AC DRIVES

AC motor Drives are used in many industrial and domestic application, such as in conveyer, lift, mixer, escalator etc.

The AC motor have a number of advantages :

- **Lightweight (20% to 40% lighter than equivalent DC motor)**
- **Inexpensive**
- **Low maintenance**

The Disadvantages AC motor :

*** The power control relatively complex and more expensive**

There are two type of AC motor Drives :

1. **Induction Motor Drives**
2. **Synchronous Motor Drives**

3 phase induction motor drives

STATOR FREQUNCY CONTROL(cont….)

- $V=2\Pi f T \varphi K_W$

$$\varphi \propto V/F$$

- **Low frequency operation at constant voltage:**

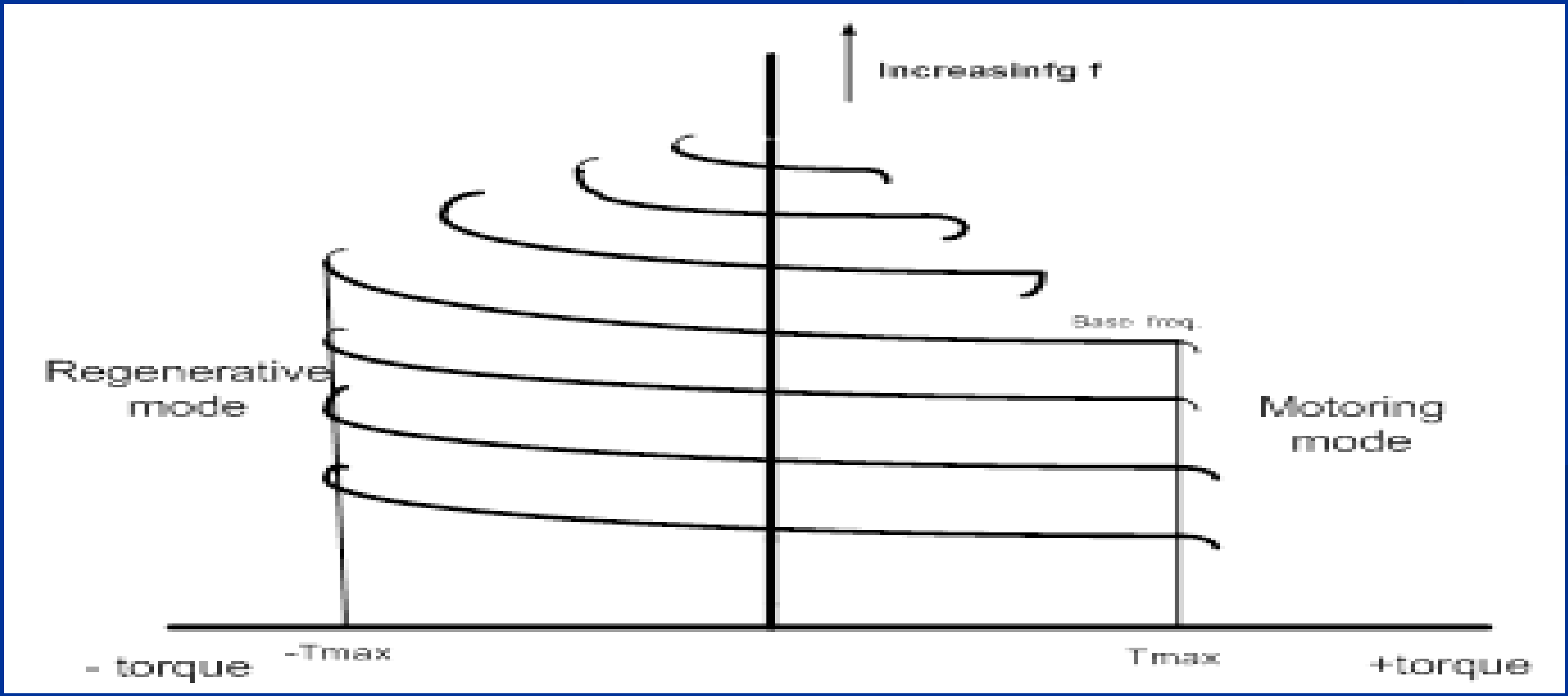
V constant; f decrease ; φ increases

- **High frequency operation at constant voltage:**

V constant ; f increase ; φ decrease

V/f control(cont….)

- f increase ; N increase ; Tmax decrease
- V increase; ; Tmax increase



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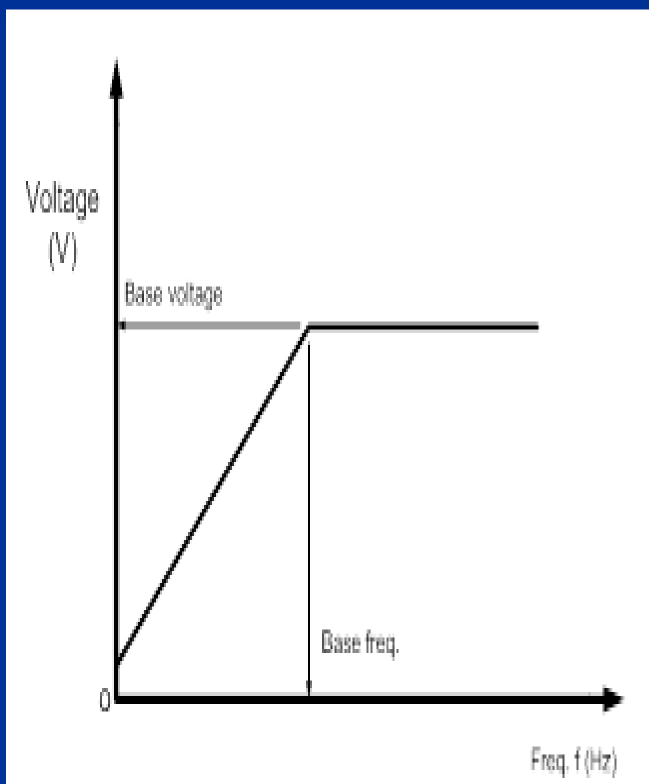
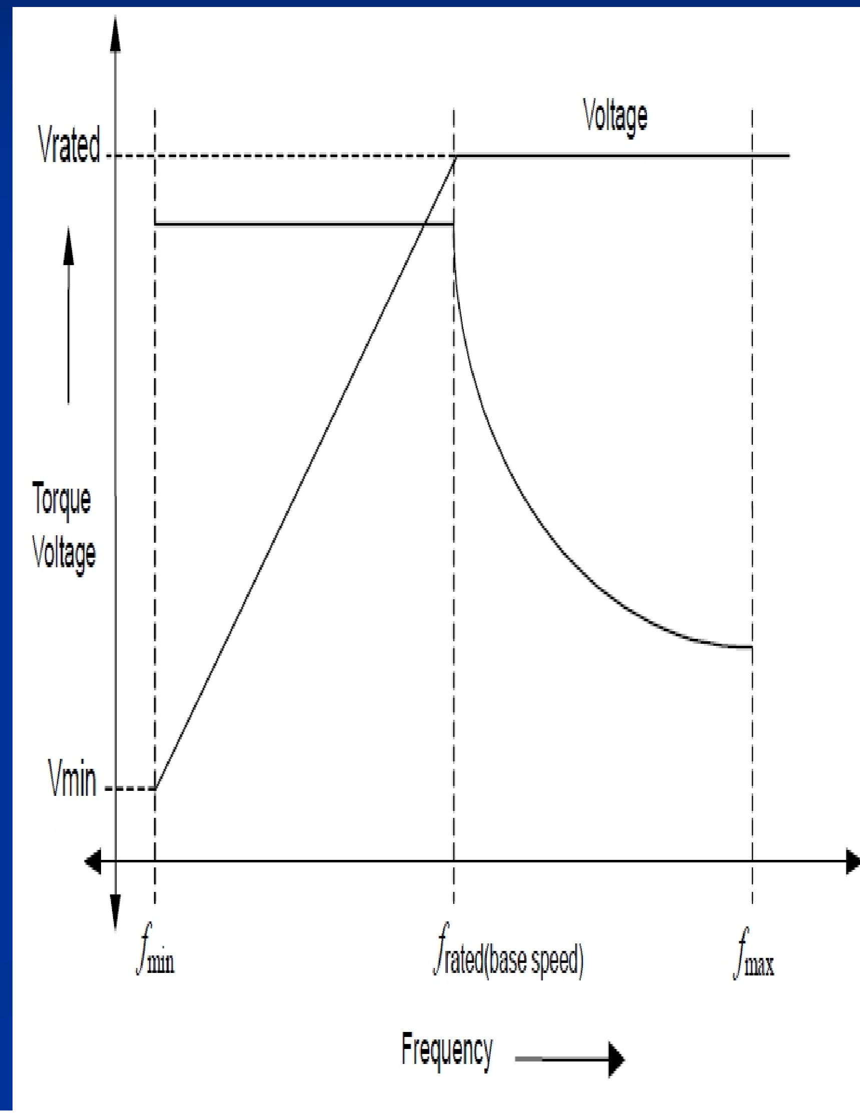


Voltage
(V)
Base voltage
Base freq.
0
Freq. f (Hz)



Vrated
Voltage
Torque
Voltage
Vmin
f_{min}
$f_{rated(base\ speed)}$
f_{max}
Frequency

(cont….)

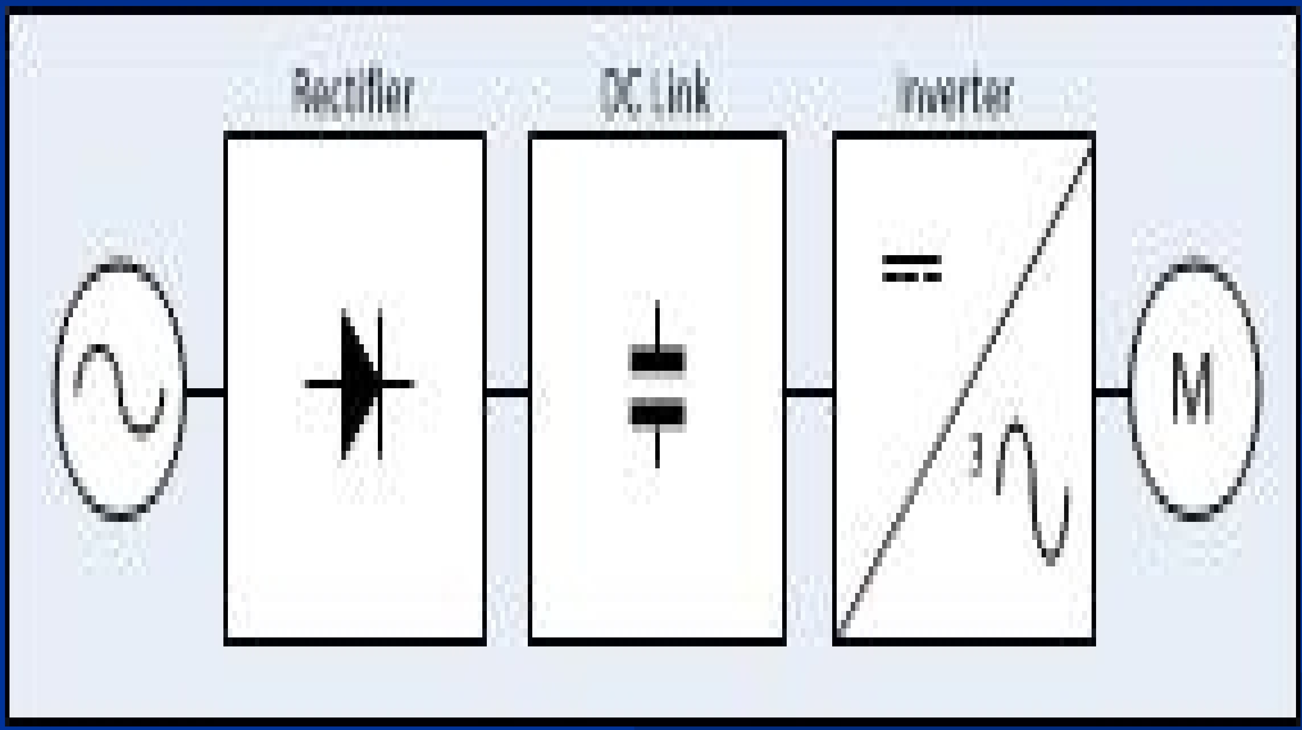
- **Applications:**
- · heating,
- · ventilation,
- · air conditioning systems,
- · waste water treatment plants,
- · blowers,
- · fans,
- · textile mills,
- · rolling mills, etc

variable voltage and variable frequency(v/f) (cont….)

