

EE3124 Assignment 2 (Solution)

Name:

Student No.:

Q1 – Specify the differences between Synchronous Motor and Asynchronous (Induction) Motor. (5 pts)

Solution: (Any 5 will be marked full point.)

Synchronous Motor	Asynchronous (Induction) Motor
Runs at synchronous speed	Runs on speed less than the synchronous speed
No slip i.e. the slip of synchronous motor is equal to 0	Slip in induction motor and it is always greater than 0
The speed of the motor depends on the supply frequency and the number of stator poles. $N_s = 120f / P$	The speed of the motor depends on the load, rotor resistance and the slip, s. it is always less than synchronous speed.
It is not self-start and require extra windings for starting the motor	Asynchronous motors are self-start and do not require extra mechanism.
Separately excited synchronous motor requires extra DC source to energize its rotor winding.	It does not require any extra source.
The fluctuations in the main supply voltage do not affect synchronous motor operation.	The mains voltage fluctuation affects its speed and operation.
Its operation is complicated.	Its operation is simple and user friendly.
By changing excitation the power factor can be adjusted accordingly as lagging, leading or unity.	Asynchronous motor runs only at a lagging power factor.

Q2 – How many major starting techniques for the starting single phase induction motors? And briefly explain the reason why the capacitor start and run motors can help to produce the start torque. (5 pts)

Solution

The three major starting techniques are

- Split-phase windings
- Capacitor-type windings
- Shaded stator poles

In a capacitor-start motor, a capacitor is placed in series with the auxiliary winding of the motor. By proper selection of capacitor size, the magnetomotive force of the starting current in the auxiliary winding can be adjusted to be equal to the magnetomotive force of the current in the main winding, and the phase angle of the current in the auxiliary winding can be made to lead the current in the main winding by 90° . Thus, the rotating magnetic field will be produced as well as the starting torque.

Q3 – A 230-V, 50 Hz, two-pole synchronous motor draws 40 A from the line at unity power factor and full load. Assuming that the motor is lossless, answer the following questions:

- What is the output torque of this motor? Express the answer in newton-meters. (4 pts)
- What must be done to change the power factor to 0.85 leading? Explain your answer, using phasor diagrams. (4 pts)
- What will the magnitude of the line current be if the power factor is adjusted to 0.85 leading? (2 pts)

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

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

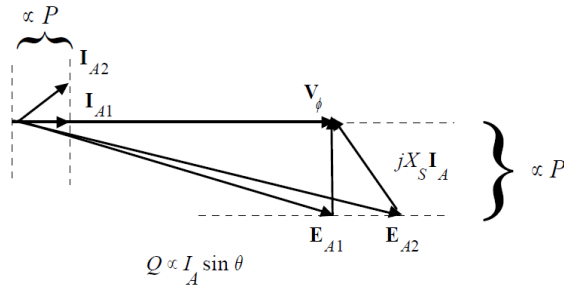
The rotational speed of the motor is

$$n_m = \frac{120 f_{se}}{P} = \frac{120(50 \text{ Hz})}{2} = 3000 \text{ rpm}$$

The output torque would be

$$\tau_{LOAD} = \frac{P_{OUT}}{\omega_m} = \frac{15.93 \text{ kW}}{(3000 \text{ rpm}) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right)} = 50.7 \text{ Nm}$$

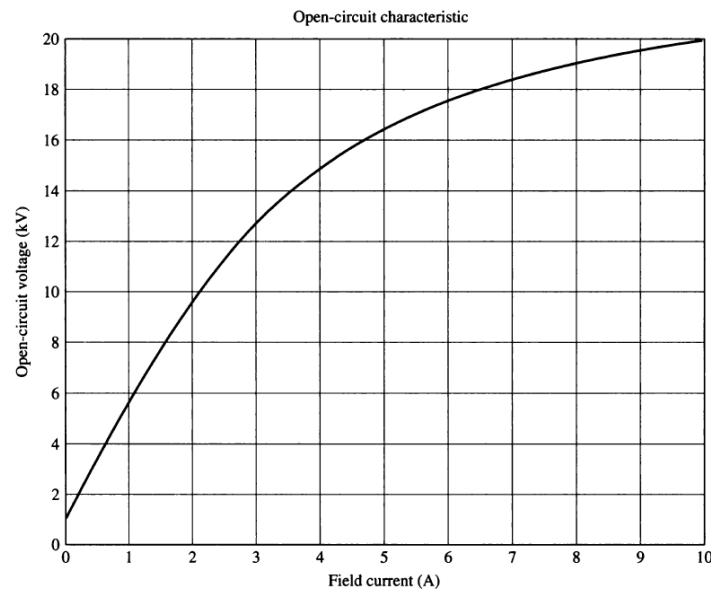
(b) To change the motor's power factor to 0.85 leading, its field current must be increased. Since the power supplied to the load is independent of the field current level, an increase in field current increases $|E_A|$ while keeping the distance $E_A \sin \delta$ constant. This increase in E_A changes the angle of the current I_A , eventually causing it to reach a power factor of 0.85 leading.



