52.9\ (N.m)$

at full load $S = 0.04 \quad I_R = \dfrac{E_{R0}}{jX_{R0} + \frac{R_R}{S}} = \dfrac{120 \angle 0}{j1 + \frac{0.2}{0.04}} = 23.5 \angle -11.3^\circ$

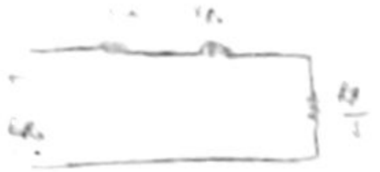
$\cos\varphi = \cos(\angle E_{R0} - \angle I_R) = \cos(11.3) \Rightarrow PF = 0.981$ پس‌فاز

$\tau_{ind} = \dfrac{P_{AG}}{\omega_{sync}} = \dfrac{3 E_{R0} I_R \cos\varphi}{\omega_{sync}} = 52.9\ (N.m)$

گشتاور القا شده در دو حالت فرق چندانی با هم ندارد.
ولی ضریب توان راه اندازی بسیار کوچکتر از ضریب توان بی باری است و جریان راه اندازی بیش از ۴ برابر جریان نامی می باشد.

2 ادامه

(ب



راه‌اندازی $s=1$ $\quad I_R = \dfrac{E_{R_0}}{jX_{R_0} + \frac{R_R}{s} + 1} = \dfrac{120\angle 0}{j3 + 1.2} = 76.8\angle -39.8^\circ$

$\cos\theta = \cos(\angle E_{R_0} - \angle I_R) = \cos(39.8) \Longrightarrow PF = 0.768$ پس‌فاز

$T_{ind} = \dfrac{P_{AG}}{\omega_s} = \dfrac{3 I_R E_R \cos\theta}{\omega_s} = 135\ N.m$

at full load. $s = 0.04$ $\quad I_R = \dfrac{E_{R_0}}{jX_{R_0} + \frac{R_R}{s} + 1} = \dfrac{120\angle 0}{j1 + \frac{0.2}{0.04} + 1} = 19.7\angle -9.4^\circ$

$\cos\theta = \cos(9.4^\circ) \Longrightarrow PF = 0.987$ پس‌فاز $\quad T_{ind} = \dfrac{P_{AG}}{\omega_s} = 44.6\ (N.m)$

☐ همانطور که قابل مشاهده است T_{ind} با افزایش مقاومت روتور کاهش و ضریب توان راه‌اندازی افزایش و جریان راه‌اندازی کاهش می‌یابد.

☐3

$P_{in} = P_{out} + P_{SCL} + P_{core} + P_{rot} + P_{RCL}$

(الف

Δ اتصال : $I_1 = \dfrac{I_L}{\sqrt{3}} = \dfrac{8}{\sqrt{3}} = 4.62^A \Longrightarrow P_{SCL} = 3 I_1^2 R_1 = 76.8\ (w)$

$660 = 76.8 + P_{core} + 0 + 420 + 0 \Longrightarrow P_{core} = 163.2\ (w)$

at full load & $P_{out} = 10^{kw}$

$I_1 = \dfrac{I_L}{\sqrt{3}} = \dfrac{18}{\sqrt{3}} = 10.39^A \Longrightarrow P_{SCL} = 3 R_1 I_1^2 = 388.8^{(w)}$ (ب

$P_{in} = P_{SCL} + P_{core} + P_{rotor\ loss} + P_{out} \Longrightarrow 11.2^{kw} = 388.8 + 163.2 + P_{rotor} + 10^{kw} \Longrightarrow P_{rotor\ loss} = 648\ w$

$P_{rotor\ loss} = P_{rot} + P_{RCL} \Rightarrow 648^w = P_{RCL} + 420^w \Longrightarrow P_{RCL} = 228\ w$

(ج

$P_{out} = \dfrac{1-s}{s} P_{RCL} \Rightarrow 10^{kw} = \dfrac{1-s}{s} \cdot 228 \Longrightarrow s = 2.2\ \%$

