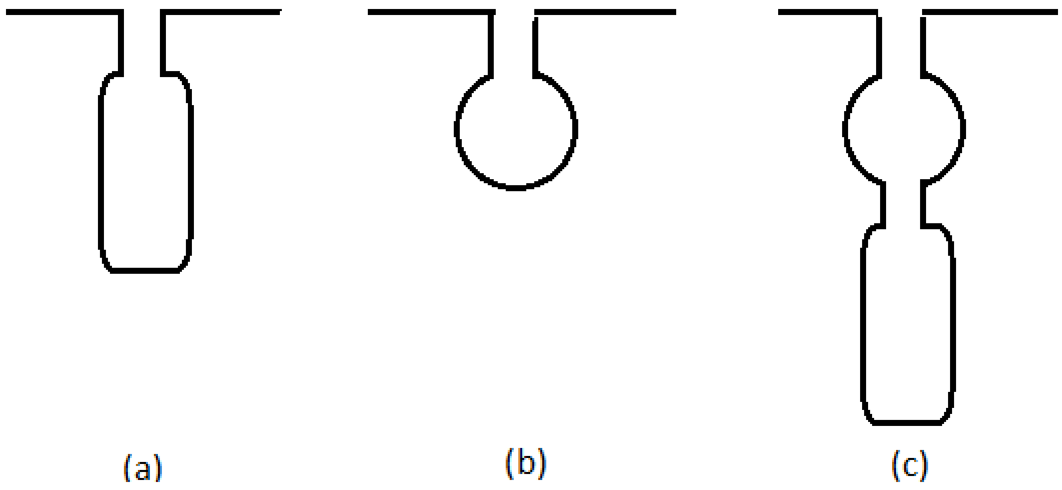
Induction Motors

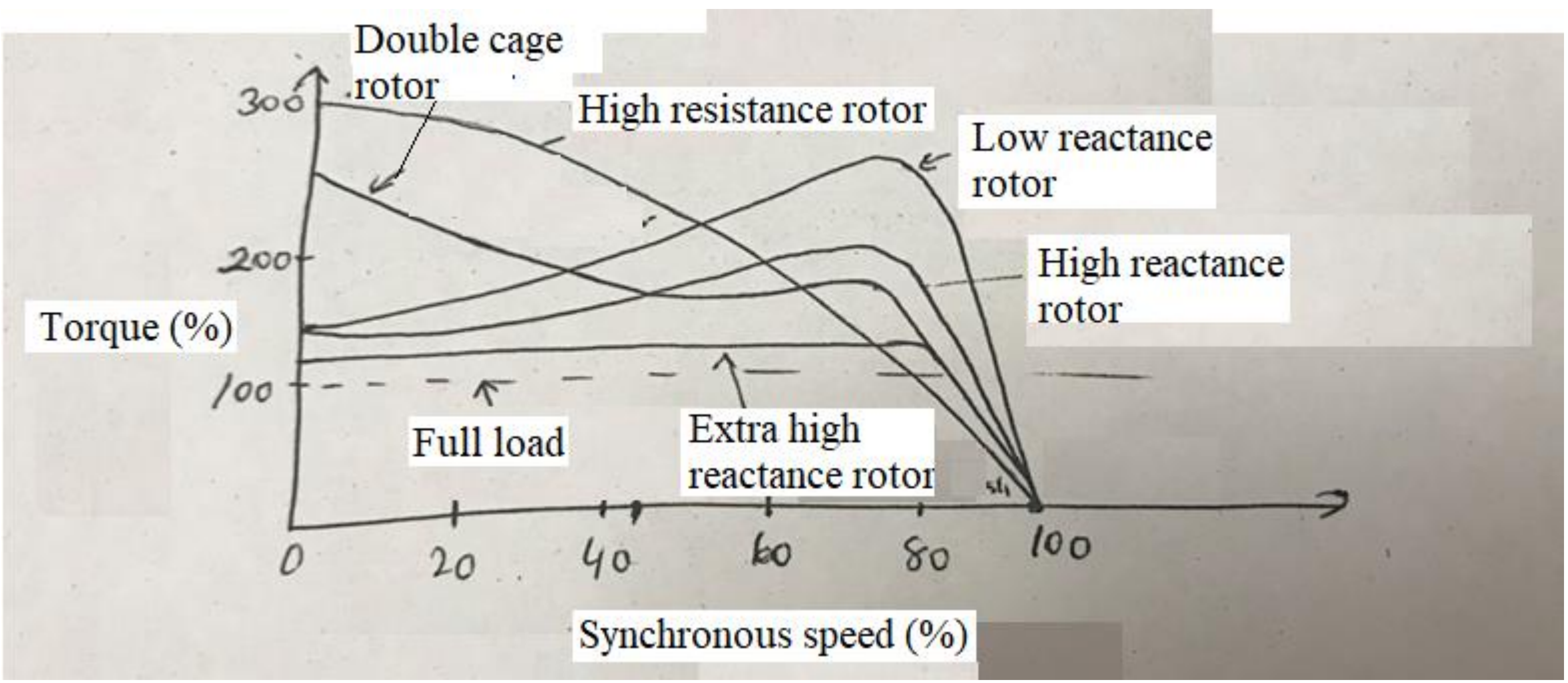
Induction Motor Characteristics

- Speed-torque characteristic of the motor can be changed by forming the rotor bars



The induction motor having a rotor structure in Fig.(c) has two squirrel cage windings in the rotor. The winding having low resistance but high reactance is placed at the bottom of the rotor slot. However, the winding placed on the top has high resistance with low reactance (also low leakage reactance).

Frequency of the rotor current is high at starting and low speeds. Hence, the rotor current tends to follow through the upper winding which has high resistance but low reactance. For this reason, starting torque of the motor is high. As the speed of the motor increases and therefore frequency of the rotor current decreases, the rotor current starts to flow through the bottom winding which has low resistance. Effect of the various rotor parameters on the motor characteristic is shown in the figure given below.



Starting Torque

