Induction Motor Drive

- **Why induction motor (IM)?**
  - Robust; No brushes. No contacts on rotor shaft
  - High Power/Weight, Lower Cost/Power ratios
  - Easy to manufacture
  - Almost maintenance-free, except for bearing and other "external" mechanical parts

- **Disadvantages**
  - Essentially a "fixed-speed" machine
  - Speed is determined by the supply frequency
  - To vary its speed need a variable frequency supply

- **Motivation for variable-speed AC drives**
  - Inverter configuration improved
  - Fast switching, high power switches
  - Sophisticated control strategy
  - Microprocessor/DSP implementation

- **Applications**
  - Conveyer line (belt) drives, Roller table, Paper mills, Traction, Electric vehicles, Elevators, pulleys, Air-conditioning and any industrial process that requires variable-speed operation.

- The state-of-the-art in IM drives is such that most of the DC drives will be replaced with IM in very near future.

Torque production (1)

- Only "squirrel-cage" IM (SCIM) is considered in this module

- Neglecting all harmonics, the stator establishes a spatially distributed magnetic flux density in the air-gap that rotate at a ***synchronous speed***, ω_1 :

$$\omega_1 = \frac{\omega_e}{p}$$

where
ω_e : supply frequency (in Hz)
p: pole pairs (p=1for 2 pole motor, p=2 for 4 pole motor etc)

- If the rotor is initially stationary, its conductor is subjected to a sweeping magnetic field, inducing rotor current at synchronous speed.

- If the rotor is rotating at synchronous speed (i.e. equals to f_1), then the rotor experience no induction. No current is induced in the rotor.

Torque production (2)

- At any other rotor speed, say wm, the speed differential ω_i-ω_2 creates slip. Per-unit slip is defined as:

$$s = \frac{\omega_1 - \omega_m}{\omega_1}; \qquad \omega_1 = \frac{\omega_e}{p}$$

where:

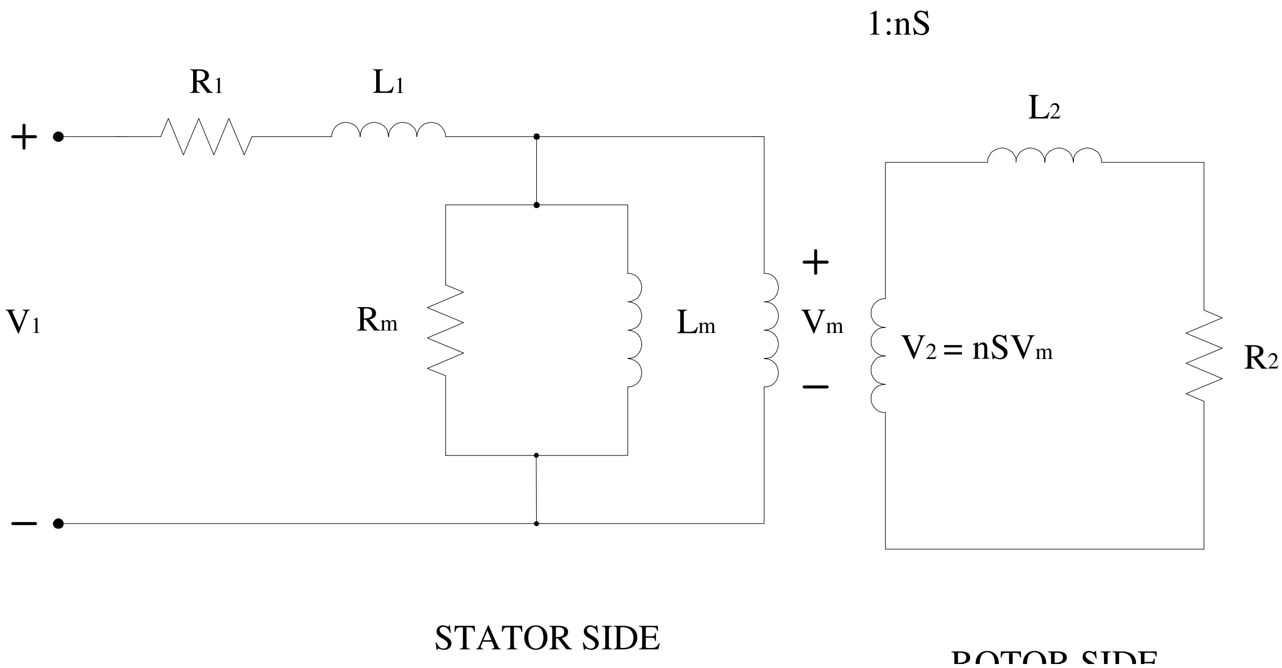
ω_e : supply frequency

ω_m : rotor frequency

p : pole pair

- Slip frequency is defined as: $\omega_2 = \omega_1 - \omega_m$.
- When rotor is rotating at ω_m., rotor current at slip frequency will be induced.
- The interaction between rotor current and air-gap flux produces torque.