(د

$T_{ind} = \dfrac{P_{conv}}{\omega_m} = \dfrac{P_{out} + P_{rot}}{\omega_m} = 7.1\ (N.m)$ $\quad T_{load} = \dfrac{P_{out}}{\omega_m} = 6.8\ (N.m)$

(ه

$\%\eta = \dfrac{P_{out}}{P_{in}} \times 100 = 89.3\ \%$

$$S_{max} = \frac{R_2'}{\sqrt{R_{th}^2 + (X_{th} + X_2)^2}} = \frac{R_2'}{X_{th} + X_2} \Longrightarrow X_{th} + X_2 = 10 R_2'$$ (1)

$$\tau = \frac{3 V_{th}^2 \frac{R_2}{S}}{\omega_s \sqrt{(R_{th} + R_2)^2 + (X_{th} + X_2)^2}} \xRightarrow{R_{th} = 0} \frac{\tau_b}{\tau_{max}} = \frac{S_{max}}{S_b} \times \frac{(\frac{R_2'}{S_{max}})^2 + (X_{th} + X_2)^2}{(\frac{R_2'}{S_b})^2 + (X_{th} + X_2)^2}$$

$$\Longrightarrow \frac{1}{2} = \frac{0.1 \left[(\frac{R_2'}{0.1})^2 + (10R_2')^2 \right]}{S_b \left[(\frac{R_2'}{S_b})^2 + (10R_2')^2 \right]} \Longrightarrow S_b = 2.36\ \%$$

$$\omega_{sync} = \frac{120 f_e}{P} = 1500\ rpm \qquad n_m = (1 - S_b) n_{sync} = 464.6\ (rpm)$$

$$P_{cu_2} = S_b P_{AG}$$

$$P_{rot} = 0 \Longrightarrow P_{out} = (1 - S_b) P_{AG}$$

$$\Longrightarrow P_{cu_2} = \frac{S_b}{1 - S_b} P_{out} = \frac{0.0236}{1 - 0.0236} \times 10^{kw} = 241.7 (W)$$ (2)

$$\tau = \frac{3 V_{th}^2 \frac{R_2'}{S}}{\omega_{sync} \left[(R_{th} + \frac{R_2'}{S})^2 + (X_{th} + X_2)^2 \right]} \xRightarrow{R_{th} = 0} \frac{\tau_{start}}{\tau_b} = \frac{S_b \left[(\frac{R_2'}{S_b})^2 + (X_{th} + X_2)^2 \right]}{\left[R_2'^2 + (X_{th} + X_2)^2 \right]}$$ (3)

$$= \frac{0.0236 \left[(\frac{R_2'}{0.0236})^2 + (10R_2')^2 \right]}{\left[R_2'^2 + (10R_2')^2 \right]} = 0.442$$

$$\tau_n = \frac{P_{conv}}{\omega_m} = \frac{P_{out} + P_{rot}}{\omega_m} = \frac{10^{kw}}{\frac{1964.6}{60} \times 2\pi} = 65.2\ (Nm)$$

$$\tau_{start} = 28.7\ (N.m)$$

$$I_S = I_R' = \frac{V_{th}}{\sqrt{(R_{th} + \frac{R_2'}{S})^2 + (X_{th} + X_2')^2}} \qquad (R_{th} = 0)$$ (4)

$$\frac{I_{start,R}}{I_{b,R}} = \frac{I'_{start,R}}{I_{b,R}} = \frac{\sqrt{(\frac{R_2'}{S})^2 + (X_{th} + X_2')^2}}{\sqrt{(\frac{R_2'}{S})^2 + (X_{th} + X_2')^2}} = \frac{\sqrt{(\frac{R_2'}{0.0236})^2 + (10R_2')^2}}{\sqrt{(R_2')^2 + (10R_2')^2}} = 4.33$$