- Starting torque and maximum torque (pullout or breakdown) can be determined from the typical speed-torque characteristic. Starting torque occurs when the rotor speed is zero (s=1). Therefore, the rotor current can written for s=1 as;

$$I'_{R(st)} = \frac{V_1}{\sqrt{(R_s + R'_R)^2 + (X_s + X'_R)^2}}$$

- The input power given to the rotor at starting;

$$RPI_{st} = 3.I'^2_{R(st)}.R'_R \quad {}_{s=1}$$

- We can calculate the starting torque as;

$$T = \frac{RPD}{\omega_R} = \frac{RPI(1-s)}{\omega_R} = \frac{RPI(1-s)}{\omega_s(1-s)}$$

$$T = \frac{RPI_{st}}{\omega_s}$$

- **<u>Example:</u>**
- 220 V, 60 Hz, 6 poles, 10 HP star connected 3-phase induction motor has equivalent parameters of:
- R_s =0.344 Ω, R'_R =0.147 Ω, X_s =0.498 Ω, X'_R =0.224 Ω, X_m=12.6 Ω
- Calculate the starting torque of the induction motor.

- **Solution:**

$$I'_{R(st)} = \frac{220/\sqrt{3}}{\sqrt{(0.344+0.147)^2+(0.498+0.224)^2}}$$

$$I'_{R(st)} = 145.45\ A$$

$$RPI_{st} = 3.\,(145.45)^2.\,0.147 = 9330\ W$$

$$T_{st} = \frac{9330}{2\pi n_s/60} \ ;\ n_s = \frac{120.60}{6} = 1200\ rmp$$

$$T_{st} = \frac{9330}{2\pi 1200/60} = 74.2\ N.m$$

Maximum Torque (Pullout or Breakdown Torque)