(c) The magnitude of the line current will be

$$I_L = \frac{P}{\sqrt{3} V_T \text{PF}} = \frac{15.93 \text{ kW}}{\sqrt{3} (230 \text{ V}) 0.85} = 47.04 \text{ A}$$

Q4 - A 13.8-kV, 50-MVA, 0.9-power-factor-lagging, 60-Hz, four-pole Y-connected synchronous generator has a synchronous reactance of 2.5Ω and an armature resistance of 0.2Ω . At 60 Hz, its friction and windage losses are 1 MW, and its core losses are 1.5 MW. The field circuit has a DC voltage of 120 V, and the maximum I_F is 10 A. The current of the field circuit is adjustable over the range from 0 to 10 A. The OCC of this generator is shown as follows. (30 pts)



- How much field current is required to make the terminal voltage V_T (or line voltage V_L) equal to 13.8 kV when the generator is running at no load?
- What is the internal generated voltage E_A of this machine at rated conditions?
- What is the phase voltage V_ϕ of this generator at rated conditions?
- How much field current is required to make the terminal voltage V_T equal to 13.8 kV when the generator is running at rated conditions?

- (e) Suppose that this generator is running at rated conditions, and then the load is removed without changing the field current. What would the terminal voltage of the generator be?
- (f) How much steady-state power and torque must the generator's prime mover be capable of supplying to handle the rated conditions?

Solution

(a) If the no-load terminal voltage is 13.8 kV, the required field current can be read directly from the open-circuit characteristic. It is 3.50 A.

(b) This generator is Y-connected, so $I_L = I_A$. At rated conditions, the line and phase current in this generator is

$$I_A = I_L = \frac{P}{\sqrt{3} V_L} = \frac{50 \text{ MVA}}{\sqrt{3} (13800 \text{ V})} = 2092 \text{ A at an angle of } -25.8^\circ$$

The phase voltage of this machine is $V_\phi = V_T / \sqrt{3} = 7967 \text{ V}$. The internal generated voltage of the machine is

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

$$\mathbf{E}_A = 7967 \angle 0^\circ + (0.20 \Omega)(2092 \angle -25.8^\circ \text{ A}) + j(2.5 \Omega)(2092 \angle -25.8^\circ \text{ A})$$

$$\mathbf{E}_A = 11544 \angle 23.1^\circ \text{ V}$$

(c) The phase voltage of the machine at rated conditions is $V_\phi = 7967 \text{ V}$

From the OCC, the required field current is 10 A.

(d) The equivalent open-circuit terminal voltage corresponding to an E_A of 11544 volts is

$$V_{T,oc} = \sqrt{3} (11544 \text{ V}) = 20 \text{ kV}$$

From the OCC, the required field current is 10 A.

(e) If the load is removed without changing the field current, $V_\phi = E_A = 11544 \text{ V}$. The corresponding terminal voltage would be 20 kV.

(f) The input power to this generator is equal to the output power plus losses. The rated output power is

$$P_{OUT} = (50 \text{ MVA})(0.9) = 45 \text{ MW}$$

$$P_{CU} = 3I_A^2 R_A = 3(2092 \text{ A})^2 (0.2 \Omega) = 2.6 \text{ MW}$$

$$P_{F\&W} = 1 \text{ MW}$$

$$P_{core} = 1.5 \text{ MW}$$

$$P_{stray} = (\text{assumed } 0)$$

$$P_{IN} = P_{OUT} + P_{CU} + P_{F\&W} + P_{core} + P_{stray} = 50.1 \text{ MW}$$

