Tutorial 4 - Variable-Speed Induction Motor Drives

1. A Y-connected three-phase, 415V, 200kW, 50Hz, 8-pole wound–rotor induction motor controls the speed of a pump. Its speed is controlled with variable rotor resistance. The torque required by the pump varies as the square of its speed. At full load, the motor operates with slip $s = 0.03$ with the slip rings short circuited. The slip-torque relationship of the motor can be assumed to be linear from no-load to full-load. The resistance R_2' of each phase of the rotor is 0.02Ω.

   (i) Find the value of the additional rotor resistance that must added to the rotor per-phase so that the motor runs at 600 rev/min.

   [0.176Ω]

   (ii) Find the value of the resistance to be added to each phase of the rotor if the motor is to develop its rated torque at start. You may neglect the stator impedance and the rotor leakage reactance for this calculation.

   [0.815Ω]

2. A Y-connected three-phase, 415V, 150kW, 50Hz, 4-pole wound–rotor induction motor controls the speed of a pump. It is driven with a slip power recovery (static Scherbius) scheme. The turns-ratio between the stator and rotor windings of the motor and the secondary to primary winding of the transformer connected between the rotor circuit and the AC mains are the same, i.e., $a = n$.

   (i) Find the firing angle α of the fully-controlled thyristor converter when the motor runs at 1200 rev/min and develops full load.

   [101.53°]

   (ii) Find the firing angle α of the thyristor converter when the motor runs at 1000 rev/min.

   [109.47°]

3. A Y-connected three-phase, 415V, 1460 rev/min, 50 Hz, 4-pole induction motor has the following parameters:

$$R_1 = 0.25\,\Omega, \qquad R_2' = 0.22\,\Omega$$

$$X_1 = X_2' = 0.42\,\Omega \qquad X_m = 4.3\,\Omega$$

   Use the Thevenin's equivalent representation and assume that $X_m >> (R_1 \text{ and } X_1)$, $R_{Th} \approx R_1$, and $X_{Th} \approx X_1$.

(i) The motor is driven with variable voltage in order to adjust its speed. Find the slip at which maximum torque will be developed if the motor is operated with rated voltage at 50 Hz. Recall that the slip at which maximum torque occurs is given by

$$s_{mT} = \frac{R_2^{'}}{\sqrt{\left[R_{th}^{'2} + \left(X_{th} + X_2^{'}\right)^2\right]}}$$

[0.251]

When the motor is supplied from a 3-phase 415V, 50Hz AC source

(ii) find the maximum developed torque, and the speed at which it is developed

[T_{max} = 486.94 Nm, 1123.5 rpm]

(iii) find the rotor current of the motor, referred to the stator, at start. [248.9A]

(iv) Find the rated rotor current, rotor power loss, rotor efficiency and developed torque of the machine if it runs with a slip of 0.055 when rated load is supplied.

[I_2 = 55.33 A, P_{sl} = 2,021 W, P_o/P_2 = 94.49%, T_{dev} = 233.74 Nm]

(v) Find the rotor power loss and efficiency when the motor operates with maximum developed torque. Compare the efficiencies for the two conditions.

[P_L = 20,335 W, 74.9%]

When the motor is supplied at half the rated voltage (207.5V RMS l-l) at 50Hz,

(vi) find the maximum developed torque, and the speed at which it is developed.

[121.67 Nm, 1123.5 rpm]

(vii) Find the rotor current of the motor, referred to the stator, at start. [124.7A]

(viii) Find the rotor power loss, and rotor efficiency when the rotor develops its maximum torque T_{max}.

[4798.5 W, 74.89%]

4. Operation of an induction machine with reduced stator voltage in order to reduce the develop torque and run the load at a lower speed, as in part (vi-viii) of question 3, results in operation with high slip. Note that operation with high slip results in high power loss in the rotor and inefficient operation. A VVVF controlled inverter can prevent such high-slip operation while developing the high torque that can be obtained at rated voltage and frequency, as shown in Question 3 (i-iii). Consider the motor of question 3, which is now driven by a VVVF controlled inverter. It is now required to develop **121.67** Nm at **1123.5** rpm (*i.e., the maximum torque and speed as in part (vi) of Question 3, corresponding to 0.5pu voltage, 50Hz operation with high slip of* s_{mT}), but now with a much reduced slip with a VVVF drive.

(i) Find the slip s, input frequency f_1 and input voltage V_1 for the VVVF drive.