Single-phase Equivalent Circuit (SPEC)



R_1 : Stator resistance

L_1 : Stator leakage inductance

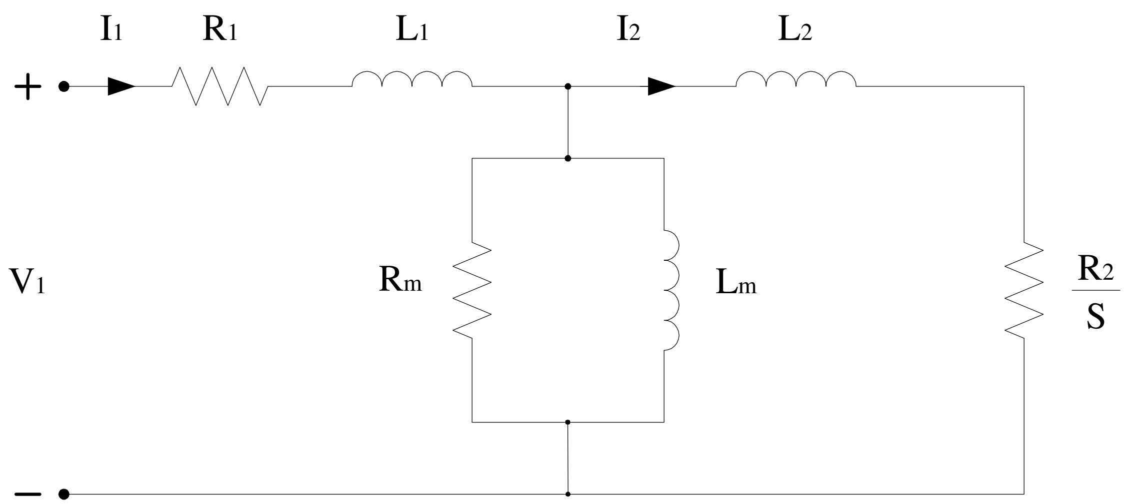
R_2 : Rotor resistance

L_2 : Rotor leakage inductance

L_m : Magnetising inductance

v_1 : Supply voltage (phase voltage)

SPEC, referred to stator



- From previous diagram, SPEC is a dual frequency circuit. On the stator is ω_1 and on the rotor ω_m
- Difficult to do calculations.
- We can make the circuit a single frequency type, by referring the quantities to the stator

Rotor current

If E_1 is the back EMF in the stator phase, then the back EMF in an equivalent rotor phase with the same effective turns ratio will be E_2 where :

$$E_2 = sE_1$$

At standstill, i.e when $\omega_{\mathrm{m}} = 0$,

$$E_2 = sE_1 = 1E_1 = E_1$$

At synchronous speed, i.e when $\omega_{\mathrm{m}} = 1$,

$$E_2 = (0)E_1 = 0$$

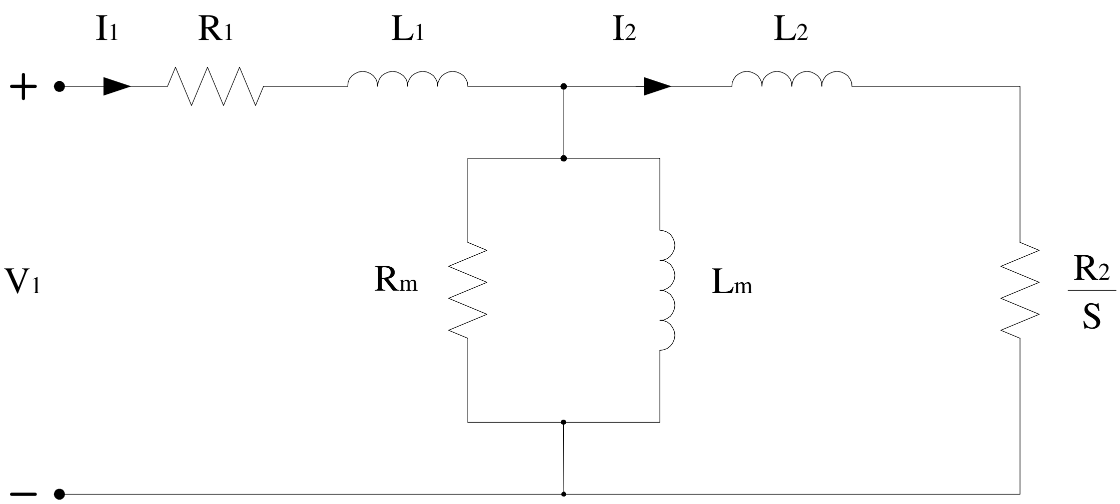
Hence the current in the rotor phase,

$$I_2 = \frac{E_2}{R_2 + jsX_2} = \frac{sE_1}{R_2 + jsX_2}$$

$$= \frac{E_1}{\frac{R_2}{s} + jX_2}$$

Note that the quantities are now referred to the stator, but with the rotor resistance alteration.

Performance calculation using SPEC



Input Power : $P_{in} = 3V_1 I_1 \cos\phi$

Note : V_1 and I_1 must be phase voltage and current

Stator copper loss : $P_{ls} = 3{I_1}^2 R_1$

Core loss : $P_{lc} = \dfrac{3{V_1}^2}{R_m}$

Power across the air - gap : $P_g = \dfrac{3{I_2}^2 R_2}{s} = P_{in} - P_{ls} - P_{lc}$

Rotor copper loss : $P_{lr} = 3{I_2}^2 R_2$

Performance calculation (2)

Gross output power :

$$P_o = P_g - P_{lr}$$

$$= \frac{3{I_2}^2 R_2}{s} - 3{I_2}^2 = \frac{3{I_2}^2 R_2 (1-s)}{s} = P_g (1-s)$$

Power at the shaft :

$P_{sh} = P_o - P_{FW}$; P_{FW} : friction and windage loss.