Therefore the prime mover must be capable of supplying 50.1 MW. Since the generator is a four-pole 60 Hz machine, to must be turning at 1800 r/min. The required torque is

$$\tau_{APP} = \frac{P_{IN}}{\omega_m} = \frac{50.1 \text{ MW}}{(1800 \text{ r/min}) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right)} = 265,800 \text{ N} \cdot \text{m}$$

Q5 - A 480-V, 60 Hz, 298.4 Kw, 0.8-PF-leading eight-pole Δ -connected synchronous motor has a synchronous reactance of 0.6Ω and negligible armature resistance. Ignore its friction, windage, and core losses for the purposes of this problem. Assume that $|\mathbf{E}_A|$ is directly proportional to the field current I_F (in other words, assume that the motor operates in the linear part of the magnetization curve), and that $\mathbf{E}_A = 480 \text{ V}$ when $I_F = 4 \text{ A}$. When the motor is operating at rated conditions. (20 pts)

(a) What are the magnitudes and angles of E_A , I_A and I_F ?

(b) Suppose the load is removed from the motor. What are the magnitudes and angles of E_A , I_A now?

Solution

(a) The line current flow at rated conditions is

$$I_L = \frac{P}{\sqrt{3} V_T \text{PF}} = \frac{298.4 \text{ kW}}{\sqrt{3} (480 \text{ V})(0.8)} = 449 \text{ A}$$

Because the motor is Δ -connected, the corresponding phase current is $I_A = 449/\sqrt{3} = 259 \text{ A}$. The angle of the current is $\cos^{-1}(0.80) = 36.87^\circ$, so $\mathbf{I}_A = 259 \angle 36.87^\circ \text{ A}$. The internal generated voltage $\mathbf{E}_A$ is

$$\mathbf{E}_A = \mathbf{V}_\phi - jX_s \mathbf{I}_A$$

$$\mathbf{E}_A = (480 \angle 0^\circ \text{ V}) - j(0.6 \Omega)(259 \angle 36.87^\circ \text{ A}) = 587 \angle -12.2^\circ \text{ V}$$

The field current is directly proportional to $|\mathbf{E}_A|$, with 480 V when $I_F = 4 \text{ A}$. Since the real $|\mathbf{E}_A|$ is 587 V , the required field current is

$$\frac{|\mathbf{E}_{A2}|}{|\mathbf{E}_{A1}|} = \frac{I_{F2}}{I_{F1}}$$

$$I_{F2} = \frac{|\mathbf{E}_{A2}|}{|\mathbf{E}_{A1}|} I_{F1} = \frac{587 \text{ V}}{480 \text{ V}} (4 \text{ A}) = 4.89 \text{ A}$$

(b) When the load is removed from the motor the magnitude of $|\mathbf{E}_A|$ remains unchanged but the torque angle goes to $\delta = 0^\circ$. The resulting armature current is

$$\mathbf{I}_A = \frac{\mathbf{V}_\phi - \mathbf{E}_A}{jX_s} = \frac{480 \angle 0^\circ \text{ V} - 587 \angle 0^\circ}{j0.6 \Omega} = 178.3 \angle 90^\circ \text{ A}$$

Q6 - A 208-V four-pole 60-Hz Y-connected wound-rotor induction motor is rated at 30 hp. Its equivalent circuit components are

$$R_1 = 0.100 \quad R_2 = 0.070 \quad X_M = 10.0$$

$$X_1 = 0.210 \quad X_2 = 0.210$$

$$P_{\text{mech}} = 500 \text{ W} \quad P_{\text{core}} = 400 \text{ W} \quad P_{\text{misc}} \approx 0$$

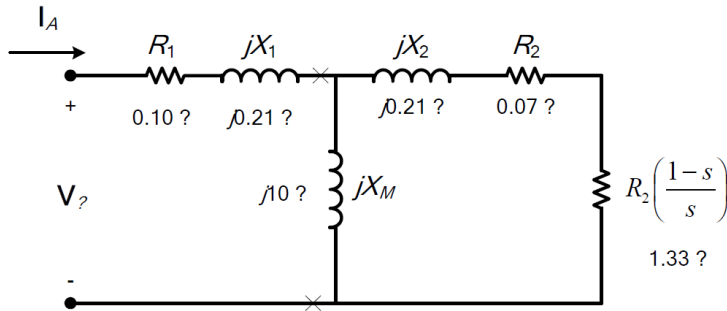
For a slip of 0.05, find

(a) The line current I_L (5 pts)