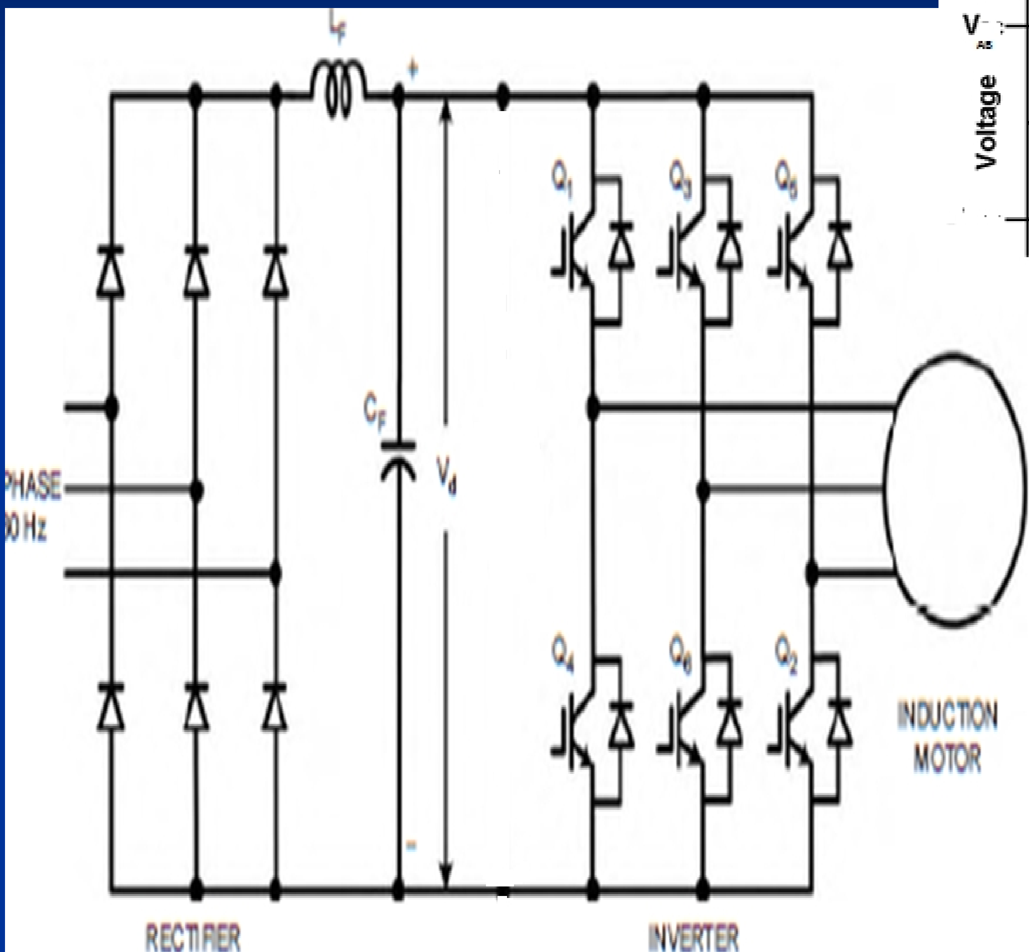
The variable frequency and variable voltage can be obtained by,

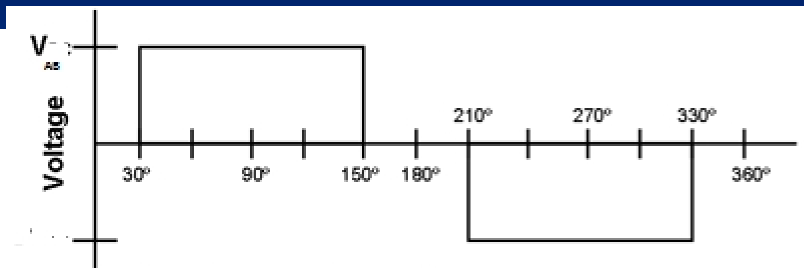
- Voltage source inverter(VSI)
- Cycloconverter control

VSI(cont….)

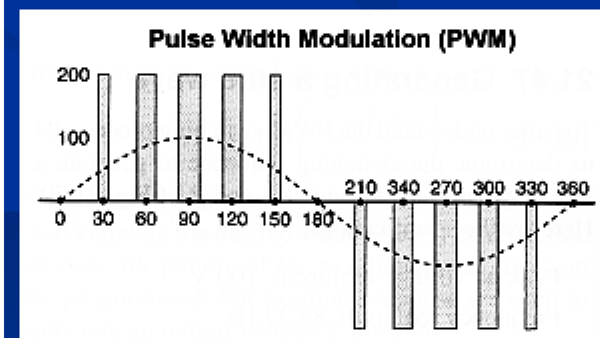


VSI

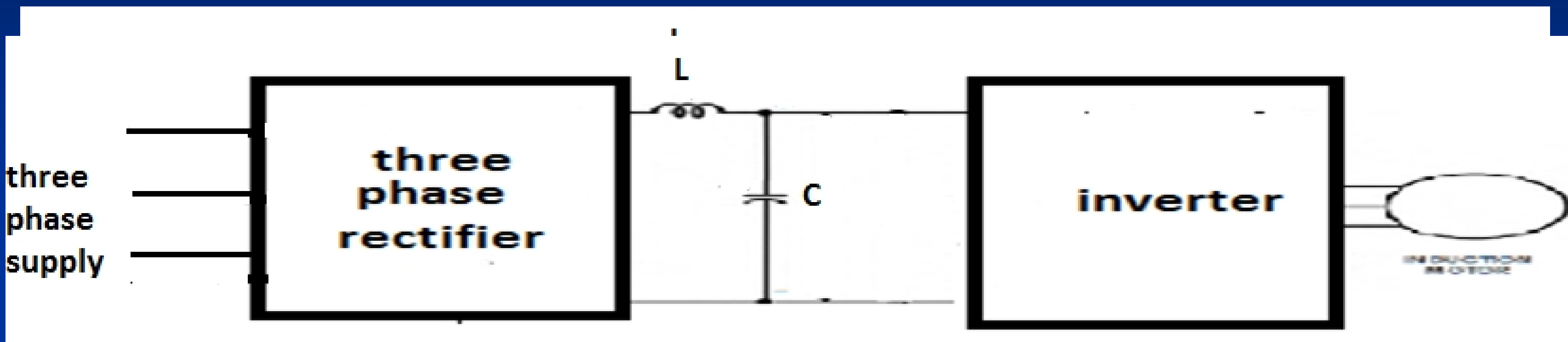


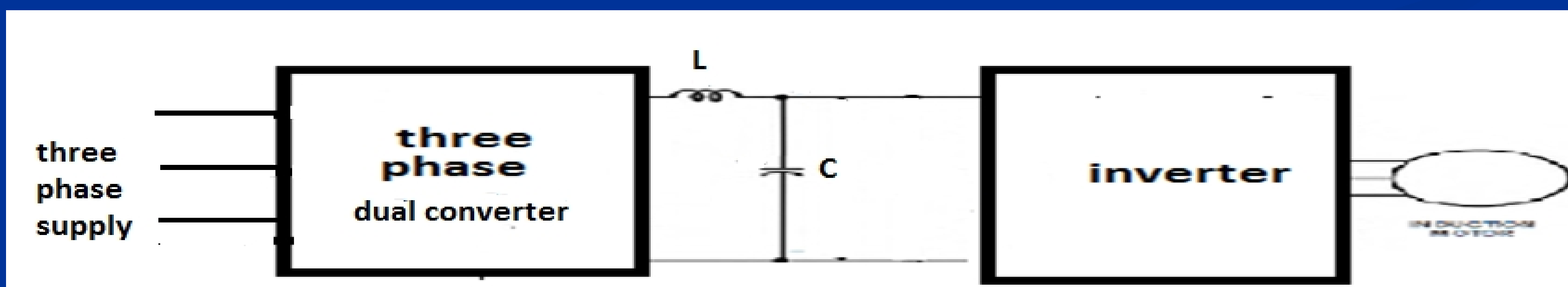


Inverter stepped wave line voltage waveform



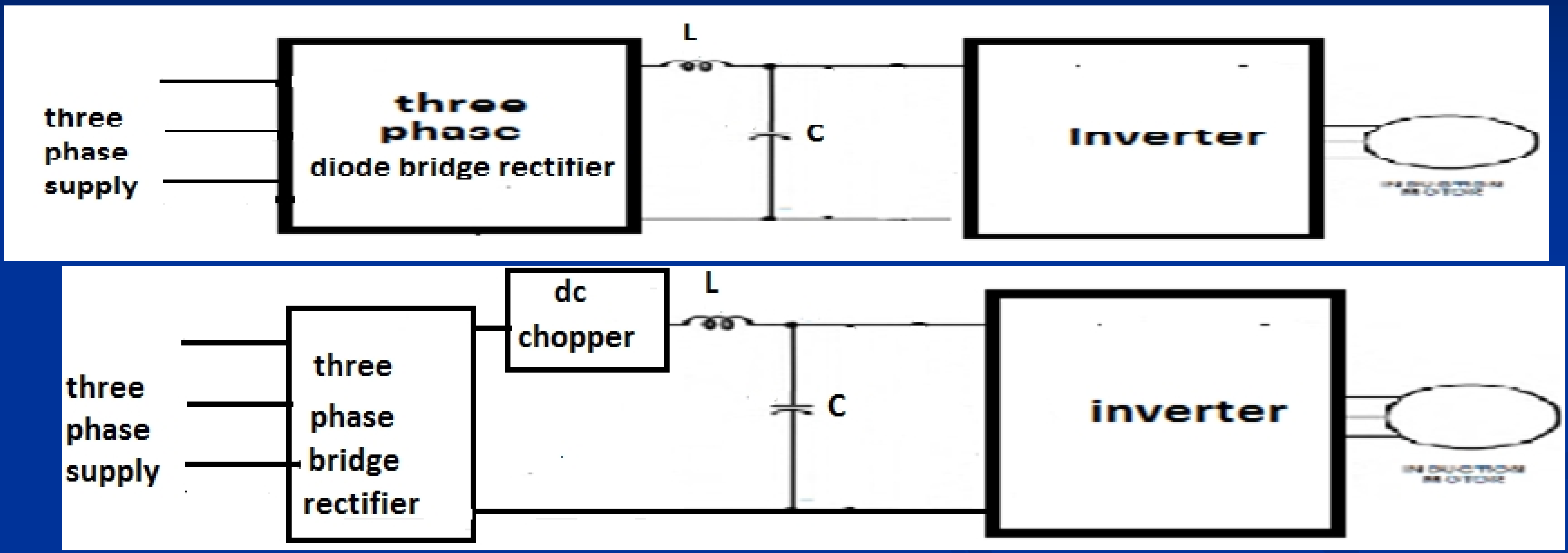
Different schemes of VSI





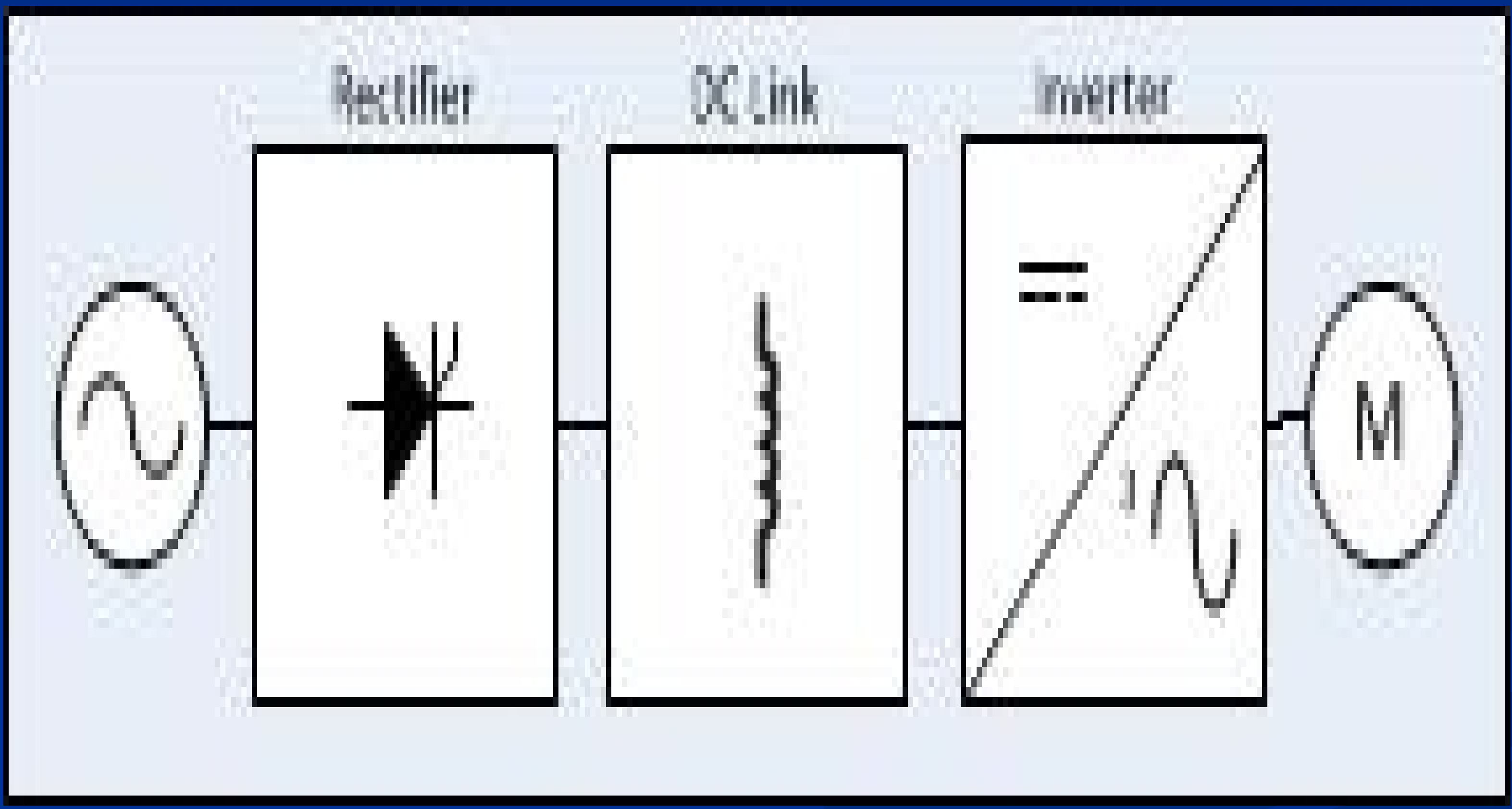
- If regeneration is necessary, the phase controlled bridge rectifier is replaced by dual converter