$$\frac{I_{max,s}}{I_{b,s}} = \frac{\sqrt{\left(\frac{R_2'}{0.0236}\right)^2 + (10R_2)^2}}{\sqrt{\left(\frac{R_2'}{0.2}\right)^2 + (10R_2')^2}} = 3.07 \tag{5}$$

$$S_{max} = \frac{R_2'}{X_{th}+X_2'} = \frac{3R}{10R} \Longrightarrow S_{max} = 2,0\ \% \tag{7}$$

$$\frac{R_2'/s_b}{\left(\frac{R_2'}{s_b}\right)^2 + (X_{th}+X_2')^2} = \frac{\frac{R'}{s_b}}{\left(\frac{R}{s_b}\right)^2 + (X_{th}+X_2')^2} \Longrightarrow \frac{\frac{3R}{s_b}}{\left(\frac{3R}{s_b}\right)^2 + (10R)^2} = \frac{\frac{R}{0.0236}}{\left(\frac{R}{0.0236}\right)^2 + (10R)^2} \tag{8}$$

$$\Longrightarrow s_b = 0.0703 \Longrightarrow \%s_b = 7.03\% \qquad n_m = (1-s_b)\,n_{sync} = 1393.8\,rpm \Longrightarrow \omega_m = \frac{n_m}{60}\times 2\pi = 146\ \frac{rad}{s}$$

$$\frac{\tau_{start}}{\tau_b} = \frac{s_b\left[\left(\frac{R_2'}{s_b}\right)^2 + (X_{th}+X_2)^2\right]}{\left[(R_2')^2 + (X_{th}+X_2)^2\right]} = \frac{0.0703\left[\left(\frac{3R}{0.0703}\right)^2 + (10R)^2\right]}{(3R)^2 + (10R)^2} = 1.23 \tag{9}$$

$$\Longrightarrow \tau_{start} = 1.23\times 65.2 = 80.3\ (N.m)$$

$$\frac{I_{start,R}}{I_{b,R}} = \frac{I'_{start,R}}{I'_{b,R}} = \frac{\sqrt{\left(\frac{3R}{0.0703}\right)^2 + (10R)^2}}{\sqrt{(3R)^2 + (10R)^2}} = 4.17 \tag{10}$$

$\cos\varphi = 0.9982 \qquad |Z_{eq}| = \frac{V_\varphi}{I_{1,nl}} = X_1 + X_m \Longrightarrow X_m = 131.756\ \Omega$ [4]

$$\frac{\left(420 \cdot \frac{X_m}{X_1 + X_m}\right)^2}{R_c} = 209 \Longrightarrow R_c = 575.97\ \Omega$$

$$I_1 = \frac{420}{\left(\frac{r_2}{s} + jX_2\right) \| R_c \| (jX_m + r_1 + jX_1)} = 7.228\angle -47.54^\circ \Longrightarrow |I_1| = 7.228\ (A)$$

$$I_2 = \frac{\left(\frac{X_m}{X_2 + X_m} V_\varphi\right)}{\frac{R_2}{s} + jX_2} = 5.667\angle -3.39^\circ \Longrightarrow |I_2| = 5.667\ (A)$$

$$\tau = \frac{3V_{th}^2 \frac{R_2}{s}}{\underset{\frac{50\pi}{3}}{\omega_s}\left[\left(R_{th} + \frac{R_2}{s}\right)^2 + \underset{X_1}{(X_{th}} + X_2)^2\right]} = 5.86 \qquad s_{max} = \frac{R_2}{\sqrt{R_{th}^2 + (X_{th} + X_2)^2}} = 0.1845$$

$$N_r = (1 - s)\underset{\frac{120f}{P}}{N_s} \Longrightarrow N_r = 407.750\ (rpm)$$

$$\tau_{max} = \frac{3V_{th}^2}{\omega_s\left(R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2)^2}\right)} = 316.05\ (N\cdot m)$$

اگر s کوچک

$$\tau = \frac{3V_{th}^2 R_2 s}{\omega_s R_2^2} = \frac{3V_{th}^2}{\omega_s R_2} s$$ [3]

