Homework 5 - SOLUTION KEY

EE-306 – Electromechanical Devices - Semester 162

Problem 1

Consider a Europeon city, it is necessary to supply 300 kW of 60 Hz power. The only power sources available operate at 50 Hz. It is decided to generate the power by means of a motor-generator set consisting of a synchronous motor driving a synchronous generator. Answer the following:

How many poles should each of the two machines have in order to convert 50 Hz power to 60 Hz power?

Solution

SOLUTION The speed of a synchronous machine is related to its frequency by the equation

$$n_m = \frac{120 f_e}{P}$$

To make a 50 Hz and a 60 Hz machine have the same mechanical speed so that they can be coupled together, we see that

$$n_{sync} = \frac{120(50 \text{ Hz})}{P_1} = \frac{120(60 \text{ Hz})}{P_2}$$

$$\frac{P_2}{P_1} = \frac{6}{5} = \frac{12}{10}$$

Therefore, a 10-pole synchronous motor must be coupled to a 12-pole synchronous generator to accomplish this frequency conversion.

Problem 2

Consider a 3-phase, 195 MVA, 15 kV, 60 Hz, star-connected synchronous machine. The open circuit ans short circuit tests data are given as follows:

Table 1: Open-Circuit Test

I_f (A)	150	300	450	600	750	900	1200
V_{LL} (kV)	3.75	7.5	11.2	13.6	15	15.8	16.5

Table 2: Short-Circuit Test

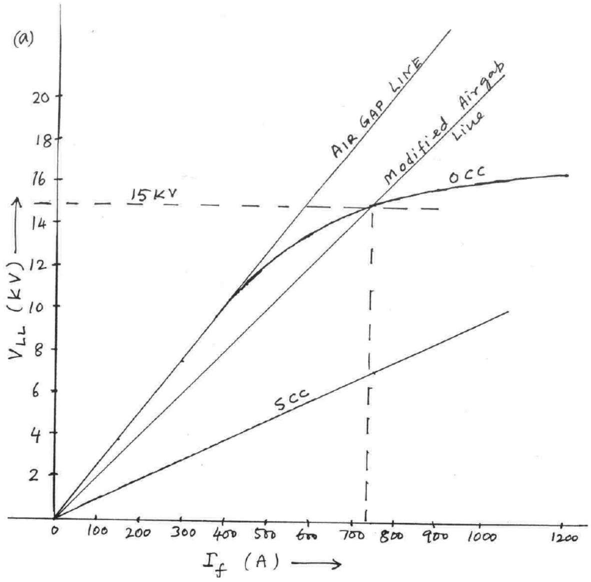
I_f (A)	750
I_A (A)	7000

(a) Draw the open-circuit characteristic, the short-circuit characteristic, the air gap line, and the modified air gap line.

(b) Determine the unsaturated and saturated values of the synchronous reactance in ohms and also in pu.

(c) Find the field current required if the synchronous machine is to deliver 100 MVA at rated voltage, at 0.8 leading power factor.

Solution



(b) $V_b = \dfrac{15\times10^3}{\sqrt{3}} = 8660.5\ V$

$I_b = \dfrac{195\times10^6}{\sqrt{3}\times15\times10^3} = 7505.8\ A$

$Z_b = \dfrac{8660.5}{7505.8} = 1.1538\ \Omega$

$X_s|_{unsat} = \dfrac{18.75\times10^3}{\sqrt{3}\times7000} = 1.5465\ \Omega$

$= \dfrac{1.5465}{1.1538} = 1.3404$ p.u.

$X_s|_{sat} = \dfrac{15\times10^3}{\sqrt{3}\times700} = 1.2372\ \Omega \rightarrow 1.0723$ p.u

(c) $I_a = \dfrac{100}{195}\angle\cos^{-1}0.8 = 0.5128\angle36.87^\circ$ p.u.

$E_f = 1\angle0^\circ + 0.5128\angle36.87 \times 1.0723\angle90$

$= 0.8016\angle33.3^\circ$ p.u.

$I_f = 0.8016 \times 750 = 601.2\ A$

Problem 3

A 3-phase, 120 MVA, 13.8 kV, 0.8 PF lagging, 60 Hz and Y-connected synchronous generator has synchronous reactance of 1.2 Ω per phase, and its armature resistance is 0.1 Ω per phase.

(a) Determine the voltage regulation,

(b) Determine the voltage and apparanet power rating if this generator is operated at 50 Hz with the same armature and field losses at it had at 60 Hz,

(c) Determine the voltage regulation of this generator at 50 Hz.