Different schemes of VSI

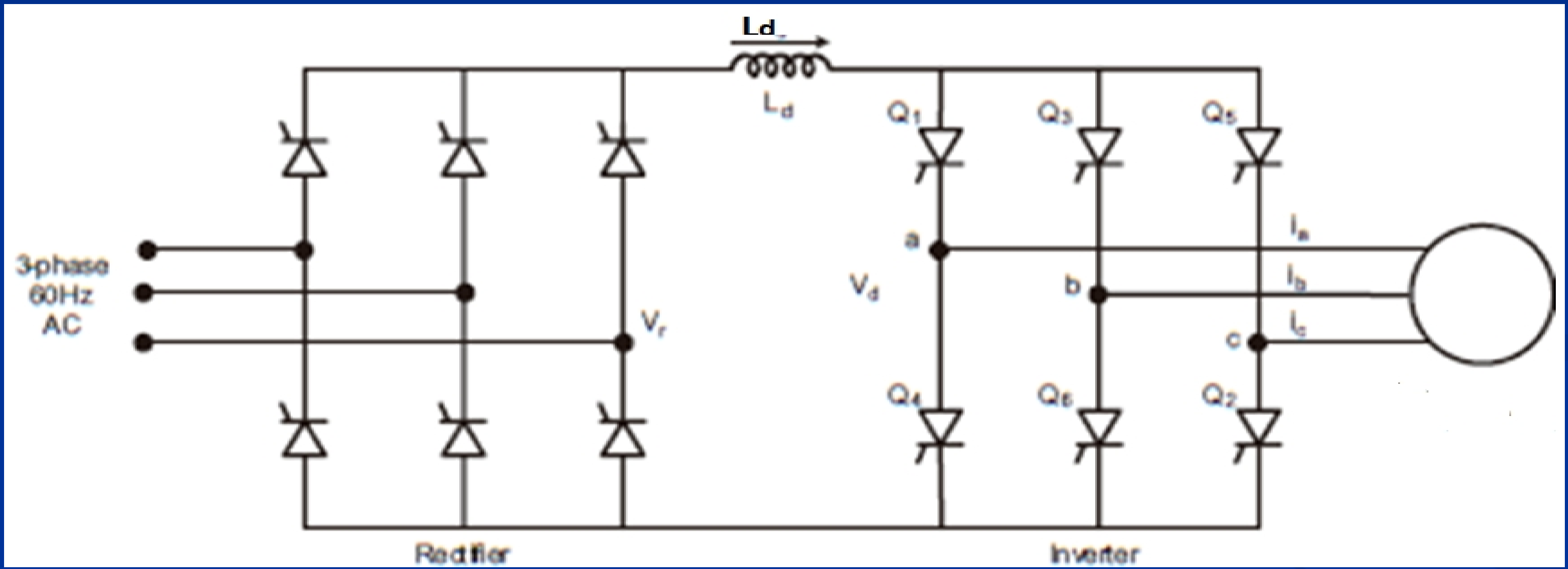


- Due to chopper ,the harmonic injection into the ac supply is reduced

Variable current and variable frequency (CSI) (cont….)

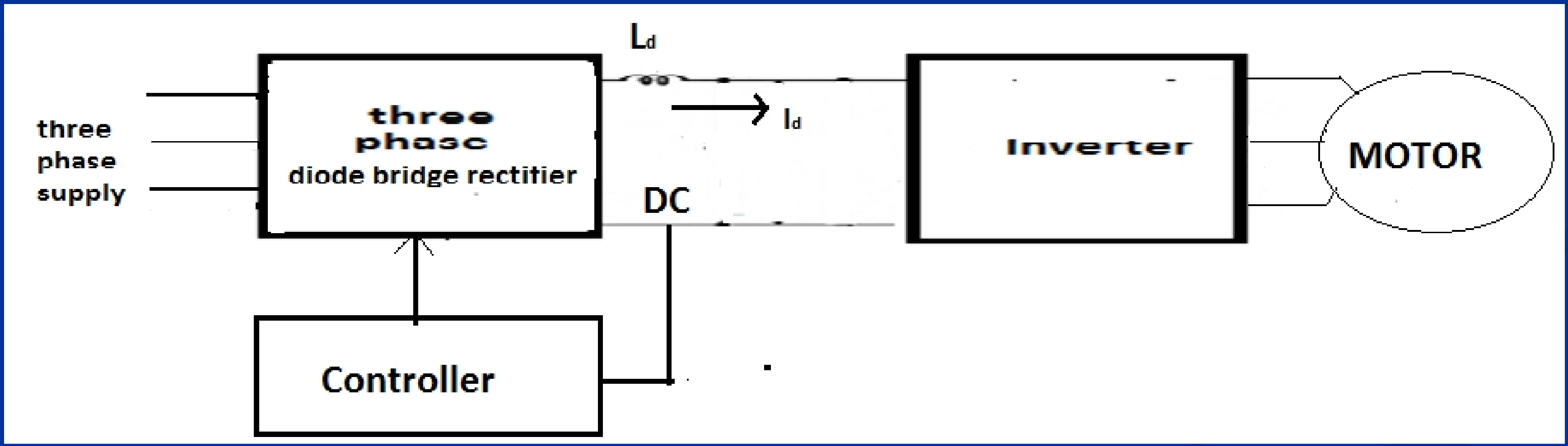


current source inverter(CSI) (cont….)

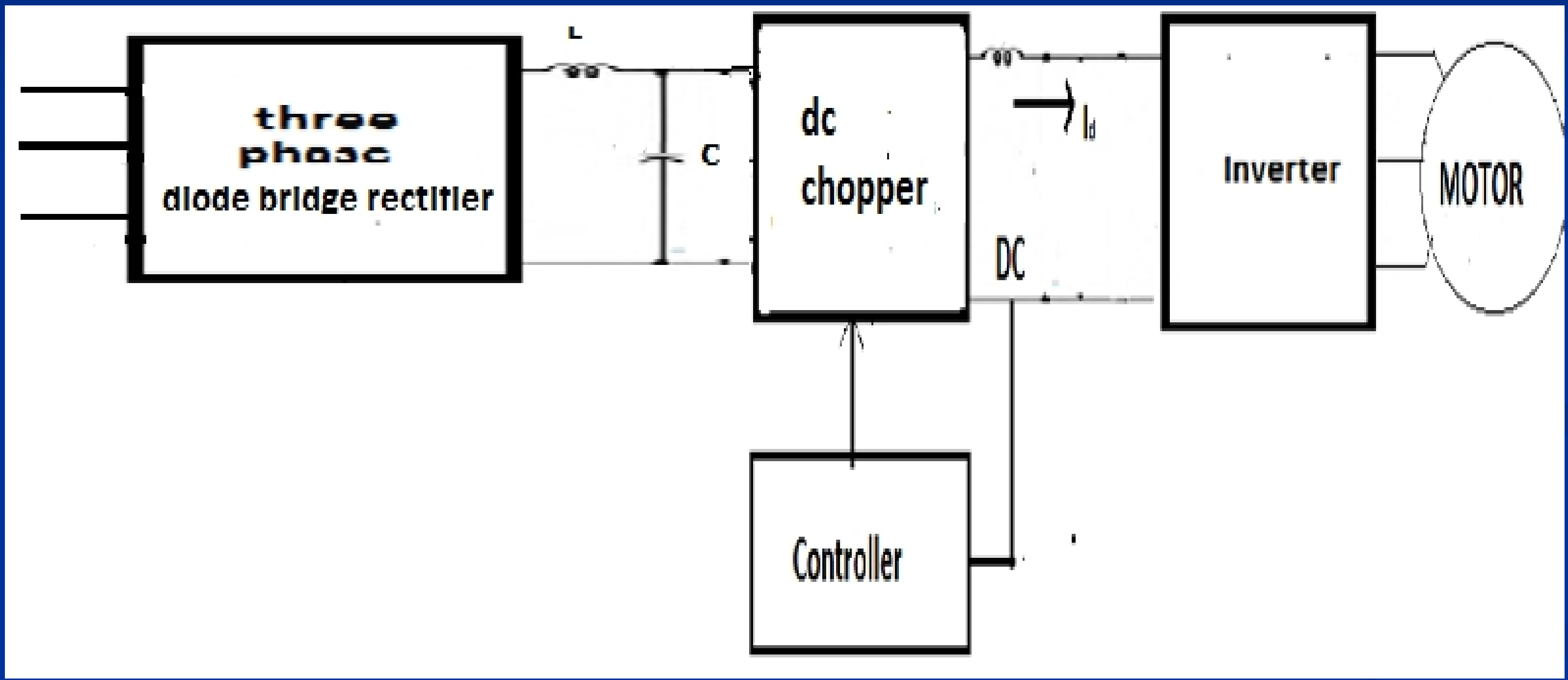


- Input voltage kept constant output current depends upon the nature of load

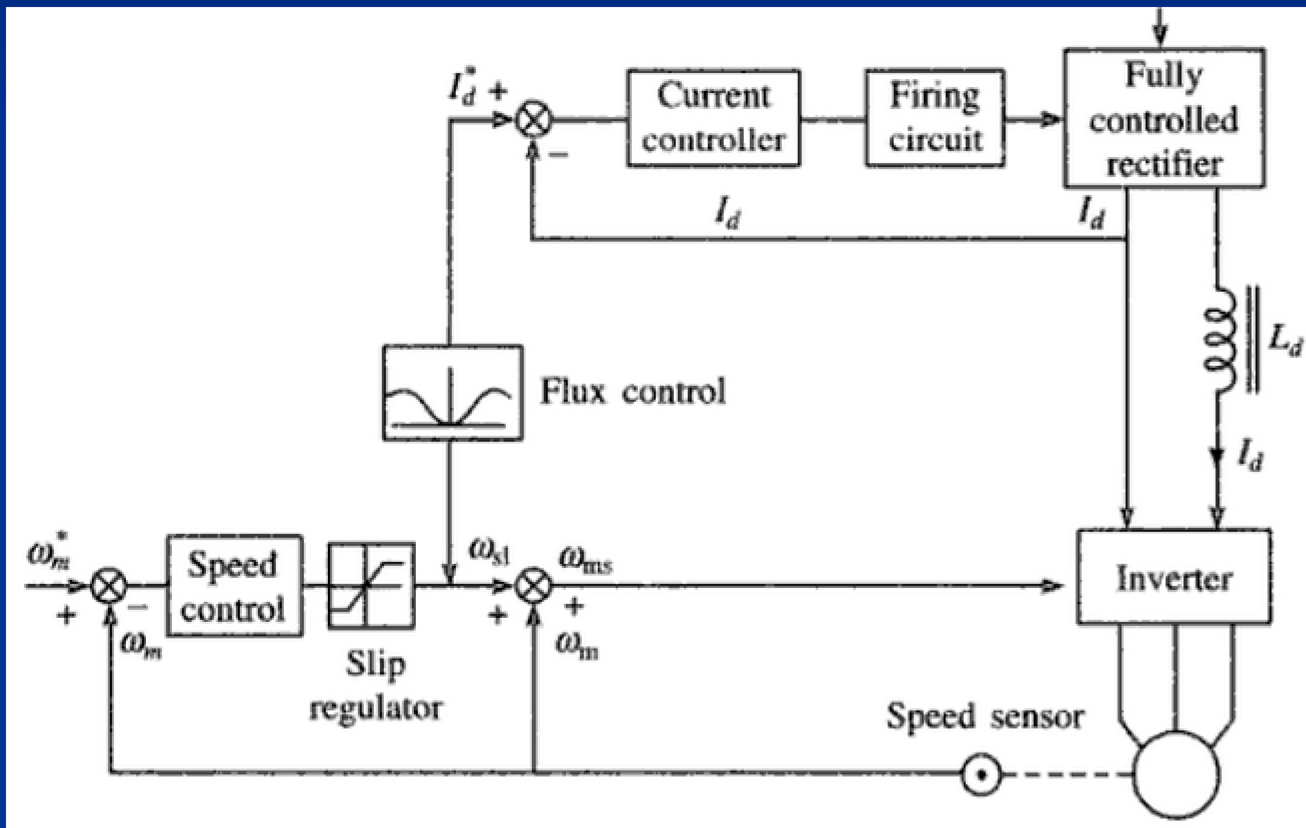
Different schemes of CSI(cont….)