Developed (electromagnetic) torque :

$$T_e = \frac{P_o}{\omega_m} = \frac{3{I_2}^2 R_2 (1-s)}{s\omega_m}$$

Since

$$s = \frac{\omega_1 - \omega_m}{\omega_1} \Rightarrow \omega_m = (1-s)\omega_1,$$

$$\therefore T_e = \frac{3{I_2}^2 R_2}{s\omega_1}$$

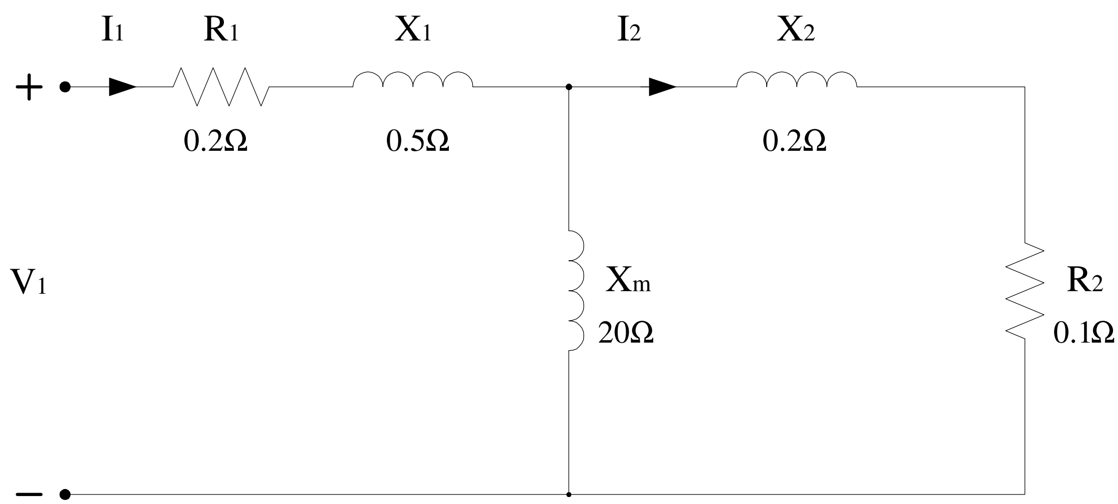
But $\omega_1 = \dfrac{\omega_e}{p}$; ω_e is the supply frequency.

Then,

$$\Rightarrow \quad T_e = \frac{3p{I_2}^2 R_2}{s\omega_e}$$

Example calculation

- A single phase equivalent circuit of a 6-pole SCIM that operates from a 220V line voltage at 60Hz is given below. Calculate the stator current, output power, torque and efficiency at a slip of 2.5%. The fixed winding and friction losses is 350W. Neglect the core loss.



$$V_1 = 220\text{V line-to line } \div \sqrt{3}$$

$$= \frac{220\text{V}}{\sqrt{3}} = 127\text{V}$$

$$= 2.5\% = 0.025$$

Calculation (solution)

$$X_1 = 0.5\Omega, X_2 = 0.2\Omega, X_m = 20\Omega$$

$$Z_{in} = (R_1 + jX_1) + jX_m // \left(\frac{R_2}{s} + jX_2 \right)$$

$$= 0.2 + j0.5 + j20 \left(\frac{\frac{0.1}{0.025} + j0.2}{\frac{0.1}{0.025} + j0.2 + j20} \right) = 4.2\angle 20^o \, \Omega$$

$$I_1 = \frac{V_1}{Z_{in}} = \frac{220/\sqrt{3}}{4.2\angle 20^o} = 30.0\angle -20^o \, A$$

$$P_{in} = 3V_1 I_1 \cos\phi = 3(220/\sqrt{3})(30)(\cos 20^o)$$
$$= 10{,}758W$$

$$P_{ls} = 3I_1^{\ 2} R_1 = 3(30^2)(0.2) = 540W$$

Power transferred to rotor (neglecting core loss)

$$P_g = P_{in} - P_{ls}$$
$$= 10{,}758 - 540 = 10{,}216W$$

Gross power

$$P_o = P_g (1 - s) = 10{,}216(1 - 0.025) = 9{,}961W$$

Power at the shaft

$$P_{sh} = P_o - P_{FW} = 9{,}961 - 350 = 9{,}611W$$

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} = \frac{9611}{10758} = 89.3\%$$

Electromagnetic Torque

$$T_e = \frac{P_o}{\omega_m} = \frac{P_o}{(\omega_{e1}/p)(1-s)} = \frac{9611}{2\pi(60/3)(1-0.025)}$$
$$= 78.4N.m$$

Starting current

- For the previous example, Calculate the stating current when motor is first switched on to rated applied voltage.

