Tutorial 3: Synchronous Motor Drive

1. A 300 kW, 6600 V, 8-pole, 50 Hz, three-phase, Y-connected, non-salient pole (i.e., cylindrical rotor) synchronous motor has the following parameters:

   $X_s = 72\ \Omega$/phase at 50 Hz, $R \approx 0\ \Omega$/phase for operation near base speed,
   and $E_{fb} = 3200$ V/phase at base speed.

   (i) What is the base speed of the motor in mechanical rad/sec and rev/min?

   (ii) Calculate the load angle δ of the motor when it delivers rated load at base speed.

   (iii) Calculate the motor input current (I) and power factor (PF) of the drive for this condition of operation.

   (iv) Calculate the maximum power and torque the motor is capable of developing while running at base speed.

   [ω_{b} = 78.5 mech rad/sec, 750 rev/min, δ = 36.2°, I = 31.33 A rms,
   PF = 0.84 lagging, P_{max} = 508 kW, T_{max} = 6,471 Nm]

2. For the motor of problem 1, the rotor excitation is adjusted such that the drive now operates at unity power factor while delivering rated power at base speed.

   (i) Calculate the motor input current I and load angle δ for this condition of operation.

   (ii) Calculate the back emf of the motor per phase.

   (iii) Calculate the maximum power and torque the motor is capable of developing while running at base speed.

   [= 26.25 A rms, δ = 26.38°, E_{fb} = 4,253.6 V rms/phase,
   P_{max} = 675.44 kW, T_{max} = 8,602 Nm]

3. Repeat problem 2 if the rotor excitation of the motor is further adjusted to operate it at 0.8 power factor leading, while developing rated power at base speed.

   [I = 32.81A, δ = 19.87°, E_{fb} = 5,558 V rms/phase,
   P_{max} = 882.34 kW, T_{max} = 11,239 Nm]

4. A 4-pole, 3-phase, 50 Hz, Y-connected, non-salient pole synchronous motor has the following parameters:

   $R = 1.5\ \Omega$/phase; $X_{sb} = 15\ \Omega$/phase at base speed.
   The motor (excitation) induced emf/phase at 1500 rev/min is 200 V rms.
   V_{rated} = 230 V rms/phase; I_{rated} = 15 A rms/phase.

   The motor is driven from a voltage source inverter the rms output voltage of which is proportional to frequency (i.e., constant V/f drive). If the stator resistance R is neglected,

   (i) find the load angles δ when the motor develops its maximum torque while running at the base speed and at 750 rev/min and 250 rev/min?

   [δ_{max} = 90° at all speeds]

(ii) find the maximum torque that the motor can develop at these three speeds.

[T_{max} = 58.6 Nm at all speeds]

5. For the motor of problem 4, calculate the maximum torque the motor will be capable of developing at 250 rev/min, this time including the effect of stator resistance.

[T_{max} = 27.87 Nm]

6. A 4-pole, 3-phase, 50 Hz, Y-connected, salient-pole synchronous motor with permanent magnet excitation has the following parameters:

$$X_d = 7.5\ \Omega/\text{phase @ 50 Hz};\ X_q = 15.7\ \Omega/\text{phase @ 50 Hz};$$
$$R \approx 0\ \Omega/\text{phase near base speed.}$$

The stator induced voltage (emf)/phase is found to be 150 V rms, when the motor runs at 1200 rev/min.

The motor is driven from a voltage source inverter. The inverter switching control is such that the motor load angle δ is restrained to 120°. The rms inverter output voltage is proportional to frequency (i.e., constant V/f control is applied). It supplies 200V rms, to the motor at 50 Hz.

Calculate the maximum torque the motor will develop while running at a speed of 1200 rev/min. [T_{max} = 105.57 Nm]

7. A 4-pole 3-phase, 50 Hz, Y-connected, non-salient pole synchronous motor has the following parameters:

$$R = 1.5\ \Omega/\text{phase};\ X_{so} = 15\ \Omega/\text{phase @ 50 Hz}$$
The motor induced emf/phase at base speed, E_{fo}, is 200 V.
$$V_{rated} = 230\ \text{V/phase};\ I_{rated} = 15\ \text{A/phase.}$$

The motor is driven from a current source inverter which supplies three-phase sinusoidal currents of variable frequency to the motor. The switching of the inverter is synchronized with rotor position in such a way that the stator current phasor of each phase can be set at any arbitrary phase angle γ, (also known as the commutation angle), with respect to the back emf phasor E_{fo} of the corresponding phase.

(i) Assuming that the motor is to be driven such that it develops its highest torque per ampere (MTPA) characteristic, calculate the amplitude of the stator current when the motor develops 60 Nm while operating at 750 rev/min.

[I_m = 22.2 A]

(ii) Calculate the power developed by the motor for this condition of operation.

[P = 4,710 W]

(iii) Calculate the power factor with which the motor will operate.

[Ans: PF = 0.724, lagging]

(iv) In order to improve the power factor of the drive, the commutation angle γ of the stator current is advanced by 30°. In other words, the I phasor is set at 30° of lead angle with respect to the E_f phasor. Calculate the stator current amplitude when the motor develops 60 Nm while operating at 750 rev/min.

[I_m = 25.65 A]

(v) Calculate the new power factor with which the motor will operate.

[PF = 0.798, lagging]

8. A 1500 kW, 3300 V, 4-pole 3-phase, 50 Hz, Y-connected, non-salient pole synchronous motor is driven from a current source thyristor inverter as shown in figure 8(a). The inverter has dc link current control, making the current supply stiff. The three-phase current waveforms in the motor are quasi-square, with 120° of conduction followed by 60° of non-conduction in each half cycle, as indicated in the figure Q8(b). The inverter is switched in synchronism with the rotor position such that the phase current waveforms are in phase with the back emf waveforms of each phase (i.e., maximum torque per ampere drive).

The motor develops a back emf (E_f) of 2000 Volts/phase when driven at the base speed. Assuming that the amplitude of the fundamental of a quasi-square waveform of 120° of conduction angle in each half cycle is equal to the amplitude of the quasi-square wave, calculate the dc link current of the inverter when the motor drives rated load at base speed.

[I_d = 353.46 A]

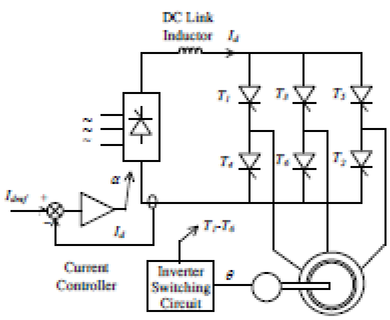

Figure Q8(a)

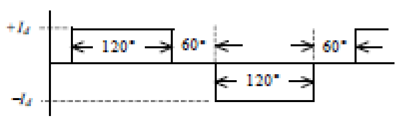

Figure Q8(b) Phase current waveform