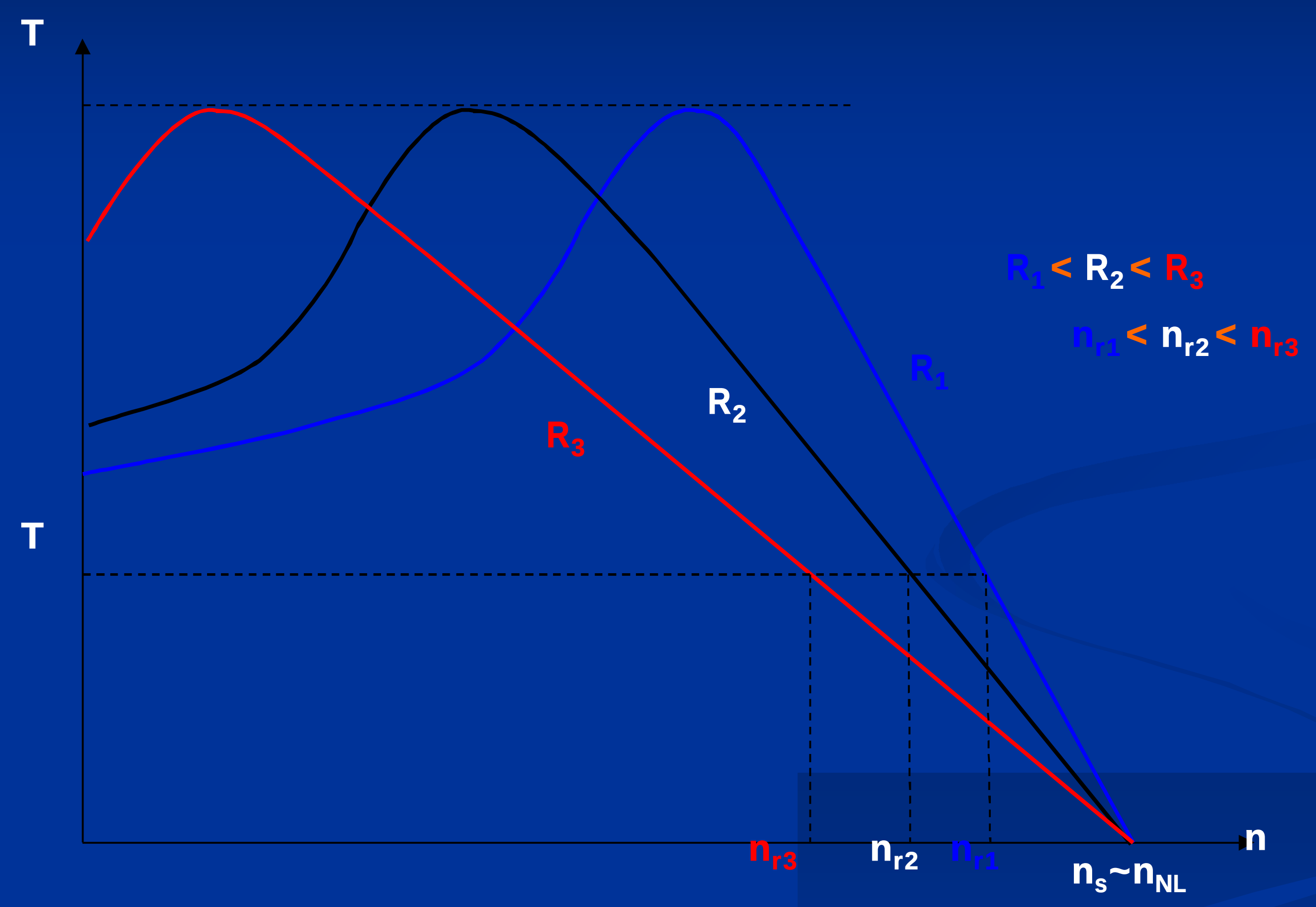
Different schemes of CSI(cont….)



Closed loop control of CSI fed IM

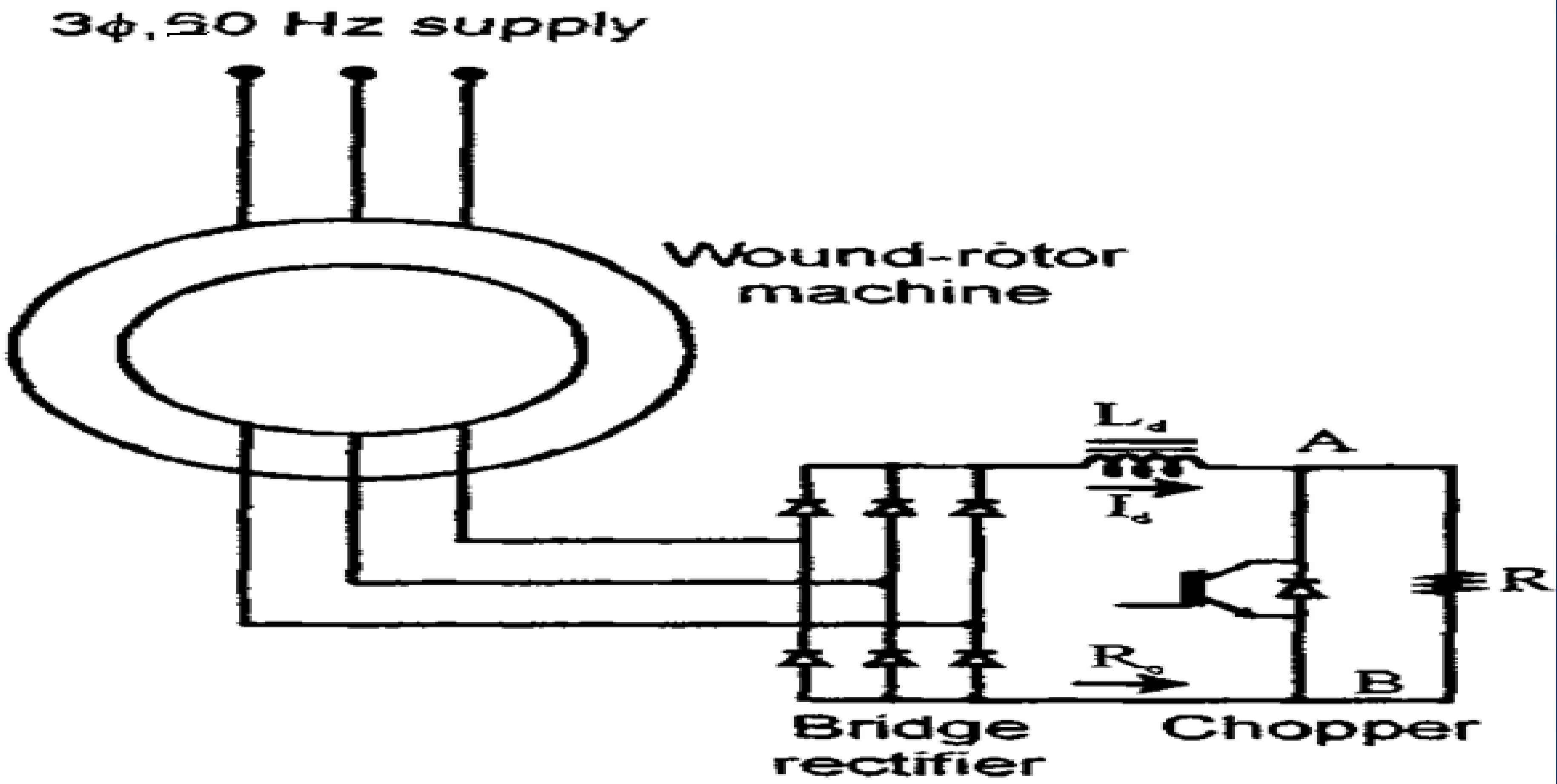


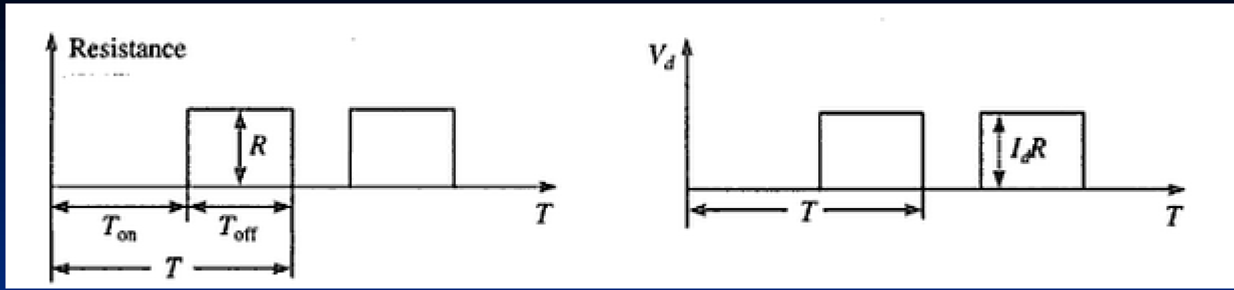
Rotor resistance control(cont….)



Static rotor resistance control(cont….)

- An electronic chopper implementation is also possible as shown below but is equally inefficient





the duty ratio of the switch T_r is defined as

$$\alpha = \frac{T_{on}}{T}$$

The effective external resistance R_{ef} is

$$R_{ef} = \frac{1}{T}\int_0^T R\,dt = \frac{1}{T}\left[\int_0^{T_{on}} R\,dt + \int_{T_{on}}^{T} R\,dt\right]$$

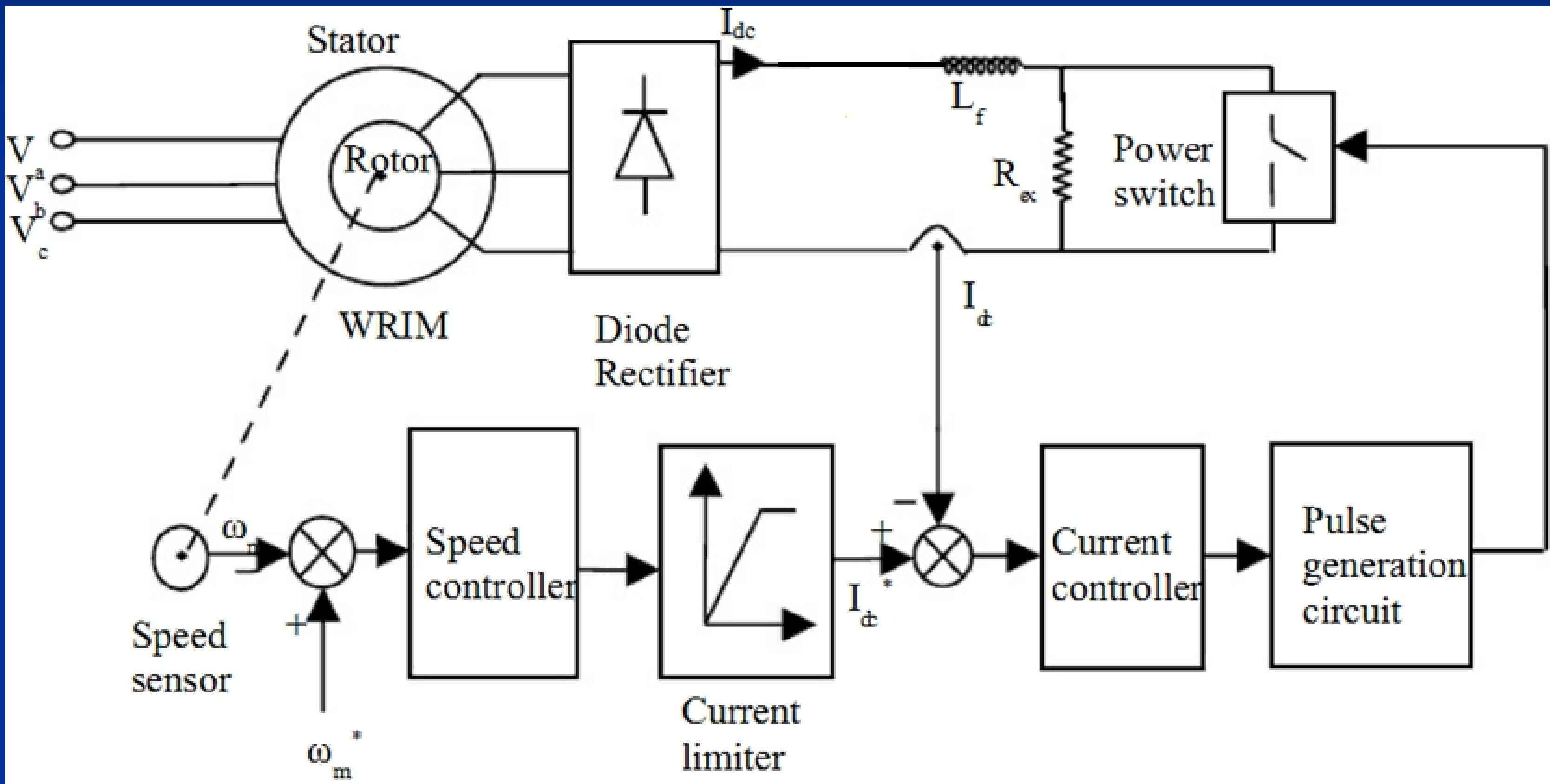
$$= \frac{1}{T}\left[\int_0^{T_{on}} 0\,dt + \int_{T_{on}}^{T} R\,dt\right]$$

$$R_{ef} = \frac{1}{T}\int_{T_{on}}^{T} R\,dt = \frac{R}{T}(T - T_{on})$$

$$R_{ef} = R\left(1 - \frac{T_{on}}{T}\right)$$

$$R_{ef} = R(1 - \alpha)$$

Closed loop control static rotor resistance(contn….)