Solution :
At standstill, $s = 1$

$$Z_{in} = = 0.2 + j0.5 + j20\left(\frac{0.1 + j0.2}{0.1 + j0.2 + j20}\right)$$

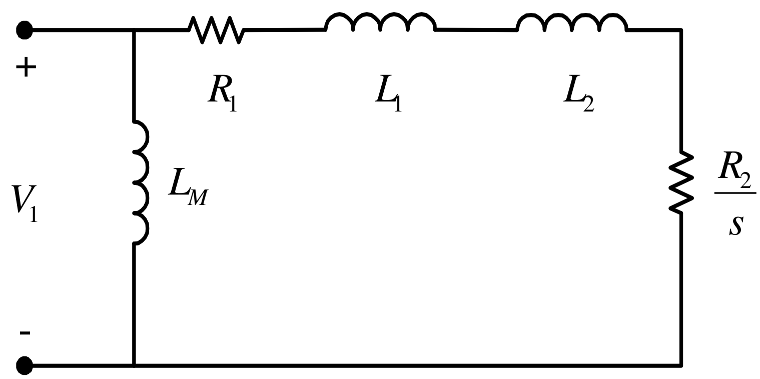
$$= 0.76\Omega$$

$$I_1 = \frac{V_1}{Z_{in}} = \frac{220/\sqrt{3}}{0.76} = 167A$$

Note that the starting current is about 5 times than full load current.

This is common for induction motors.Care should be taken when starting induction motors.

Approximate SPEC



Since L_m is large, the circuit above can be drawn

$$I_2 = \frac{V_1}{\sqrt{\left(R_1 + \frac{R_2}{s}\right)^2 + \omega_1{}^2 (L_1 + L_2)^2}}$$

Power at the rotor (per phase),

$$P_o = I_2{}^2 \left(\frac{R_2}{s}\right)$$

Electromagnetic (developed) torque,

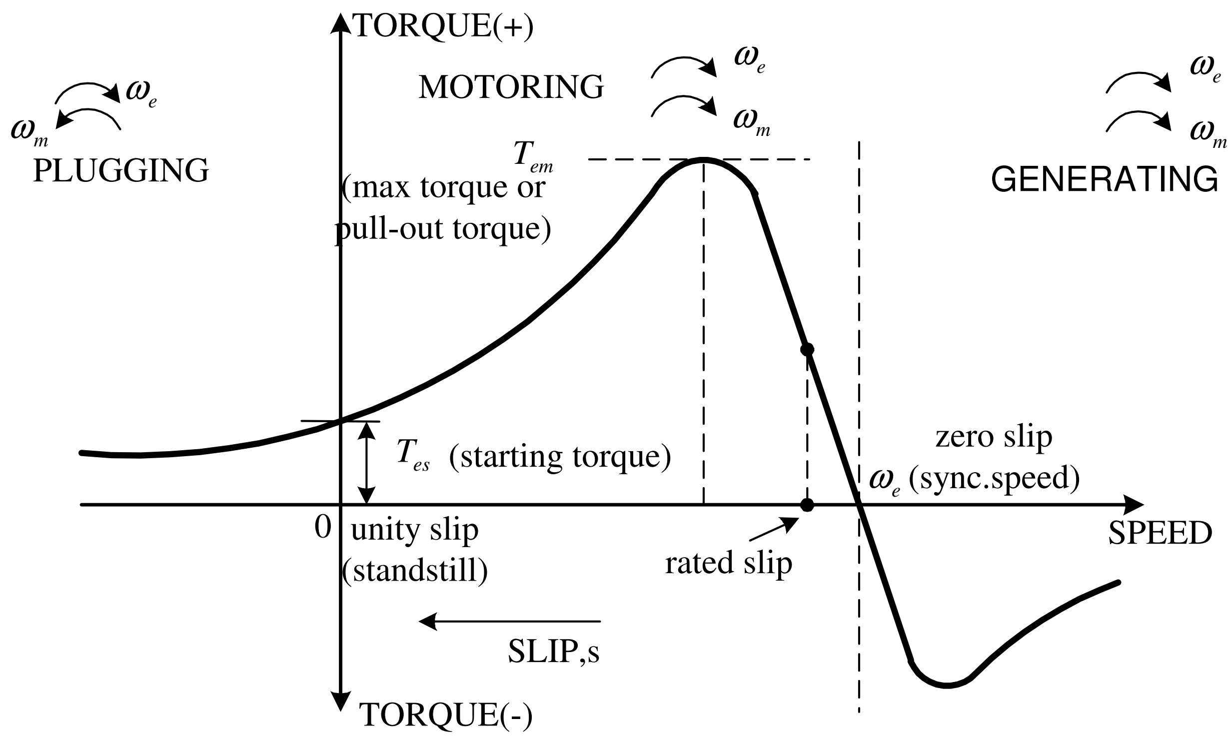
$$T_e = \frac{3P_o}{\omega_1} = \frac{3R_2 V_1{}^2}{s\omega_1 \left[\left(R_1 + \frac{R_2}{s}\right)^2 + \omega_1{}^2 (L_1 + L_2)^2\right]}$$