- As the motor load increases, the slip will also increase to meet the load torque. This load can be increased more than the rated values as long as the motor heat values are in its limit.
- If we keep increasing the load torque in such a way we will reach a point where the motor will not be able to produce enough torque to meet the load torque. In this case the motor will decelerate and stop. The slip value where this event happens is;

$$s_{mt} = \frac{R'_R}{\sqrt{(R_s{}^2 + (X_s + X'_R)^2}}$$

- Since Rs is usually smaller than Xe=Xs+X'R, Rs can be neglected. Therefore, the slip can be rewritten as;

$$s_{mt} = \frac{R'_R}{X_e}$$

- Where; s_{mt} is the slip value at the maximum torque point. The rotor current and rotor input power can be found by using this slip value as;

$$I'_R = \frac{V_1}{\sqrt{(R_s + R'_R/s)^2 + (X_s + X'_R)^2}}$$

$$\frac{R'_R}{s} = \frac{R'_R}{s_{mt}} = X_e = (X_s + X'_R)$$

- Rs is neglected and taken as zero.

$$I'_{Rmt} = \frac{V_1}{\sqrt{(X_s + X'_R)^2 + (X_s + X'_R)^2}}$$

$$I'_{Rmt} = \frac{V_1}{\sqrt{2}X_e}$$

$$RPI_{mt} = 3I'^2_{Rmt}\frac{R'_R}{s_{mt}} = \frac{3V_1^2}{2X_e^2}\cdot\frac{R'_R}{\frac{R'_R}{X_e}}$$

$$RPI_{mt} = \frac{3V_1^2}{2X_e}$$

- From this equation the power produced in the rotor can be found as;
- RPD = RPI(1-s)
- The output power on the shaft is;
- Pout = RPD – Prot
- Maximum torque;

$$T_{mt} = \frac{P_{out}}{\omega_R}$$

- It is worth to notice that maximum torque is independent of the rotor winding resistance (R'_R). An increase in the rotor resistance will increase the slip value at the point where maximum torque occurs. However, it will not make any change on the amplitude of the maximum torque.
- **Example:**
- 220 V, 60 Hz, 6 poles, 10 HP star connected 3-phase induction motor has equivalent parameters of:
- $R_s = 0.344\ \Omega$, $R'_R = 0.147\ \Omega$, $X_s = 0.498\ \Omega$, $X'_R = 0.224\ \Omega$, $X_m = 12.6\ \Omega$
- Core and rotation losses (P_{rot}) of the motor is 262 W.
- Calculate;
- Maximum torque of the induction motor.
- Speed of the motor at maximum torque point.

- **Solution:**

$$s_{mt} = \frac{R'_R}{X_s} = \frac{0.147}{(0.498 + 0.224)} = 0.20$$

$$n_s = \frac{120.60}{6} = 1200\ rpm$$

$$n_{Rmt} = n_s(1 - s_{mt}) = 1200(1 - 0.20) = 960\ rpm$$

$$RPI_{mt} = \frac{3V_1^2}{2X_s} = \frac{3(\frac{220}{\sqrt{3}})^2}{2(0.722)} = 33509\ W$$

$$RPD_{mt} = RPI_{mt}(1 - s_{mt}) = 33509(1-0.20) = 26807\ W$$

$$T_{mt} = \frac{RPD_{mt} - P_{rot}}{\omega_{Rmt}} = \frac{26807 - 262}{2\pi 960/60} = 264\ N.m$$