[s = 0.0344, f_1 = 38.78 Hz, V_1=185.8 V]

(ii) Find the slip s at which the maximum torque will be developed if the motor is operated by a VVVF voltage source inverter drive (V-f) assuming that the air-gap flux remains constant.

[0.315]

(iii) Find the maximum torque the motor will develop with this type of drive.

[486.94Nm]

(iv) Find the starting frequency if the motor must be started with the maximum possible torque.

[26.19 Hz]

5. The motor of question 3 is supplied from a VVVF inverter with constant V/f ratio (for constant air gap flux).

(i) find the slip at which maximum torques will occur when supply frequency to the motor is 10 Hz and 5 Hz.

[0.73; 0.834]

(ii) find the maximum torque that it will develop with the V-f drive when it is operated at (a) 10 Hz and (b) 5 Hz. You may assume that $V_{Th} \approx V_1$, $R_{Th} \approx R_1$, and $X_{Th} \approx X_1$ at these input frequencies.

[(a) 195.2 Nm; (b) 106.24 Nm]

(iii) compare these maximum torque values with the T_{max} obtained with rated voltage and frequency.

[T_{max} at 10 and 5 Hz are considerably lower than 486.94 Nm for base conditions]

6. A three-phase, 415V (RMS), 50Hz, 4-pole induction motor has following parameters:

$$R_1 = 1.54\Omega, \quad L_1 = 0.01155\text{ H}, \quad L_m = 0.125\text{ H}$$

$$R_2' = 2.7\Omega, \quad L_2' = 0.01155\text{ H}.$$

The motor is supplied from a three-phase PWM V/f VSI. You may assume that the inverter supplies RMS output voltage which is proportional to supply frequency up to the base frequency f_0 = 50Hz. For $f_1 > f_0$, V_1 remains constant at V_0 (the rated stator voltage/phase).

(i) When the motor is operated at base frequency, the operating slip with rated load is 0.055. Calculate the developed total developed torque, rotor power (P_2), rotor power loss (P_{rl}) and rotor efficiency for this operating condition. You may ignore the stator parameters R_1 and L_1 for operation near and above base speed.

[T_{dev} = 22.21Nm, P_2 = 3295 W, P_{rl} = 191.87 W, Rotor efficiency = 94%]

(ii) Calculate the maximum torque which the drive will develop at base frequency and the corresponding rotor current I_2'. At what slip and speed does will this torque develop?

[s_{mT} = 0.744, I_2' =46.68 A, T_{max} = 150.5 Nm, Speed when T_{max} occurs = 384 rpm]

(iii) Calculate the developed rotor power (P_2), rotor power loss (P_{sl}) and rotor efficiency for the operating condition of (ii).

[P_2 = 23722 W, P_{sl} = 17650 W, Rotor efficiency at T_{max} = 25.6%]

(iv) The motor is operated with stator frequency which is 1.6 times the base frequency. The stator input voltage per phase is limited to the rated value (leading to operation with field weakening). Calculate the maximum torque that the drive will develop and the operating speed for this condition of operation.

[T_{max} = 58.96, s_{mT} = 0.465, Speed at which T_{max} is developed = 1284 rpm]

(v) Calculate I_2', the developed rotor power (P_2), rotor power loss (P_{sl}) and rotor efficiency for the operating condition of (iv).

[I_2' =29.16 A, P_2 = 14812 W, P_{sl} = 6887 W, Rotor efficiency = 53.5%]

(vi) Comment on the losses, rotor efficiency of the drive for the three operating conditions. Also comment on the constant-power capability of the drive when operated at higher than base speed.

[The rotor power loss is much higher than for rated condition of operation. The motor develops lower torque at higher speed, resulting in a constant-power like characteristic which is suitable for traction drives]

7. The motor of question 3 is driven with a current-source inverter which delivers regulated 3-phase sinusoidal currents of arbitrary amplitude and frequency.

(i) Find the slip s at which maximum torque will be developed if the motor is operated at base frequency f_o (50 Hz)

[0.0466]

(ii) Find the maximum torque the motor will develop at 50 Hz, assuming that slip frequency and the supply current are so adjusted that the air-gap flux remains constant at the rated value.

[230.2 Nm]

(iii) Find the starting frequency if the maximum torque, found in (ii), occurs at start.

[2.33 Hz]

(iv) If the motor is to develop 487 Nm at maximum, during acceleration for example, find the required supply current limit.

[114.1 A]

(v) Find the slip and the slip frequency for which this maximum torque will be developed, assuming constant air gap flux operation when the machine is operated at 50 Hz.

[0.085, 4.24Hz]