Single (fixed supply) frequency characteristics

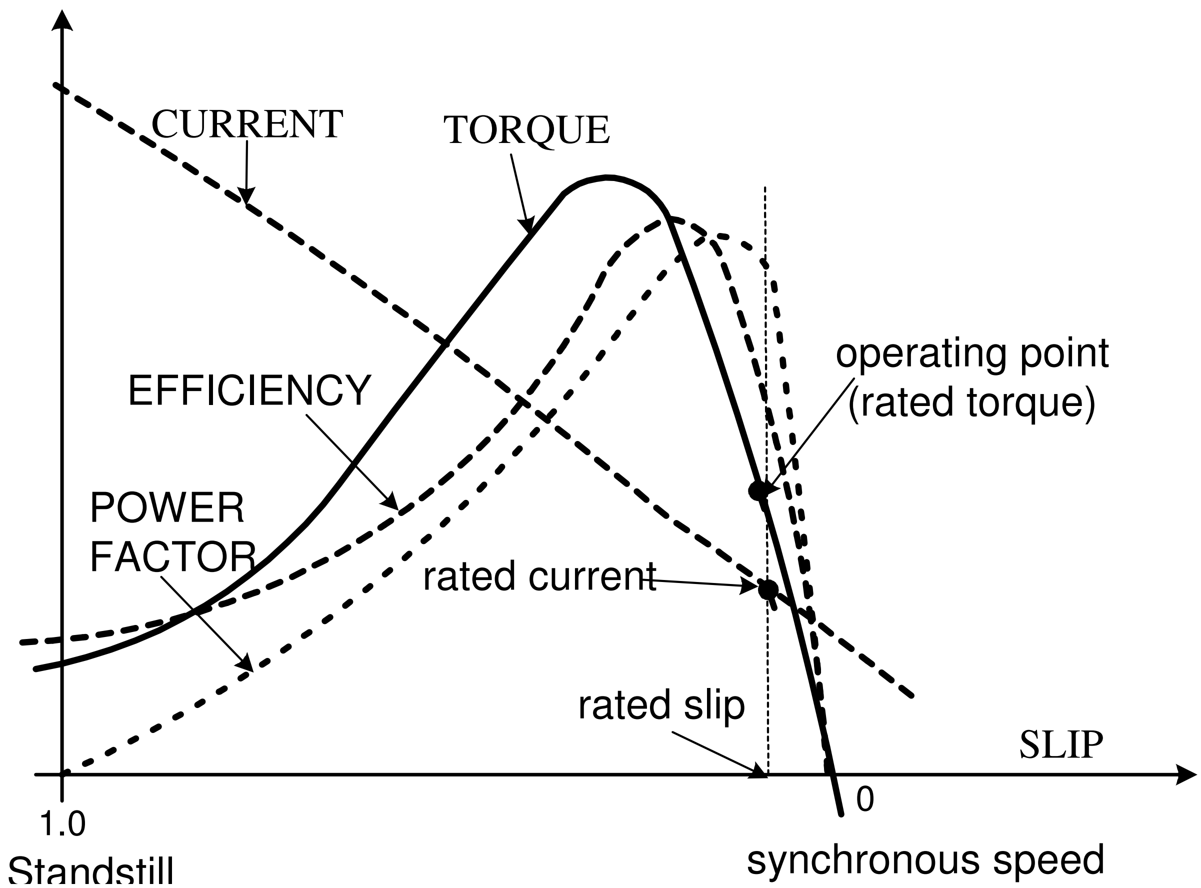
For a give frequency ω_1, the torque (versus slip) characteristics can be shown as below.

Note that :

$$s = \frac{\omega_1 - \omega_m}{\omega_1}; \text{ at standsill } s = 1, \text{ at sync speed, } s = 0.$$