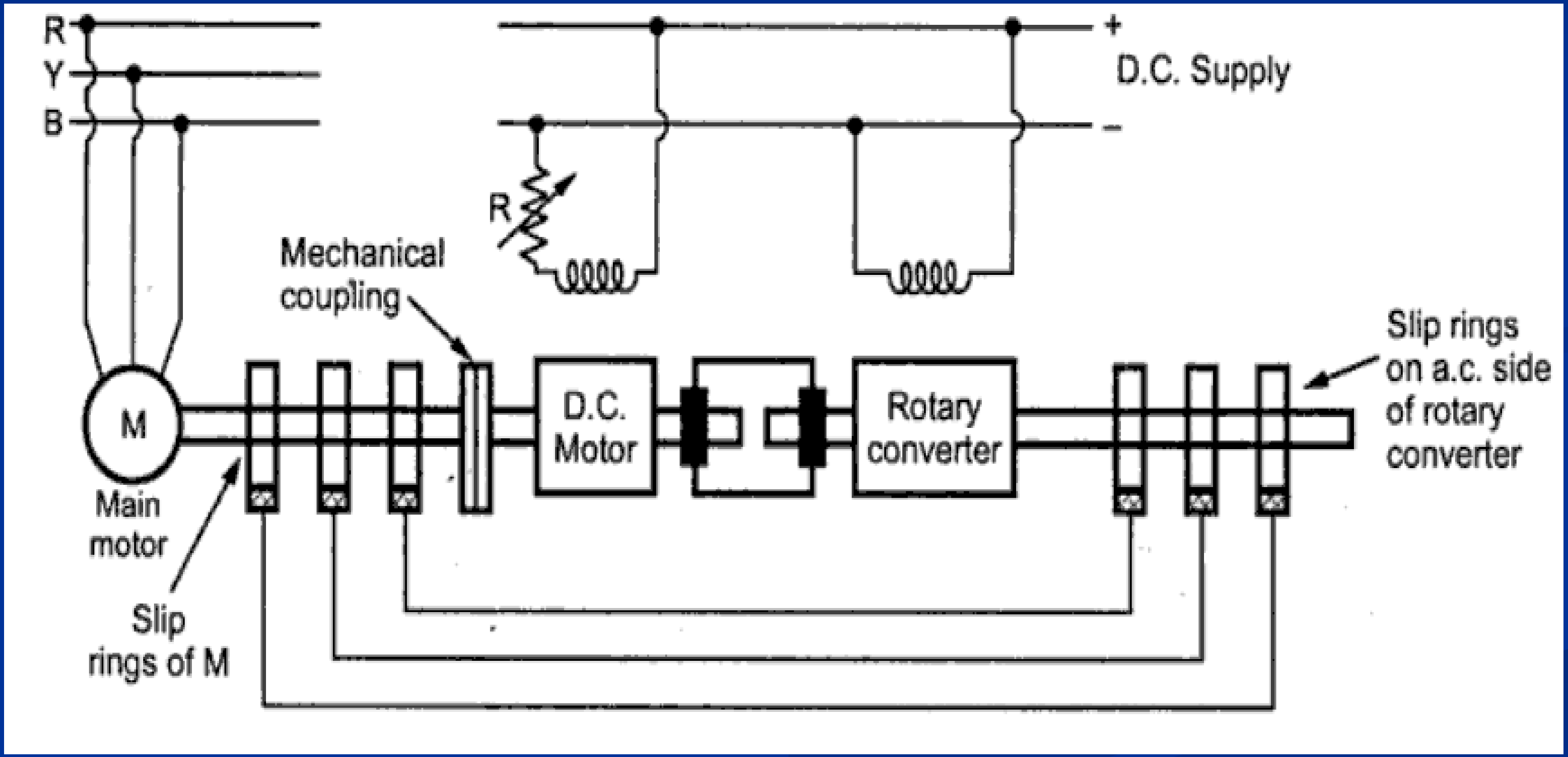
Slip power recovery

- Instead of wasting the slip power in the rotor circuit resistance, a better approach is to convert it to ac line power and return it back to the line. Two types of converter provide this approach:

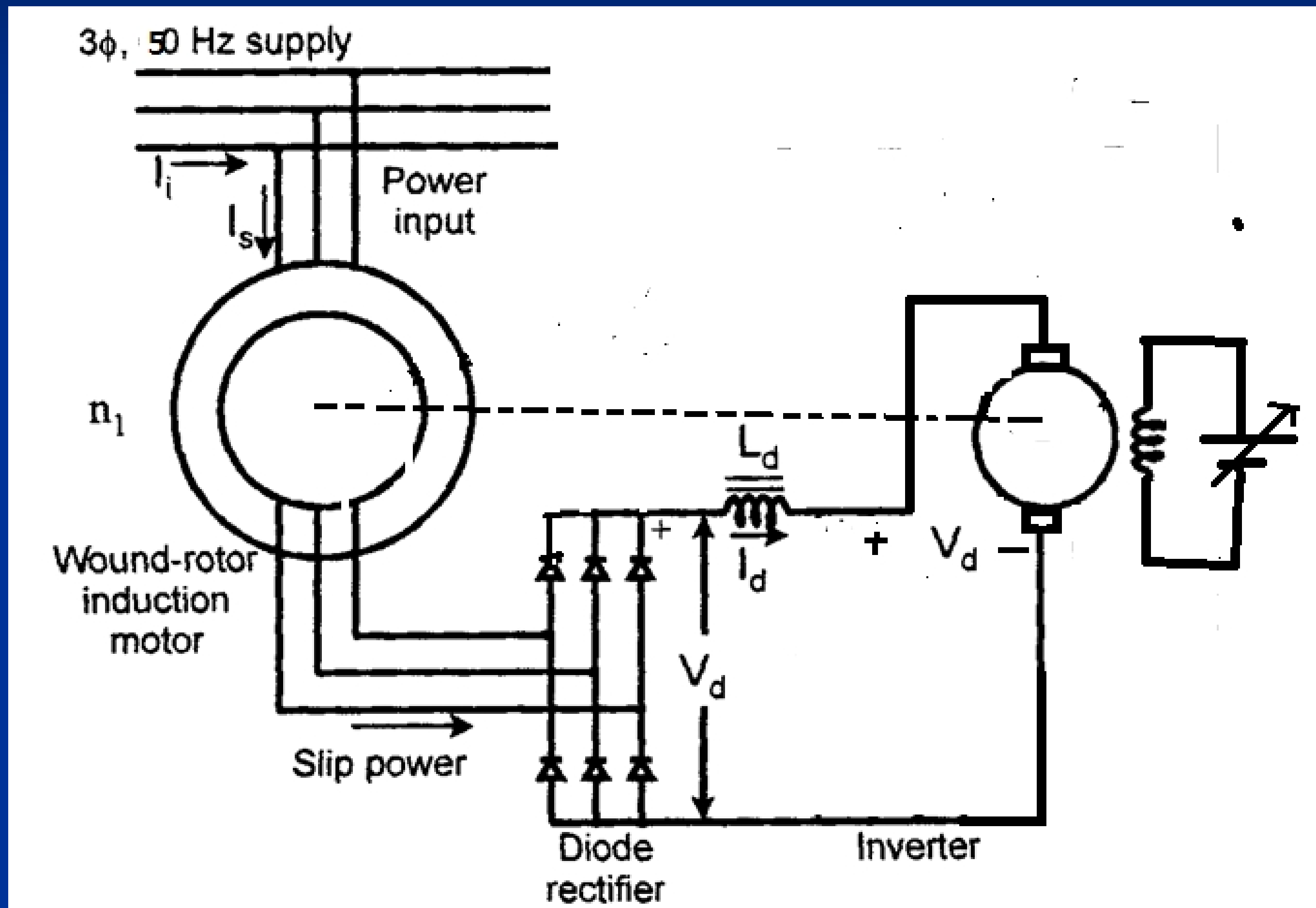
1) Static Kramer Drive - only allows operation at sub-synchronous speed.

2) Static Scherbius Drive - allows operation above and below synchronous speed

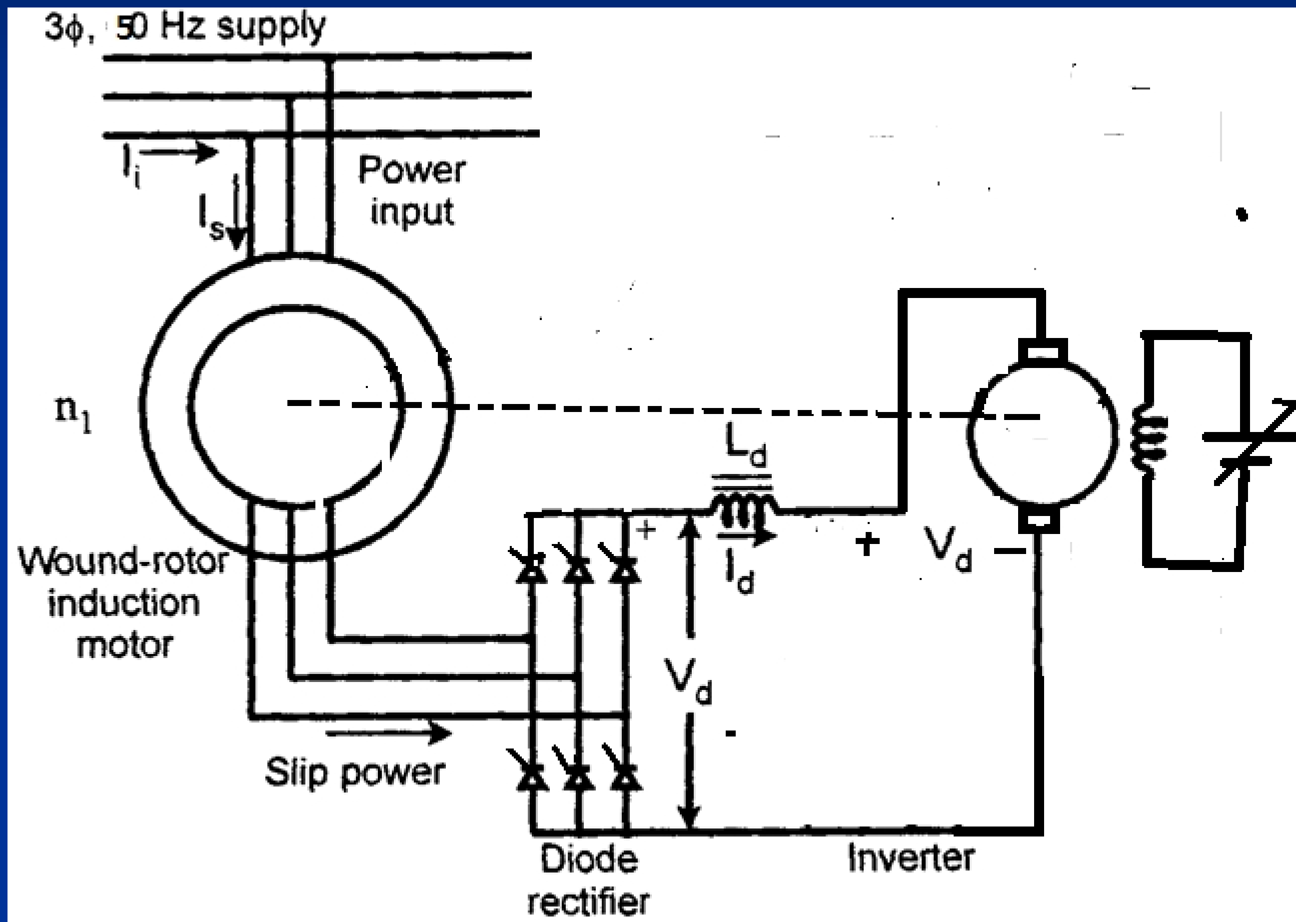
Conventional kramer sysytem(contn….)



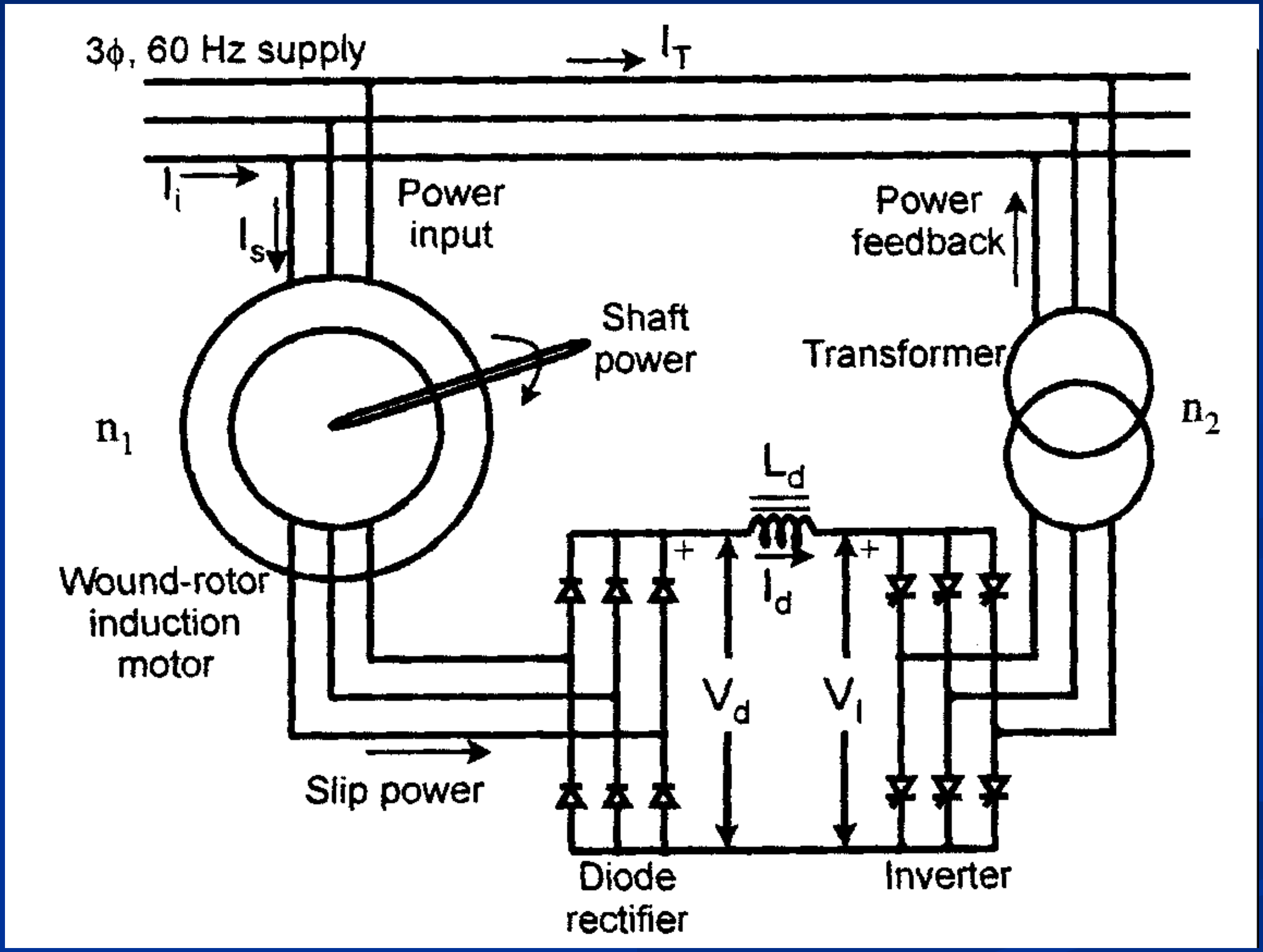
Improved version of kramer system(Ns to half of Ns) (contn….)