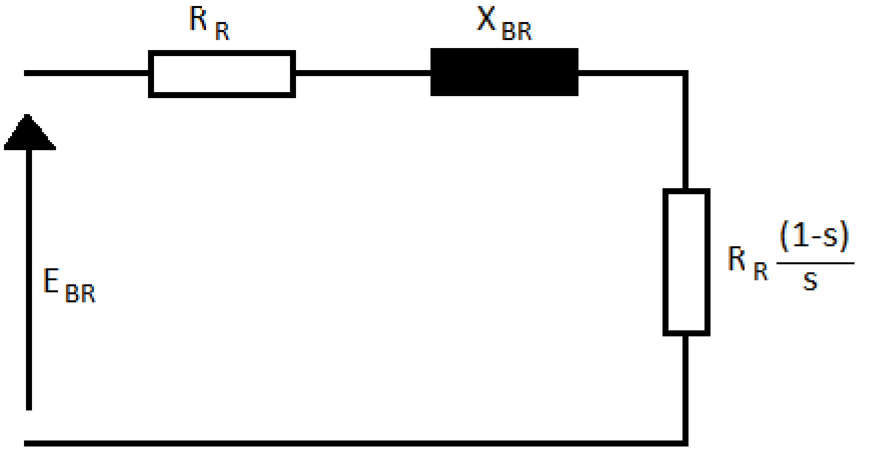
- Maximum torque occurs at 960 rpm and the motor will stop if the load torque increases further.

Wound Rotor Induction Motors

- As we know before, the basic difference between the squirrel cage and wound rotor induction motors is their rotor structure. They both have similar stator structure. Squirrel cage induction motor has constant rotor resistance.
- At normal operation conditions high efficiency is required. For this, the rotor resistance must be small. However, small rotor resistance causes high starting currents and low starting torque. Therefore, the rotor design must meet both requirements (low starting current and high starting torque).
- There is an effective way in wound rotor induction motors for both preventing high starting currents (therefore obtaining high starting torque) and increasing the efficiency at normal operation conditions by keeping the rotor resistance small. It is possible to do this by connecting the rotor windings to the external resistances through slip rings and brushes.