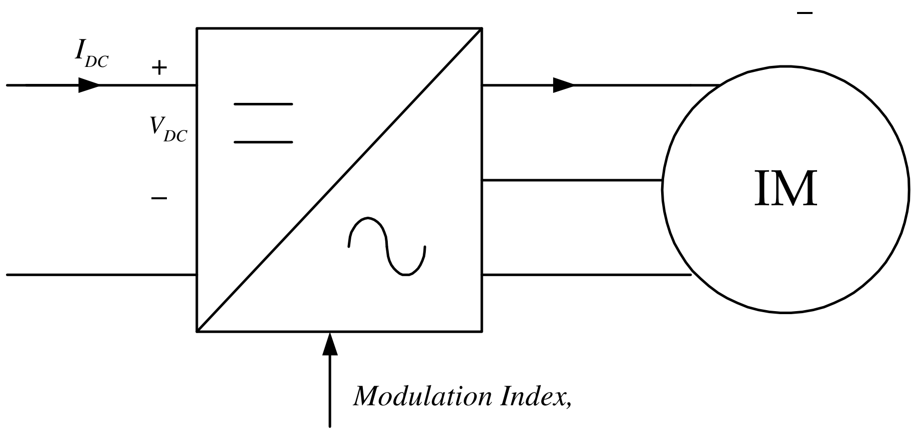
Single frequency characteristics



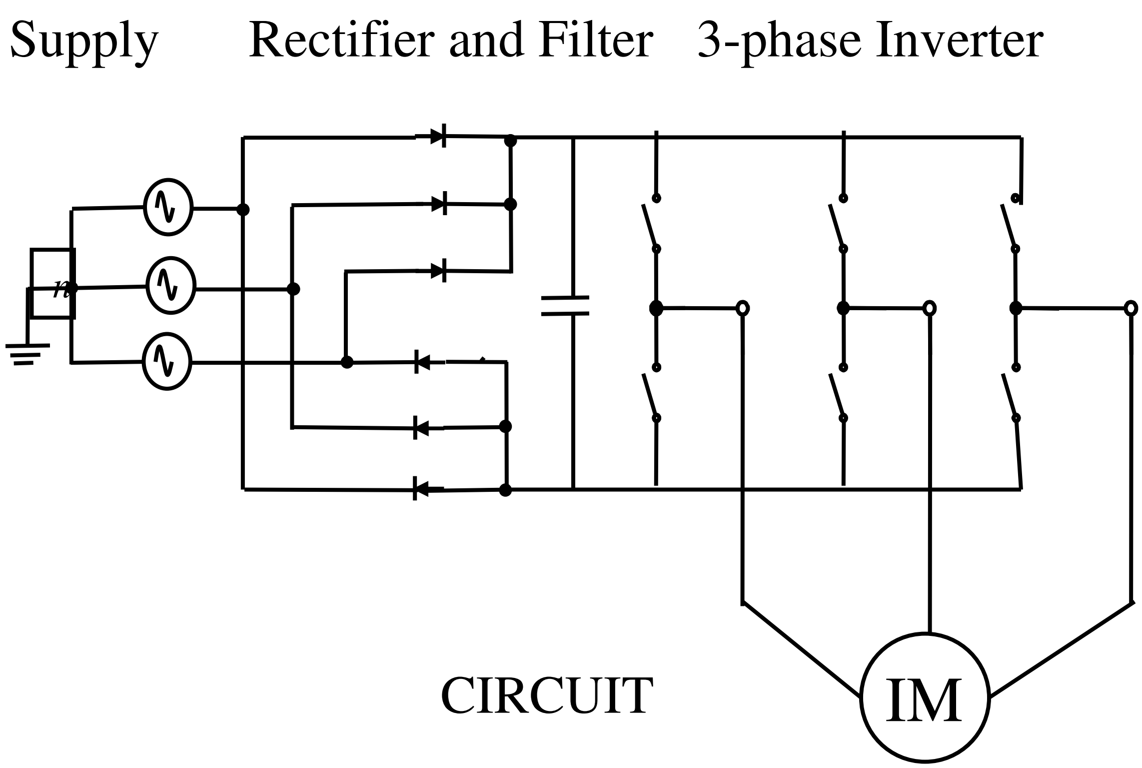
Single frequency characteristic

- As slip is increased from zero (synchronous), the torque rapidly reaches the maximum. Then it decreases to standstill when the slip is unity.
- At synchronous speed, torque is almost zero.
- At standstill, torque is not too high, but the current is very high. Thus the VA requirement of the IM is several times than the full load. Not economic to operate at this condition.
- Only at “low slip”, the motor current is low and efficiency and power factor are high.

Typical IM Drive System



BLOCK DIAGRAM



CIRCUIT

Variable speed characteristics

- For variable speed operation, the supply is an inverter.
- The frequency of the fundamental AC voltage will determine the speed of IM. To vary the speed of IM, the inverter fundamental frequency need to be changed.
- The inverter output frequency must be kept close to the required motor speed. This is necessary as the IM operates under low slip conditions.
- To maintain constant torque, the **slip frequency** has to be maintained over the range of supply frequencies.

Variable voltage, variable frequency (VVVF) operation

- In order for maximum torque production, motor flux should be maintained at its rated value.

$$\Phi = \Phi_m \sin \omega_1 t$$

But the back emf is :

$$e_1 = N \frac{d\Phi}{dt} = N\omega_1 \Phi_m \cos \omega_1 t$$

In RMS,

$$E_1 = \frac{1}{\sqrt{2}} N\omega_{11}\Phi_m = 4.44 f_1 N_1 \Phi_m$$

or $$\frac{E_1}{f_1} = 4.44 N_1 \Phi_m$$

Therefore, in order to maintain the motor flux, the $\left(E_1 / f_1\right)$ ratio has to be kept constant.

This is popularly known as the constant Volt/Hertz operation

Constant Torque region

- Hence for VVVF operation, there is a need to control the fundamental voltage of the inverter if its frequency (and therefore the frequency of the IM) need to be varied.

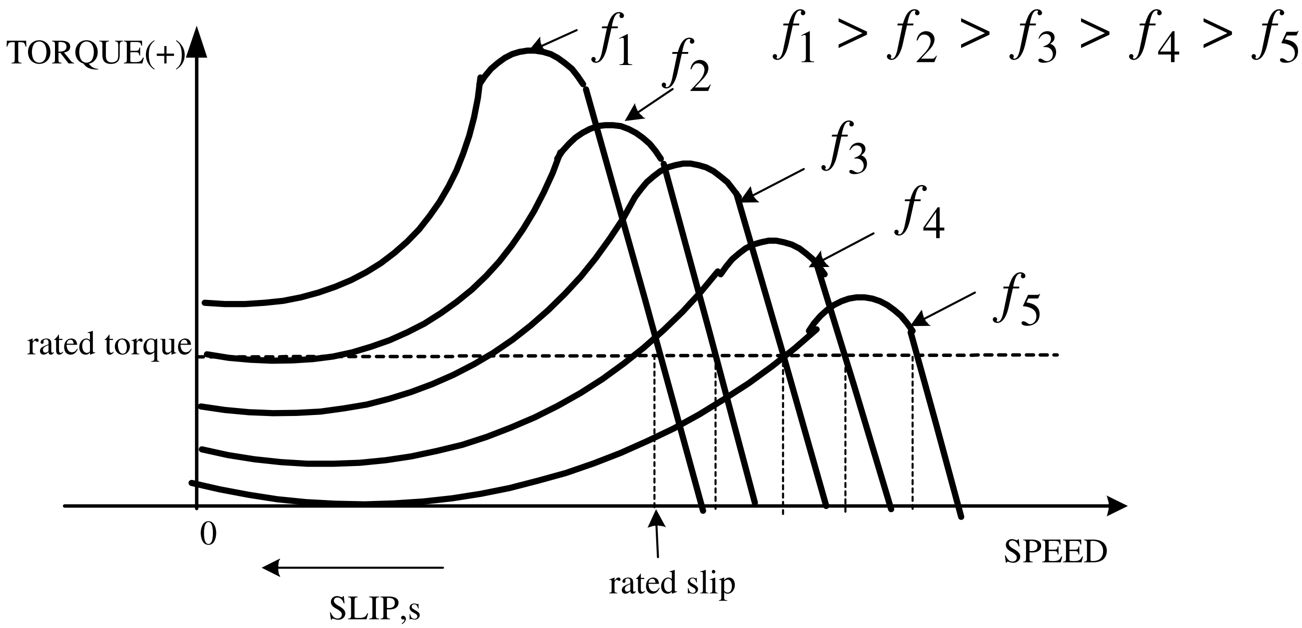
- To vary the fundamental component of the inverter, the MODULATION INDEX can be changed.