Improved version of kramer system(zero to Ns) (contn….)



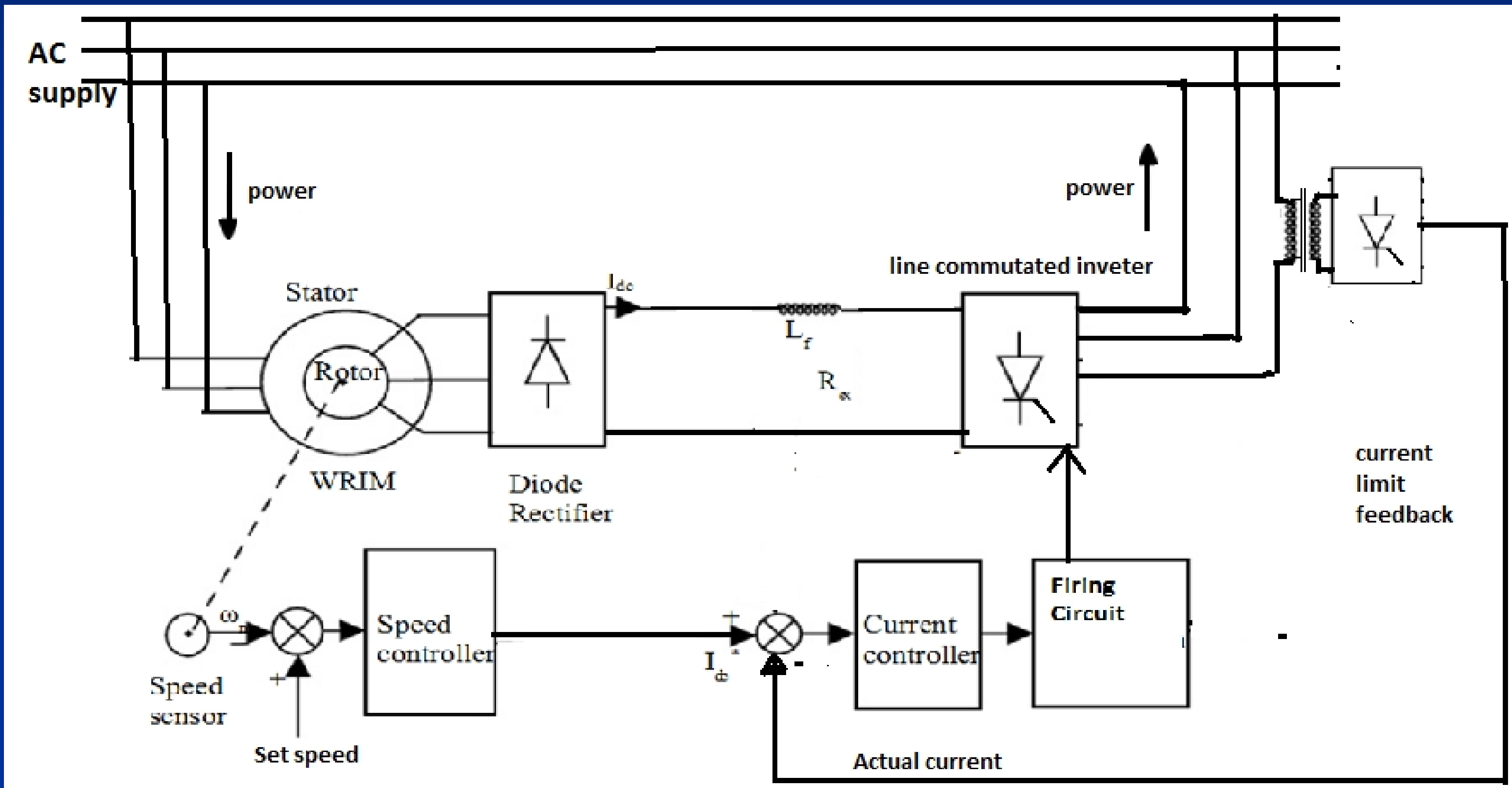
Static kramer system(contn….)



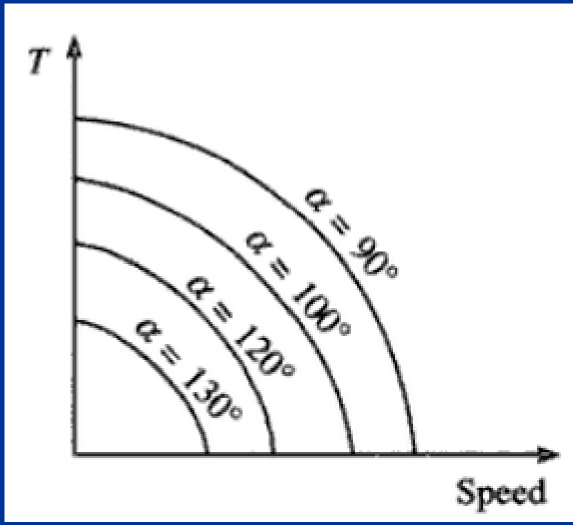
Appliaction(contn….)

- Large pumps
- Fan type loads

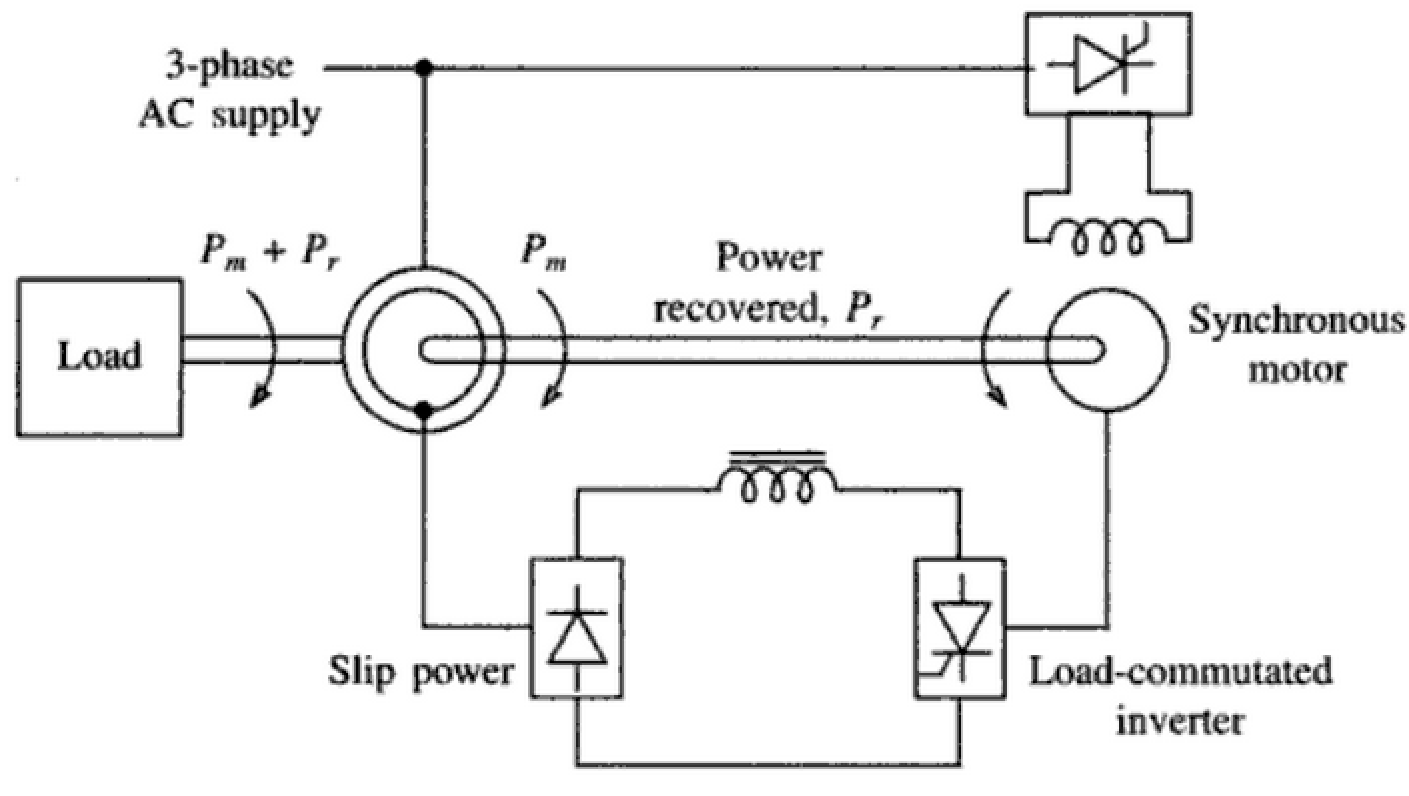
Closed loop control of static kramer system(contn….)



(contn….)

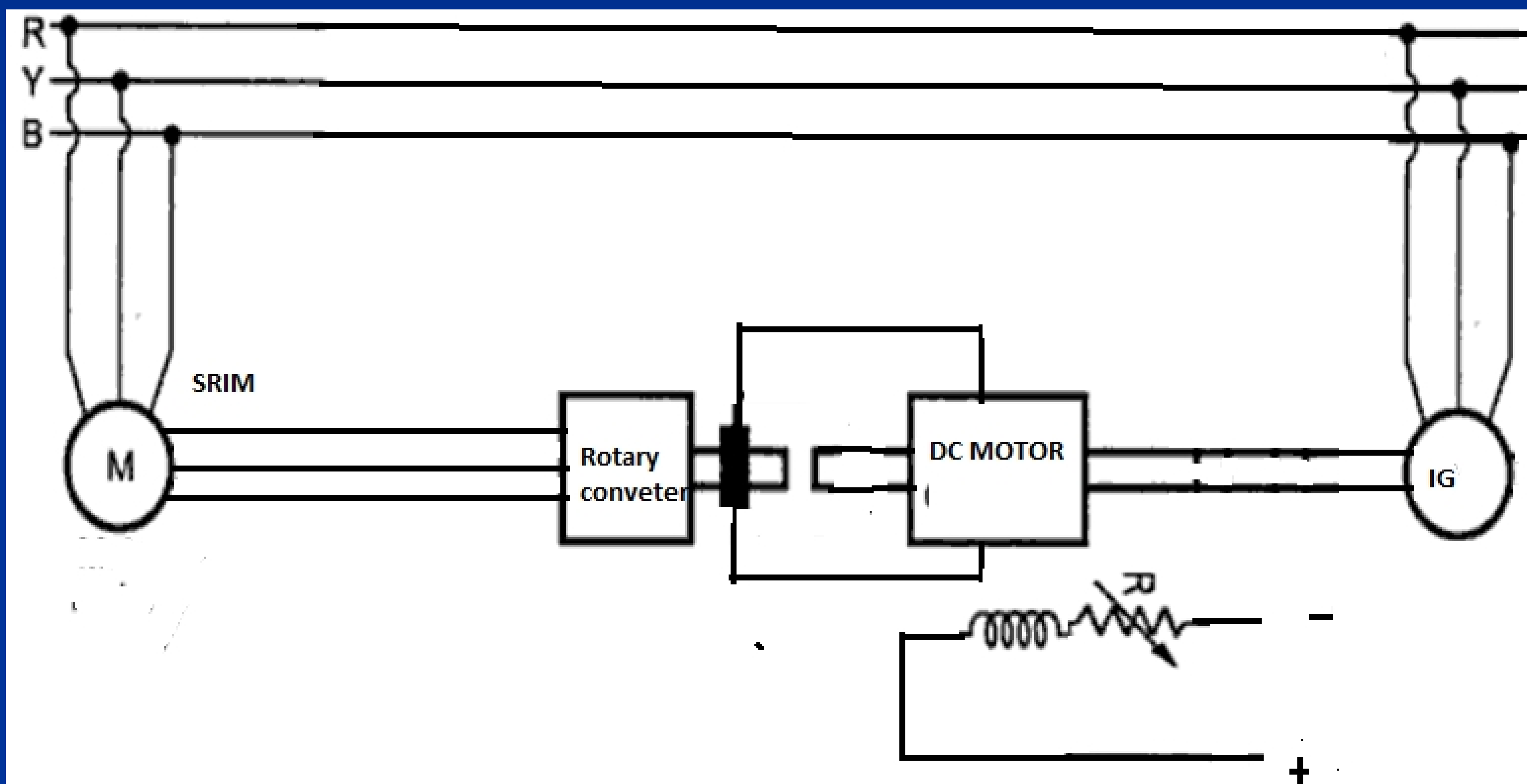


Modified kramer system(contn….)