Solution

$$I_A = I_L = \frac{S}{\sqrt{3}\ V_T} = \frac{120\text{ MVA}}{\sqrt{3}(13.8\text{ kV})} = 5020\text{ A}$$

The power factor is 0.8 lagging, so $\mathbf{I}_A = 5020\angle -36.87°\text{ A}$. The phase voltage is 13.8 kV / $\sqrt{3}$ = 7967 V. Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$\mathbf{E}_A = 7967\angle 0° + (0.1\ \Omega)(5020\angle -36.87°\text{ A}) + j(1.2\ \Omega)(5020\angle -36.87°\text{ A})$$

$$\mathbf{E}_A = 12{,}800\angle 20.7°\text{ V}$$

The resulting voltage regulation is

$$\text{VR} = \frac{12{,}800 - 7967}{7967} \times 100\% = 60.7\%$$

(b) If the generator is to be operated at 50 Hz with the same armature and field losses as at 60 Hz (so that the windings do not overheat), then its armature and field currents must not change. Since the voltage of the generator is directly proportional to the speed of the generator, the voltage rating (and hence the apparent power rating) of the generator will be reduced by a factor of 5/6.

$$V_{T,\text{rated}} = \frac{5}{6}(13.8\text{ kV}) = 11.5\text{ kV}$$

$$S_{\text{rated}} = \frac{5}{6}(120\text{ MVA}) = 100\text{ MVA}$$

Also, the synchronous reactance will be reduced by a factor of 5/6.

$$X_S = \frac{5}{6}(1.2\ \Omega) = 1.00\ \Omega$$

(c) At 50 Hz rated conditions, the armature current would be

$$I_A = I_L = \frac{S}{\sqrt{3}\ V_T} = \frac{100\text{ MVA}}{\sqrt{3}(11.5\text{ kV})} = 5020\text{ A}$$

The power factor is 0.8 lagging, so $\mathbf{I}_A = 5020\angle -36.87°\text{ A}$. The phase voltage is 11.5 kV / $\sqrt{3}$ = 6640 V. Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi + R_A\mathbf{I}_A + jX_S\mathbf{I}_A$$

$$\mathbf{E}_A = 6640\angle 0° + (0.1\ \Omega)(5020\angle -36.87°\text{ A}) + j(1.0\ \Omega)(5020\angle -36.87°\text{ A})$$

$$\mathbf{E}_A = 10{,}300\angle 18.8°\text{ V}$$

The resulting voltage regulation is

$$\text{VR} = \frac{10{,}300 - 6640}{6640} \times 100\% = 55.1\%$$

Problem 4

A 3-phase, 5 kVA, 208 V, four-pole, 60 Hz, star-connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 8 Ω per phase at rated terminal voltage. This synchronous machine is operated as a synchronous motor from the 3-phase, 208 V, 60 Hz power supply. The field excitation is adjusted so that the power factor is unity when the machine draws 3 kW from the supply.

(a) Find the excitation voltage and the power angle. Draw the phasor diagram for this condition,

(b) If the field excitation is held constant and the shaft load is slowly increased, determine the maximum torque (i.e., pull-out torque) that the motor can deliver.

Solution

The per-phase equivalent circuit for motoring operation is shown in Fig. 1 (a).

(a) $3V_tI_a\cos\phi = 3\text{ kW} = 3V_tI_a$ for $\cos\phi = 1$.

$$I_a = \frac{3000}{3\times 120} = 8.33\text{ A}$$

$$\begin{aligned} E_f &= V_t - I_a jX_s \\ &= 120\angle 0^\circ - 8.33\angle 0^\circ \cdot 8\angle 90^\circ \\ &= 137.35\angle -29^\circ \end{aligned}$$

Excitation voltage $E_f = 137.35$ V/phase
Power angle $\delta = -29^\circ$

Note that because of motor action, the power angle is negative.

The phasor diagram is shown in Fig. 1 (b). E_f and δ can also be calculated from the phasor diagram.

$$\begin{aligned} E_f &= \sqrt{|V_t|^2 + |I_aX_s|^2} = \sqrt{120^2 + (8.33\times 8)^2} \\ &= 137.35\text{ V/phase} \end{aligned}$$

$$\tan\delta = \frac{|I_aX_s|}{|V_t|} = \frac{8.33\times 8}{120} = 0.555$$

$$|\delta| = 29^\circ$$

$$\delta = -29^\circ$$

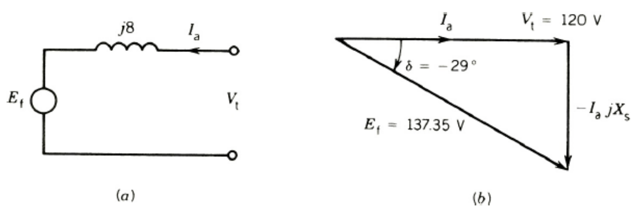


Figure 1: Solution 1.