[*] اگر ولتاژ ۹۰٪ شود یعنی 0.9 برابر شود پس Vth 0.9 برابر می شود و چون T ثابت است پس s باید $\left(\frac{10}{9}\right)^2$ برابر شود یعنی 1.235 برابر

$$N_{r_2} = (1 - 1.235s) N_s$$
$$N_{r_1} = (1 - s) N_s$$
$\Longrightarrow$ [*] سرعت روتور کاهش می یابد تا سرعت تقریبا ثابت است.

$$P_{cu,r} = s P_{AG} = s \frac{R_2}{s} I_R^2 = R_2 \frac{V_{th}^2}{\left(\frac{R_2}{s}\right)^2 + (X_2)^2}$$

[*] در اینجا Vth در 0.9 و s در $\left(\frac{10}{9}\right)^2$ ضرب می شود.

no load: $X_1 + X_m = \frac{\frac{400}{\sqrt{3}}}{7.5} = 30.792\ \Omega$

[8]

locked rotor:
$$\begin{cases} R_1 + R_2 = \frac{\frac{150}{\sqrt{3}}}{35} \times 0.44 = 2.474 \\ X_1 + X_2 = \frac{150}{\sqrt{3} \times 35} \times 0.89 = 2.22\ \Omega \\ X_1 = 2X_2 \end{cases} \Longrightarrow X_1 = 1.481\ \Omega,\ X_2 = 0.74\ \Omega$$
$$X_m = 39.311\ \Omega$$

ادامه حل سؤال 8 .

ⓔ با توجه به اینکه X_m خیلی بزرگ است پس تقریبا $I_1 = I_2$ ⟹ $R_1 \approx R_2$

$$P_{cu,r} = R_2 I_2^2 = R_2 \frac{V_{th}^2}{\left(\frac{R_2}{S}\right)^2 + X_2^2} = 62.472$$

$$960 = \frac{120 f_e}{P} \Rightarrow P = 6 \Rightarrow S = \frac{1000 - 960}{1000} = 0.04$$

$$P_{AG} = \frac{P_{cu,r}}{S} = 1561.8 \Rightarrow P_{out} = P_{conv} = (1-S) P_{AG} = 1299.33 \ (W)$$

(الف) و (ب) و (ج)

$$\tau = \frac{P_{out}}{\omega_m} = \frac{P_{conv}}{(1-S)\omega_{sync}} = \frac{P_{AG}}{\omega_{sync}} = 14.914$$

$$\%\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{out}}{P_{out} + 2P_{cu,r}} = 92.3\%$$

$\boxed{9}$

$$2R_S \parallel R_S = 0.6 \Rightarrow \frac{2R_S \times R_S}{3R_S} = 0.6 \Rightarrow R_1 = \frac{3 \times 0.6}{2} = 0.9\,\Omega$$

$$\cos\theta = \frac{P_{in}}{3 V_L \frac{I_L}{\sqrt{3}}} = \frac{P_{in}}{\sqrt{3} V_L I_L} = \frac{5^{kW}}{\sqrt{3} \times 210 \times 20} = 0.687$$

$$R_1 + R_2 = \frac{210}{\frac{20}{\sqrt{3}}} \cdot 0.687 = 12.5 \Rightarrow R_1 = 0.9\,\Omega \ , \ R_2 = 11.6\,\Omega$$

$$X_1 + X_2 = \frac{210}{\frac{20}{\sqrt{3}}} \times \sqrt{1 - (0.687)^2} = 13.2$$

$$\tau_{راه‌اندازی} = \frac{3 V_{th}^2 \frac{R_2}{S}}{\omega_s \left[(\underbrace{R_{th}}_{\simeq R_1} + \frac{R_2}{S})^2 + (\underbrace{X_{th}}_{\simeq X_1} + X_2)^2 \right]} = \frac{3 \overset{420^V}{V_\Phi^2} \overset{11.6}{R_2}}{50 \times (12.5^2 + 13.2^2)} \simeq 118.25$$