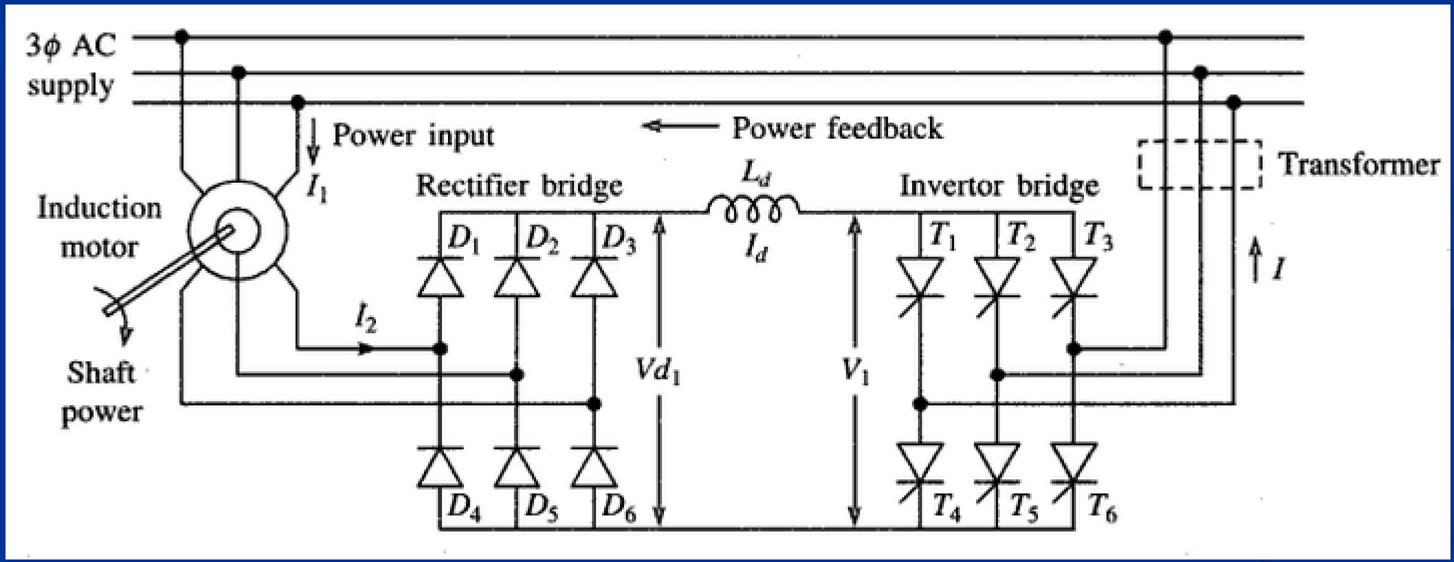
Commutatorless Kramer drive.

Scherbius system(conventional scherbius system) (contn….)

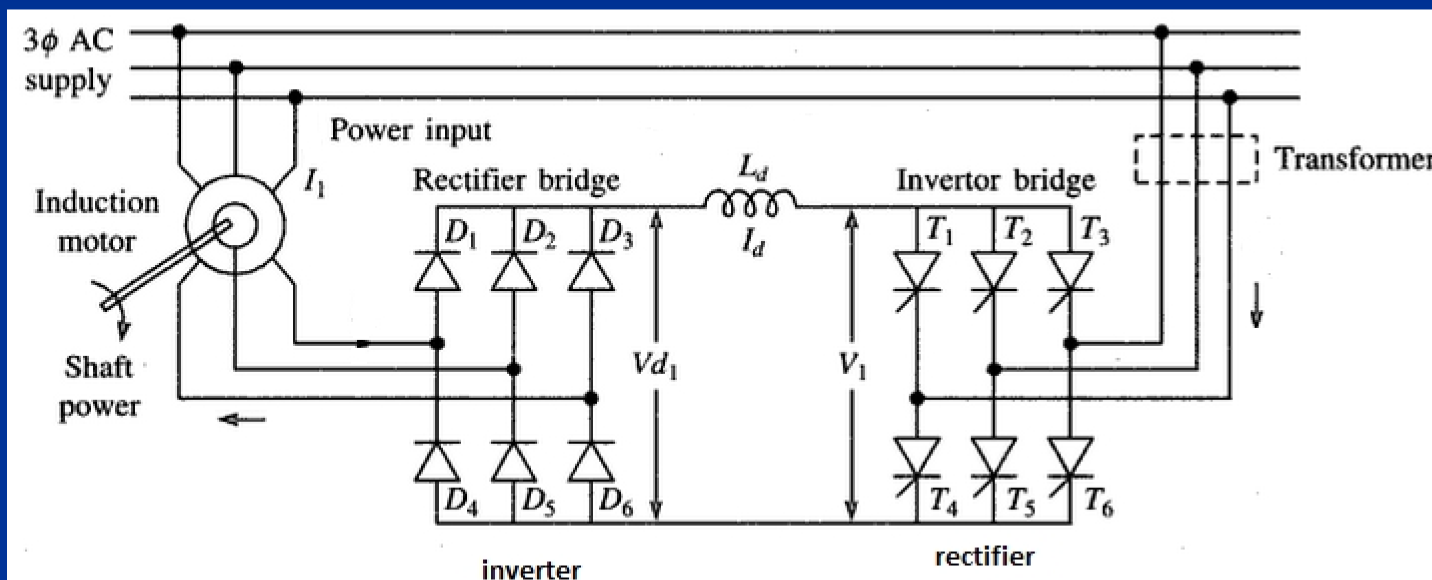


Static scherbius system(contn….)

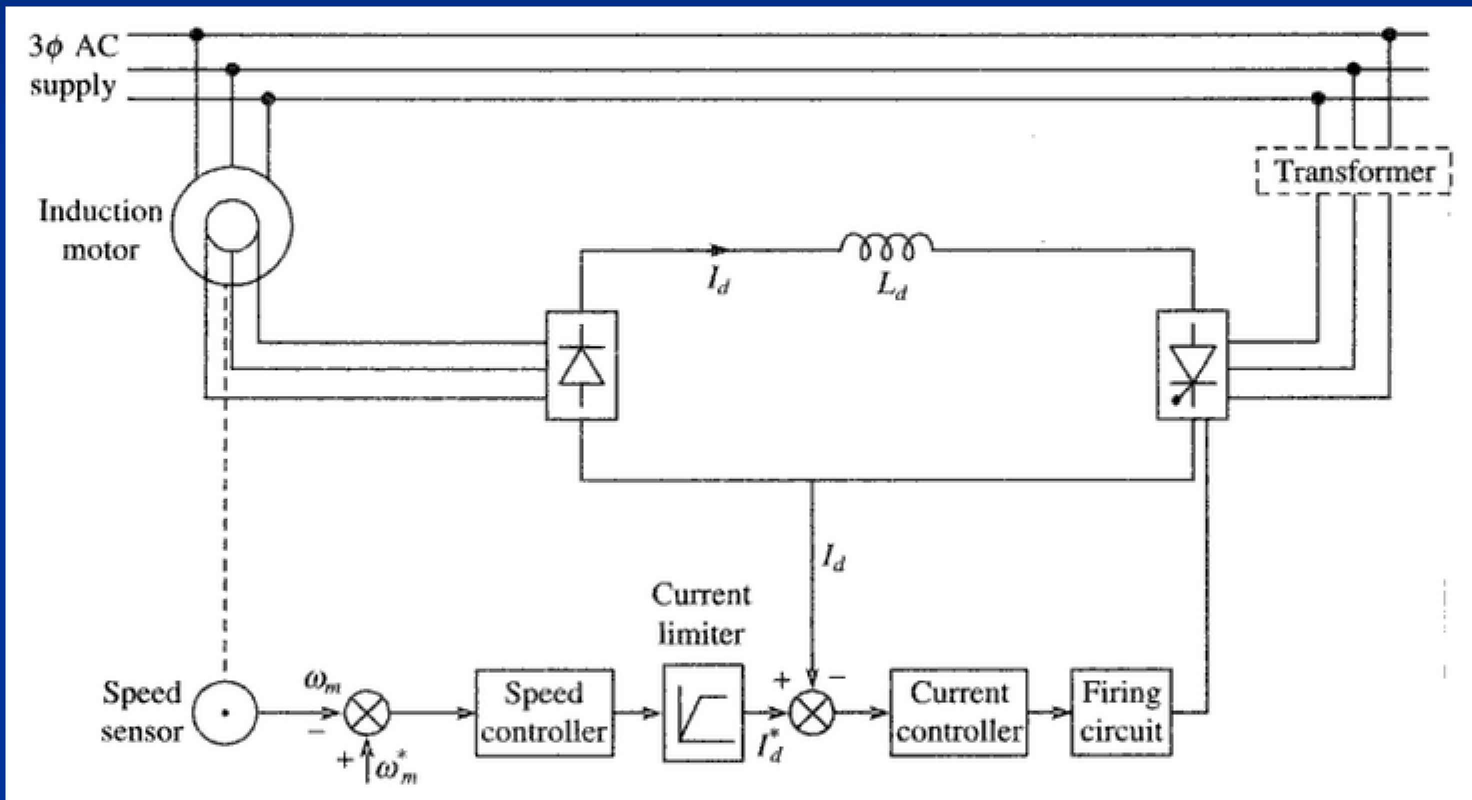
slip power –rectifier-inveter-transformer-supply



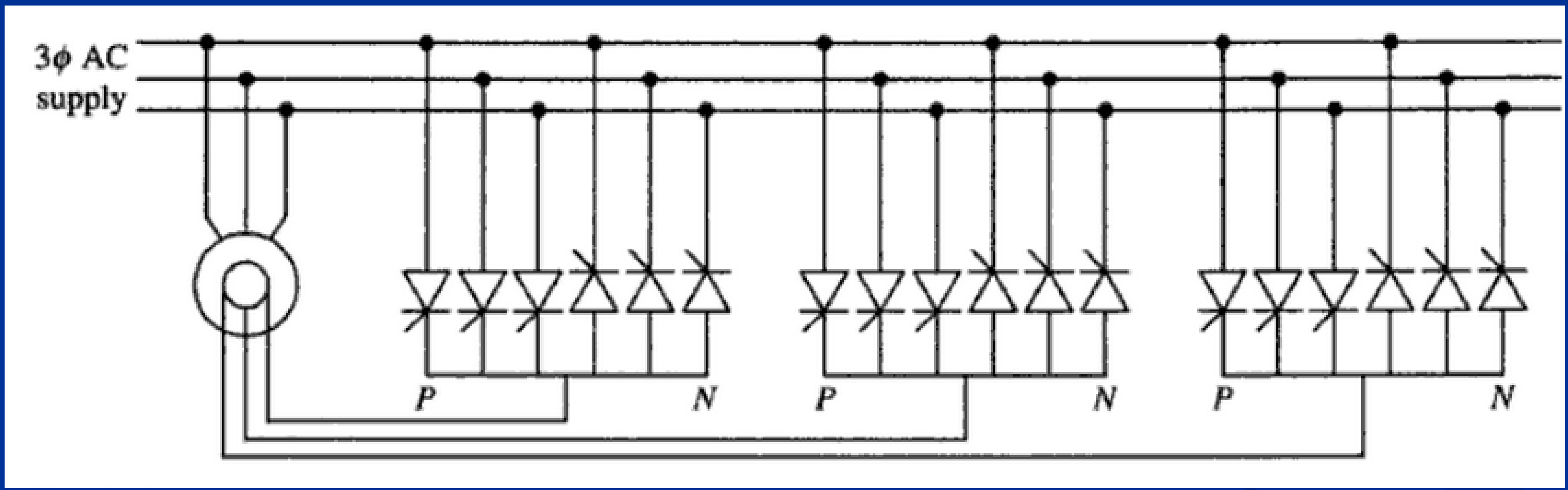
Supply-transformer-rectifier-inverter-rotor circuit(contn….)



Closed loop control of scherbius sytem(contn….)



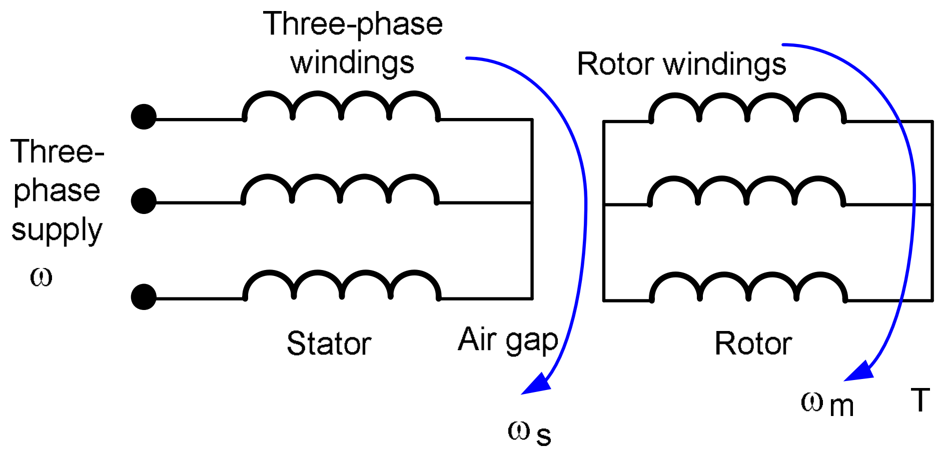
Cycloconverter static scherbius(contn….)