(b)

Maximum torque will be developed at $\delta = 90^o$, and since $P_{max} = \dfrac{3|V_t||E_f|}{|X_s|}$

Therefore, P_{max} = $\dfrac{3 \times 137.35 \times 120}{8}$, and

$T_{max} = \dfrac{P_{max}}{\omega_{syn}} = \dfrac{6180.75}{1800/60 \times 2\pi} = 32.8$ N. m

Problem 5

A 230 V, 50 Hz, two-pole,synchronous motor draws 40 A from the line at unity power factor and full load. Determine the following assuming that the motor is lossless:

(a) Output torque of the motor,

(b) What should be done to change the power factor to 0.85 leading,

(c) Magnitude of the line current if the power factor is adjusted to 0.85 leading.

Solution

(a) If this motor is assumed lossless, then the input power is equal to the output power. The input power to this motor is

$$P_{IN} = \sqrt{3} V_T I_L \cos\theta = \sqrt{3}(230\text{ V})(40\text{ A})(1.0) = 15.93\text{ kW}$$

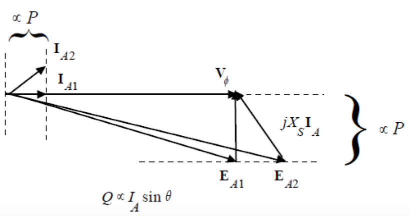
The rotational speed of the motor is

$$n_m = \frac{120 f_{se}}{P} = \frac{120(50\text{ Hz})}{4} = 1500\text{ r/min}$$

The output torque would be

$$\tau_{LOAD} = \frac{P_{OUT}}{\omega_m} = \frac{15.93\text{ kW}}{(1500\text{ r/min})\left(\frac{1\text{ min}}{60\text{ s}}\right)\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)} = 101.4\text{ N}\cdot\text{m}$$

(b) To change the motor's power factor to 0.8 leading, its field current must be increased. Since the power supplied to the load is independent of the field current level, an increase in field current increases $|\mathbf{E}_A|$ while keeping the distance $E_A \sin\delta$ constant. This increase in E_A changes the angle of the current $\mathbf{I}_A$, eventually causing it to reach a power factor of 0.8 leading.



(c) The magnitude of the line current will be

$$I_L = \frac{P}{\sqrt{3}\, V_T\, \text{PF}} = \frac{15.93\text{ kW}}{\sqrt{3}(230\text{ V})(0.8)} = 50.0\text{ A}$$

Problem 6

A 3-phase synchronous motor is installed to provide 300 hp to a new industrial process with the following loads:

Induction motors: 1000 hp; 0.7 average power factor; 0.85 average efficiency, and

Lighting and heating load: 100 kW

If the installed synchronous motor operates at 92% efficiency, determine the following:

(a) The kVA rating of the synchronous motor if the overall factory power factor is to be raised to 0.95,

(b) The power factor of the synchronous motor.

Solution

Induction Motor (IM), Lighting and Heating (LH), Synchronous Motor (SM)

$P_{IM} = \frac{1000 \times 746}{0.85} = 877.6471 \text{ KW}$ $\quad S_{IM} = \frac{P_{IM}}{0.7} = 1253.7815 \text{ KVA}$

$Q_{IM} = S_{IM} \sin(\cos^{-1} 0.7) = 895.3791 \text{ KVAR}$

Lighting and heating load (LH)

$P_{LH} = 100 \text{ KW} \qquad Q_{LH} = 0$

Synchronous motor (SM)

$P_{SM} = 300 \times 746 = 223.8 \text{ KW}$

Factory Power

$P_F = 877.6471 + 100 + 223.8 = 1201.45 \text{ KW}$

$PF_F = 0.95 \qquad S_F = \frac{1201.45}{0.95} = 1264.68 \text{ KVA}$

$Q_F = 1264.68 \sin(\cos^{-1} 0.95) = 394.9 \text{ KVAR}$

Sychronous motor has to provide

$Q_{SM} = 895.3791 - 394.9 = 500.48 \text{ KVAR}$

$S_{SM} = \sqrt{223.8^2 + 500.48^2} = 548.24 \text{ KVA}$

$PF_{SM} = \cos\left(\tan^{-1} \frac{500.48}{223.8}\right) = 0.4082 \text{ (leading)}$

!End of Homework Solutions!