- Starting current is reduced by the external resistances and starting torque is increased and therefore the power factor is improved.

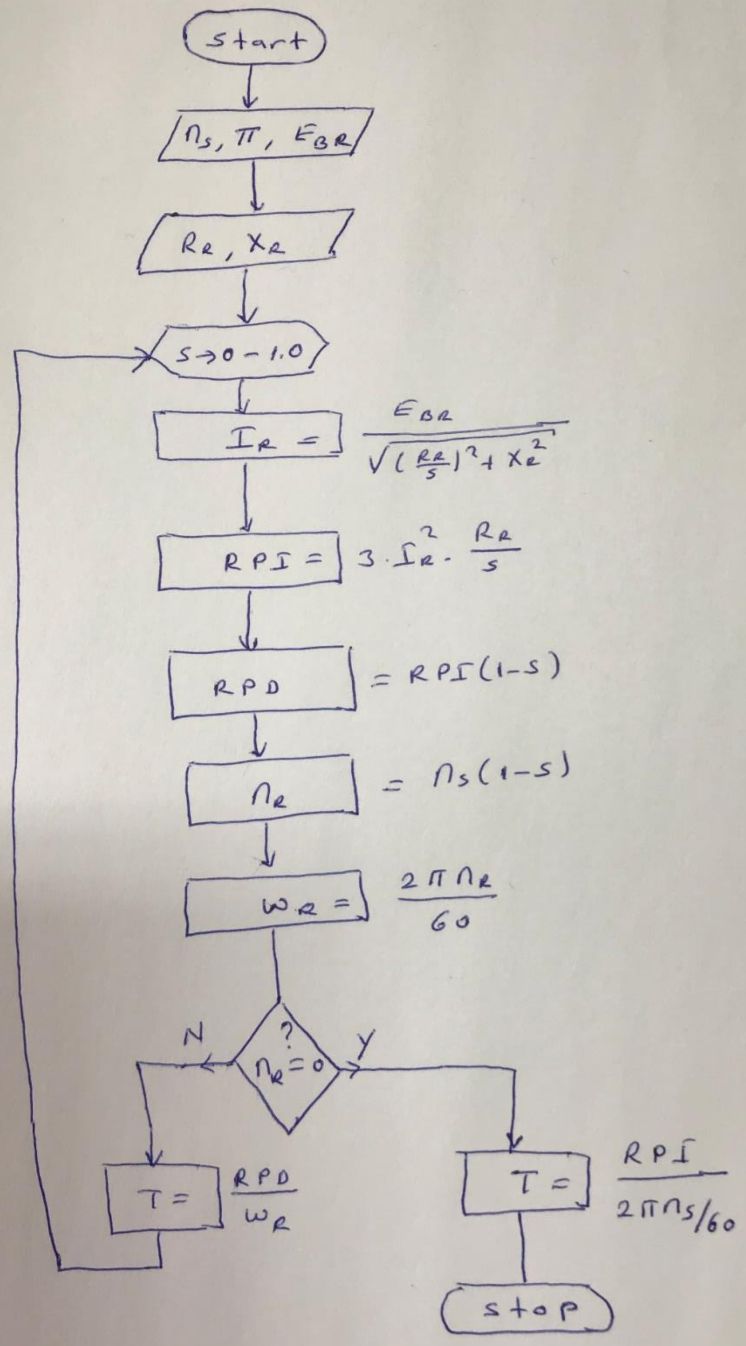
- As can be seen from $s_{mt} = \frac{R'_R}{X_e}$ equation that slip point where the maximum torque occurs depends on the rotor resistance. Hence, starting torque can be made equal to the maximum torque by adding extra resistance in series to the rotor circuit if a high starting torque is required. Maximum torque can be provided during acceleration of the motor by extracting external resistances from the rotor circuit in proper way. When the motor reaches its normal speed the external resistance is made short circuited through the brushes.
- Since it is possible to have maximum torque during acceleration ,wound rotor induction motors can be preferred to drive loads having high torque of inertia. Since I^2R power losses are dissipated on the external rotor resistance this will be advantage from the point of the motor heating. However, it is disadvantage for high power rate motors since huge amount of energy loss is dissipated on the external resistances especially at low speeds (big slips).