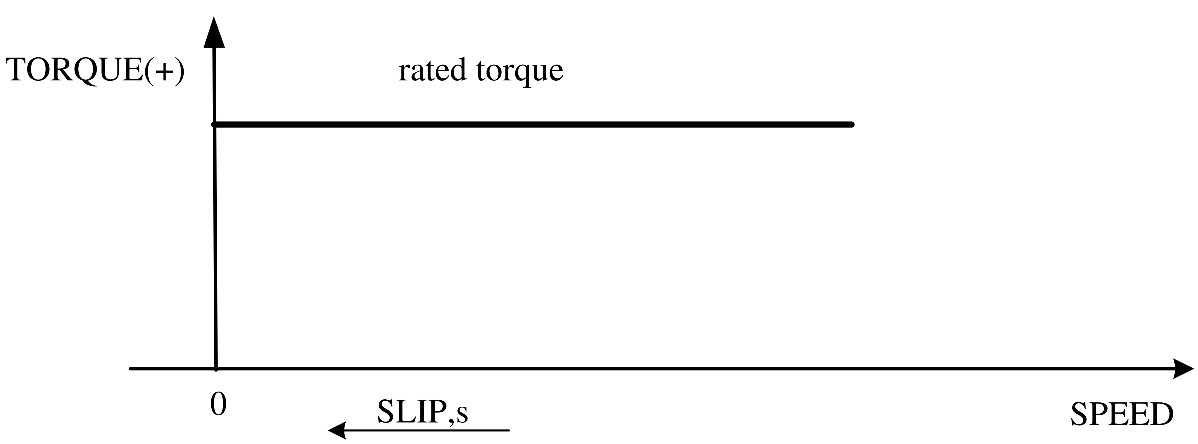
- The rated supply frequency is normally used as the base speed

- At frequencies below the base speed, the supply magnitude need to be reduced so as to maintain a constant Volt/Hertz.

- The motor is operated at rated slip at all supply frequencies. Hence a "constant torque" region is obtained.