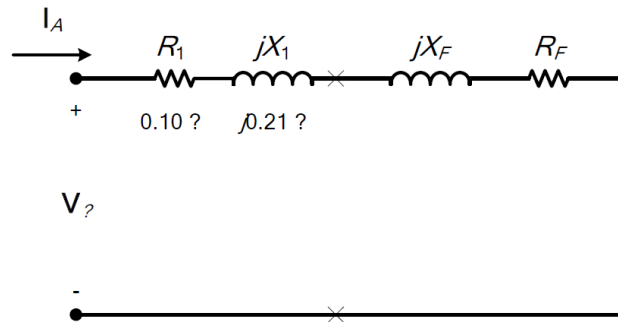
- (b) The stator copper losses P_{SCL} (5 pts)
 - (c) The air-gap power P_{AG} (5 pts)
 - (d) The power converted from electrical to mechanical form P_{conv} (5 pts)
 - (e) The induced torque τ_{ind} (5 pts)
 - (f) The load torque τ_{load} (5 pts)
 - (g) The overall machine efficiency (5 pts)
 - (h) The motor speed in revolutions per minute and radians per second. (5 pts)
- (Any correct 6 answers will have full score) (30 pts)

Solution

The equivalent circuit of this induction motor is shown below:



(a) The easiest way to find the line current (or armature current) is to get the equivalent impedance Z_F of the rotor circuit in parallel with jX_M , and then calculate the current as the phase voltage divided by the sum of the series impedances, as shown below.



The equivalent impedance of the rotor circuit in parallel with jX_M is:

$$Z_F = \frac{1}{\frac{1}{jX_M} + \frac{1}{Z_2}} = \frac{1}{\frac{1}{j10 \Omega} + \frac{1}{1.40 + j0.21}} = 1.318 + j0.386 = 1.374 \angle 16.3^\circ \Omega$$

The phase voltage is $208/\sqrt{3} = 120$ V, so line current I_L is

$$I_L = I_A = \frac{V_\phi}{R_1 + jX_1 + R_F + jX_F} = \frac{120 \angle 0^\circ \text{ V}}{0.10 \Omega + j0.21 \Omega + 1.318 \Omega + j0.386 \Omega}$$

$$I_L = I_A = 78.0 \angle -22.8^\circ \text{ A}$$

(b) The stator copper losses are

$$P_{SCL} = 3I_A^2 R_1 = 3(78.0 \text{ A})^2 (0.10 \Omega) = 1825 \text{ W}$$

(c) The air-gap P_{AG}

$$P_{AG} = P_{in} - P_{SCL} - P_{core} = \sqrt{3} \times V_L \times I_L \times \cos(-22.8^\circ) - 1825 - 400 = 23.68 \text{ kW}$$

(d) The power converted from electrical to mechanical form is

$$P_{conv} = (1 - s) P_{AG} = (1 - 0.05) 23.68 \text{ kW} = 22.5 \text{ kW}$$

(e) The induced torque in the motor is

$$\tau_{ind} = \frac{P_{AG}}{\omega_{sync}} = \frac{23.68 \text{ kW}}{(1800 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)} = 125.6 \text{ Nm}$$

(f) The output power of this motor is

$$P_{OUT} = P_{conv} - P_{mech} - P_{misc} = 22.5 - 0.5 - 0 \text{ kW} = 22.0 \text{ kW}$$

The output speed is

$$n_m = (1 - s) n_{sync} = (1 - 0.05)(1800 \text{ r/min}) = 1710 \text{ r/min}$$

Therefore the load torque is

$$\tau_{load} = \frac{P_{OUT}}{\omega_m} = \frac{22.0 \text{ kW}}{(1710 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right)} = 122.9 \text{ Nm}$$

(g) The overall efficiency is

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100\% = \frac{P_{OUT}}{3V_\phi I_A \cos \theta} \times 100\%$$

$$\eta = \frac{22.0 \text{ kW}}{3(120 \text{ V})(78.0 \text{ A}) \cos 22.8^\circ} \times 100\% = 84.9 \%$$

(h) The motor speed in revolutions per minute is 1710 r/min. The motor speed in radians per second is

$$\omega_m = (1710 \text{ r/min}) \left(\frac{2\pi \text{ rad}}{1 \text{ r}} \right) \left(\frac{1 \text{ min}}{60 \text{ s}} \right) = 179 \text{ rad/s}$$