- In order to demonstrate the effect of the variable rotor resistance on the torque-speed characteristic of the motor lets solve an example given below. For simplicity the calculations have been restricted only with the rotor circuit.

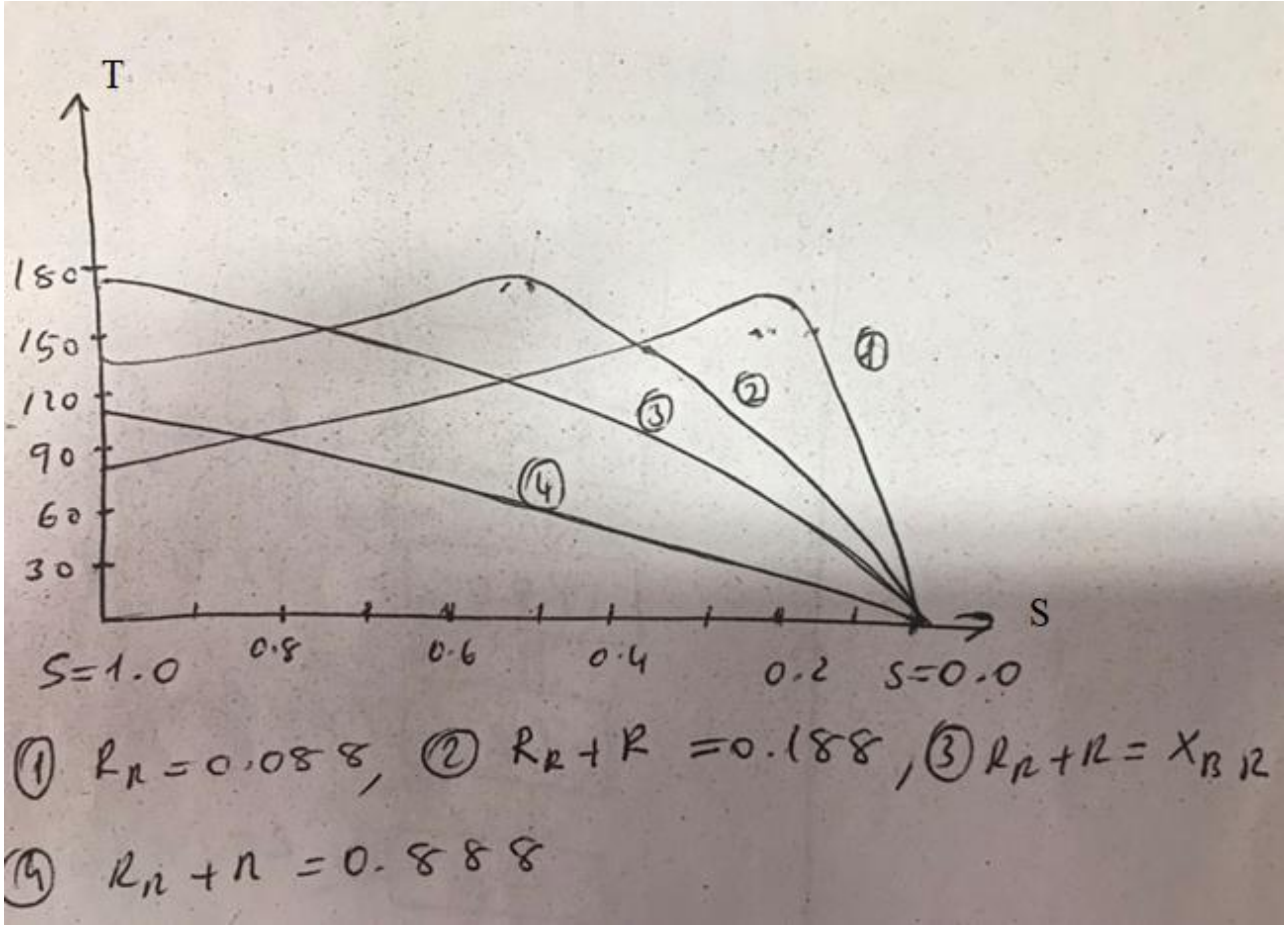


- Line current, power factor and input power can be calculated by referring the rotor side to the stator side.

- **Example:**
- Stator and rotor windings of a three-phase, 60 Hz, 4 poles, 220 V wound rotor induction motor are connected in delta and star, respectively. Rotor reactance is X_R=0.352 Ω and rotor resistance is R_R=0.088 Ω. Rotor turn number is 40% of stator turn number.
- a) Determine the speed-torque characteristic of this motor.
- b) Repeat part (a) of the question for the external resistances of 0.1 Ω, 0.264 Ω and 0.8 Ω connected to the rotor circuit.
- **Solution:**
- a) E_{BR}=40% * V_{stator}/phase = 0.4*220 = 88 Volt.
- n_s= 120f/P = 120*60/4 = 1800 rpm


start
ns, π, EBR
RR, XR
S→0 – 1.0
IR = EBR / √((RR/S)² + XR²)
RPI = 3 · IR² · RR/S
RPD = RPI(1–S)
nR = ns(1–S)
ωR = 2π nR / 60
? nR = 0
N
Y
T = RPD / ωR
T = RPI / (2π ns/60)
stop

- By following flowchart given above we can draw torque-speed characteristic of the motor.
- b) By putting the values of R_R+0.1, R_R+0.264 and R_R+0.8 instead of R_R resistance we can repeat the steps in (a) and obtain the characteristics given below.



- As can be seen from the figure, the slip value where the maximum torque occurs gets close to the origin as the rotor resistance increases. Starting torque will be equal to the maximum torque where the total rotor resistance is equal to the rotor reactance ($R_R + R = X_R$). The curve, 4 in the figure has negative slop for the whole accelerating interval. This negative slop is desirable from the point of stability in control system applications and it represents positive damping.
- Two-phase induction motors having high rotor resistances are known as servo motors.