Constant Torque Region

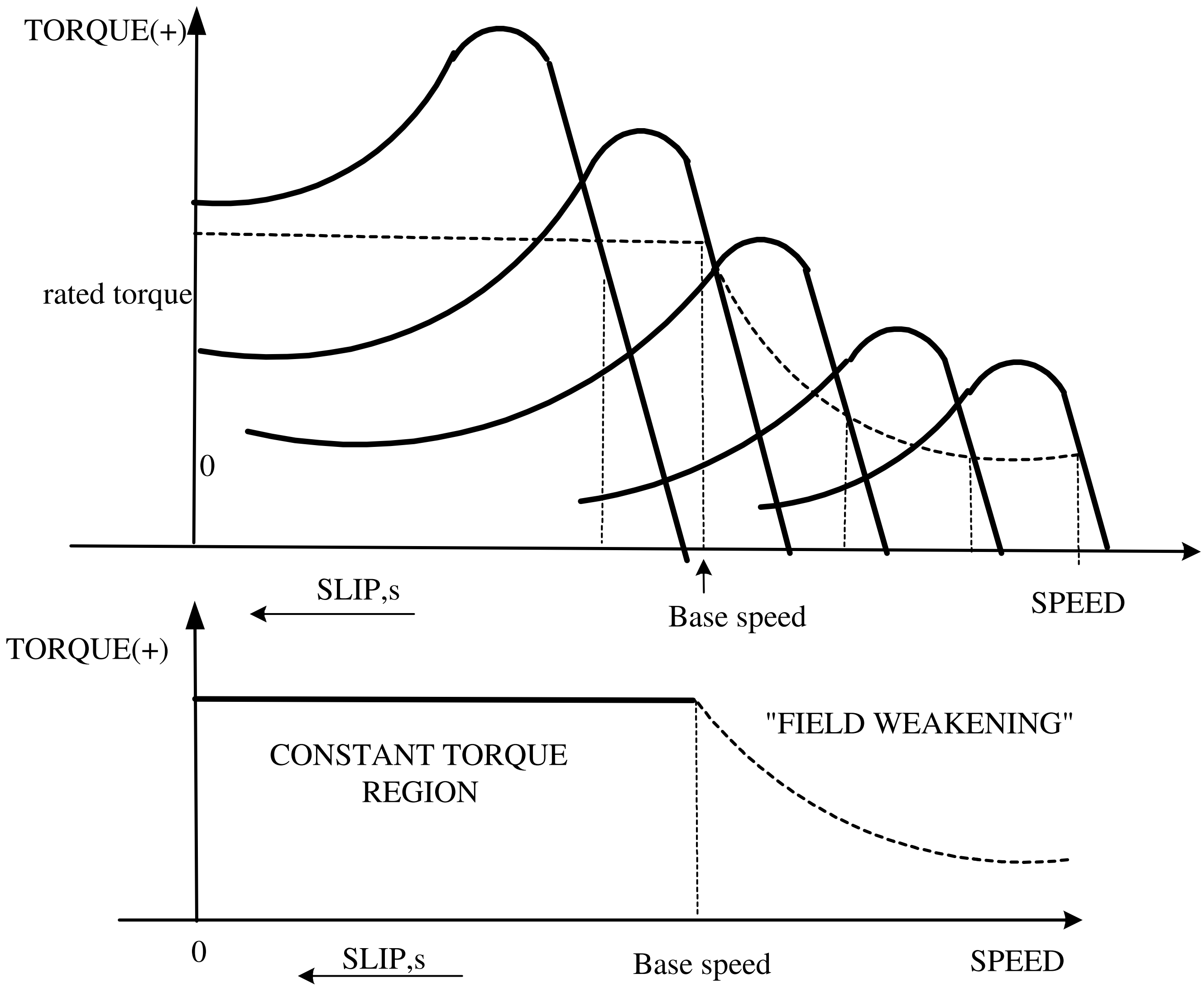




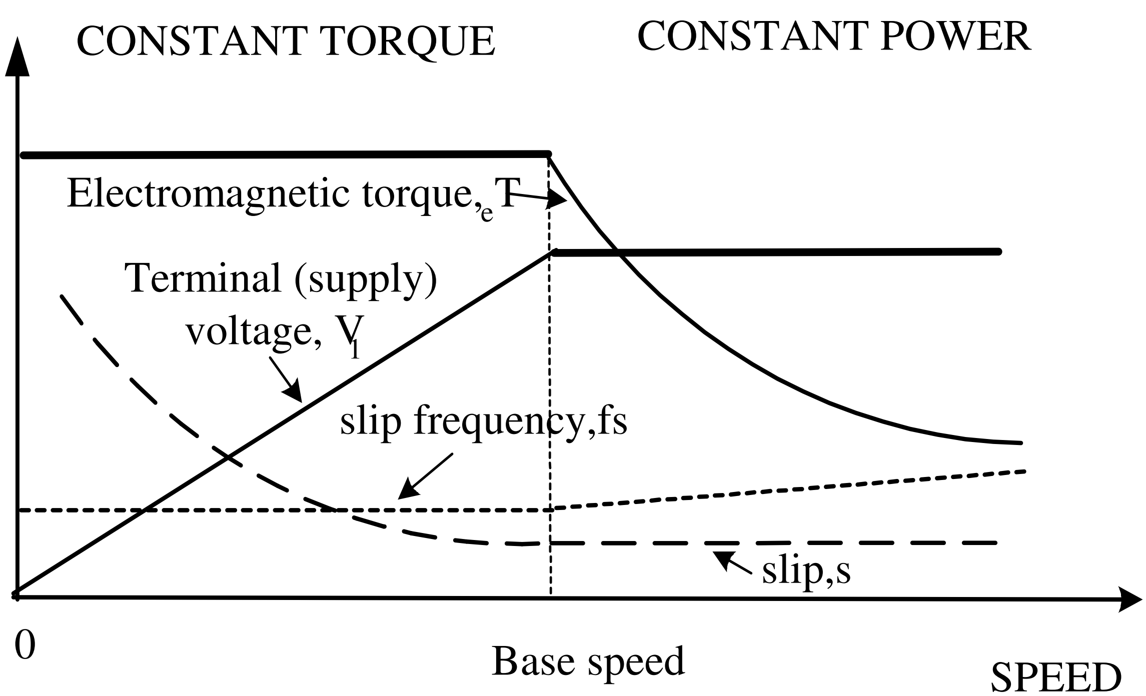
Constant Power region

- Above base speed, the stator voltage reaches the rated value and the motor enters a constant power region.
- In this region, the air-gap flux decreases. This is due to increase in frequency frequency while maintaining fixed voltage.
- However, the stator current is maintained constant by increasing the slip. This is equivalent to field weakening mode of a separately excited DC motor.

Constant Power region



VVVF Summary



Examples

- A three-phase 4-pole, 10 horsepower, 460V rms/60Hz (line-to line) runs at full-load speed of 1746 rpm. The motor is fed from an inverter. The flux is made to be constsnt. Plot the torque-speed graphs for the following frequency: 60Hz, 45 Hz, 30Hz, 15Hz.

- A three-phase induction motor is using a three-phase VSI for VVVF operation. The IM has the following rated parameters:
  - voltage: 415V (RMS)
  - frequency: 50Hz
  - slip (p.u) 5%
  - pole pair 2
  - If the inverter gives 415V (RMS) with modulation index of 0.8, calculate the required modulation index if the motor need to be operated at rotor mechanical speed of 10Hz.