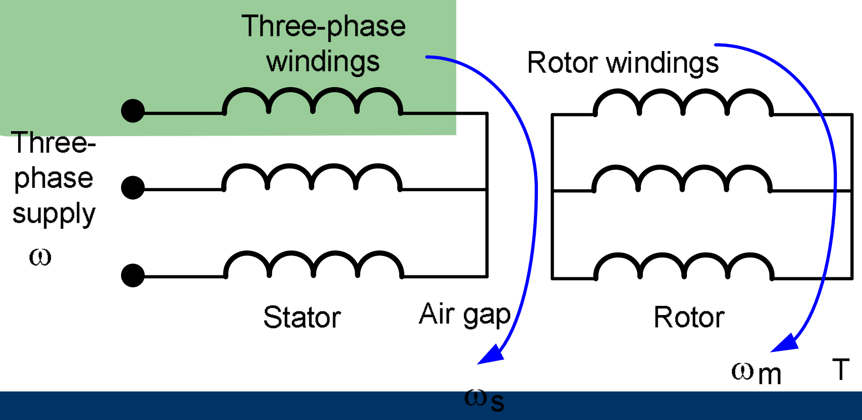
INDUCTION MOTOR DRIVES

Three-phase induction motor are commonly used in adjustable-speed drives (ASD).

Basic part of three-phase induction motor :



- **Stator**
- **Rotor**
- **Air gap**



The stator winding are supplied with balanced three-phase AC voltage, which produce induced voltage in the rotor windings. It is possible to arrange the distribution of stator winding so that there is an effect of multiple poles, producing several cycle of magnetomotive force (mmf) or field around the air gap.

The speed of rotation of field is called the **synchronous speed** ω_s, which is defined by :

$$\omega_s = \frac{2\omega}{p}$$

or

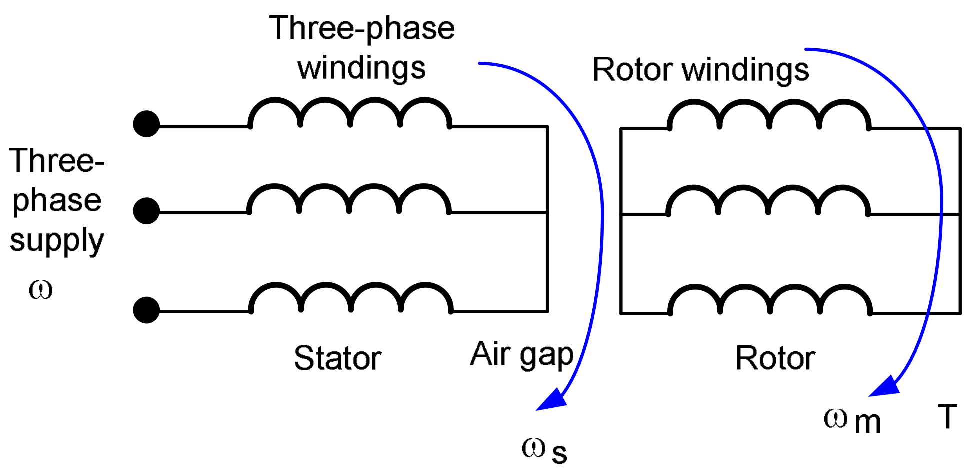
$$N_s = \frac{120\ f}{p}$$

ω_s is syncronous speed [rad/sec]
N_s is syncronous speed [rpm]
p is numbers of poles
ω is the supply frequency [rad/sec]
f is the supply frequency [Hz]
N_m is motor speed

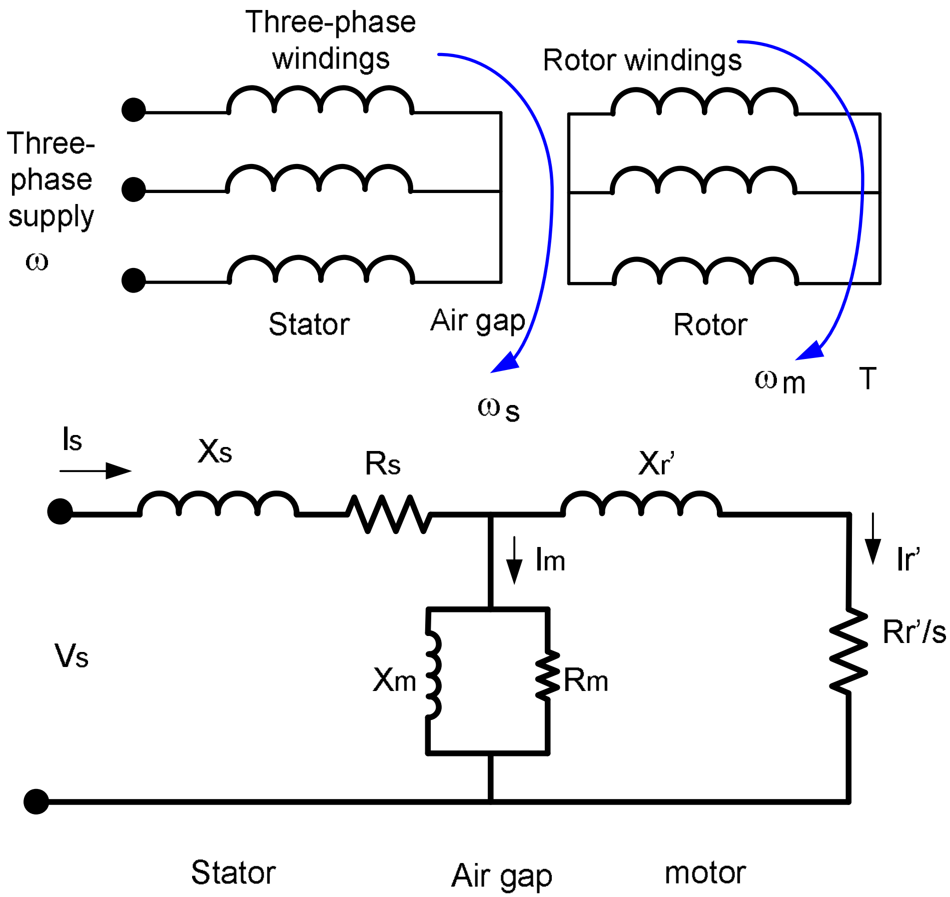
The motor speed

The rotor speed or motor speed is : $$\omega_m = \omega_s\,(1 - S)$$

Where S is slip, as defined as : $$S = \frac{\omega_S - \omega_m}{\omega_S}$$ Or $$S = \frac{N_S - N_m}{N_S}$$



Equivalent Circuit Of Induction Motor



Where :

Rs is resistance per-phase of stator winding

Rr is resistance per-phase of rotor winding

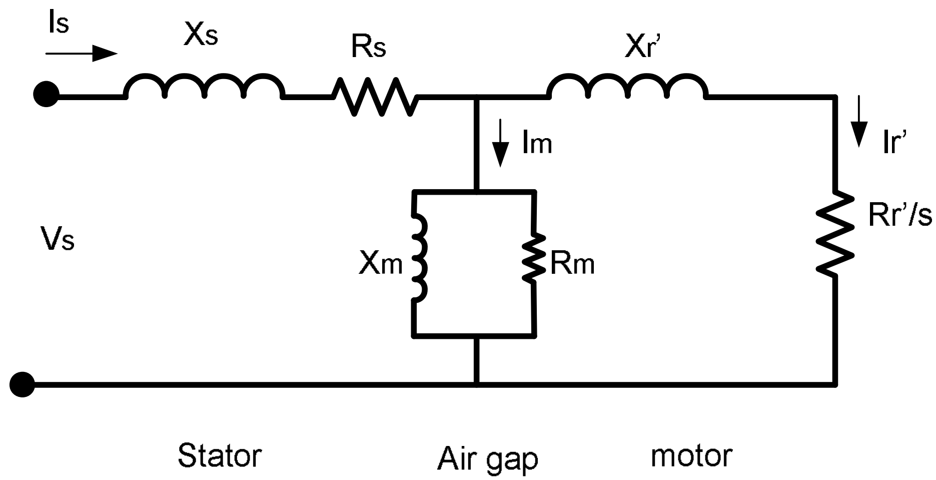
Xs is leakage reactance per-phase of the winding stator

Xs is leakage reactance per-phase of the winding rotor

X_m is magnetizing reactance

$R_{m\ is}$ Core losses as a reactance

Performance Characteristic of Induction Motor



Stator copper loss : $$P_{scu} = 3 I_s^{\,2} R_s$$

Rotor copper loss : $$P_{rcu} = 3 (I_r^{'})^2 R_r^{'}$$

Core losses : $$P_c = 3\frac{V_m^{\,2}}{R_m} \approx 3\frac{V_s^{\,2}}{R_m}$$

Performance Characteristic of Induction Motor

- **Power developed on air gap (Power fropm stator to rotor through air gap) :**

$$P_g = 3(I_r^{'})^2 \frac{R_r^{'}}{S}$$

- **Power developed by motor :** $P_d = P_g - P_{rcu} = 3(I_r^{'})^2 \frac{R_r^{'}}{S}(1-S)$

or $P_d = P_g(1-S)$

- **Torque of motor :** $T_d = \frac{P_d}{\omega_m}$ **or** $T_d = \frac{P_d\, 60}{2\pi N_m}$

or $= \frac{P_g(1-S)}{\omega_S(1-S)} = \frac{P_g}{\omega_s}$

Performance Characteristic of Induction Motor

Input power of motor :

$$P_i = 3V_s I_s \cos\phi_m$$
$$= P_c + P_{scu} + P_g$$

Output power of motor :

$$P_o = P_d - P_{noload}$$

Efficiency :

$$\eta = \frac{P_o}{P_i} = \frac{P_d - P_{noload}}{P_c + P_{scu} + P_g}$$

Performance Characteristic of Induction Motor

If $P_g >> (P_c + P_{scu})$

and $P_d >> P_{no\,load}$

so, the efficiency can calculated as :

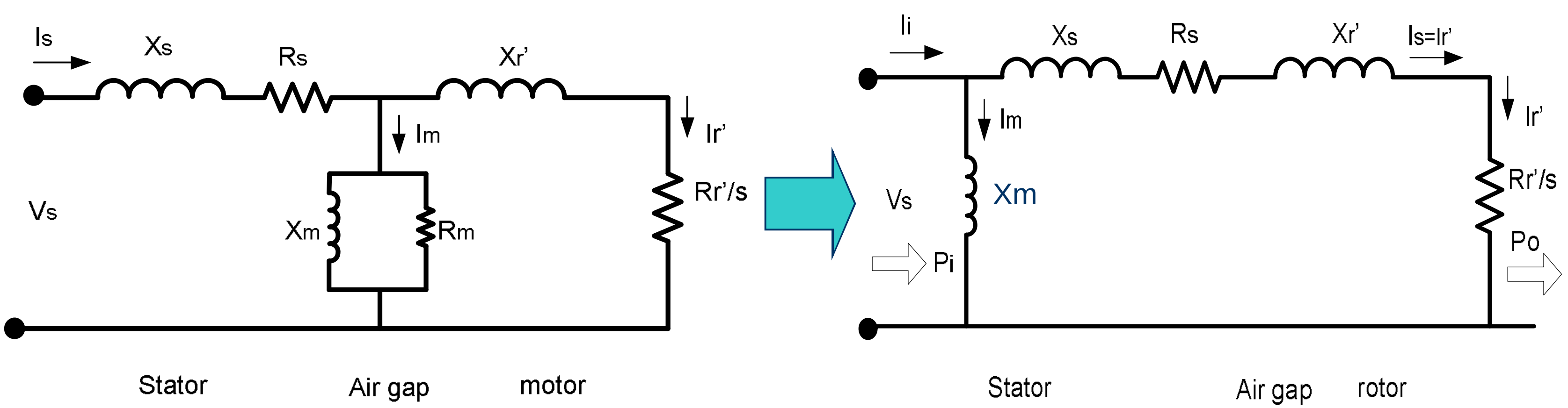
$$\eta \approx \frac{P_d}{P_g} = \frac{P_g(1-S)}{P_g} = 1 - S$$

Performance Characteristic of Induction Motor

Generally, value of reactance magnetization X_m >> value Rm (core losses) and also $X_m^2 >> (R_s^2 + X_s^2)$

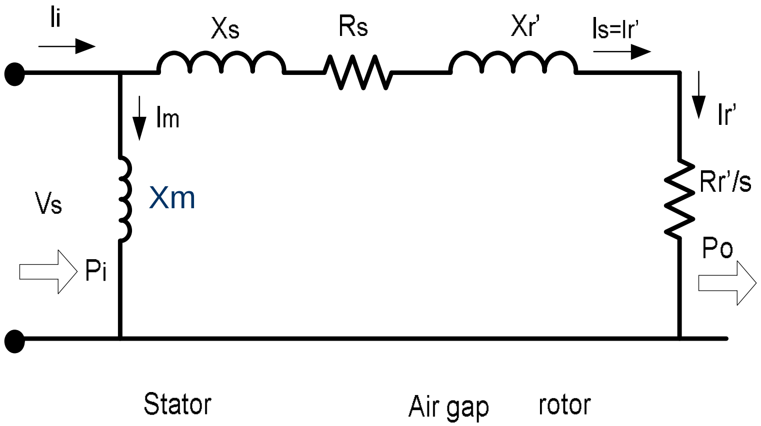
So, the magnetizing voltage same with the input voltage : $V_m \approx V_s$

Therefore, the equivalent circuit is ;



Performance Characteristic of Induction Motor

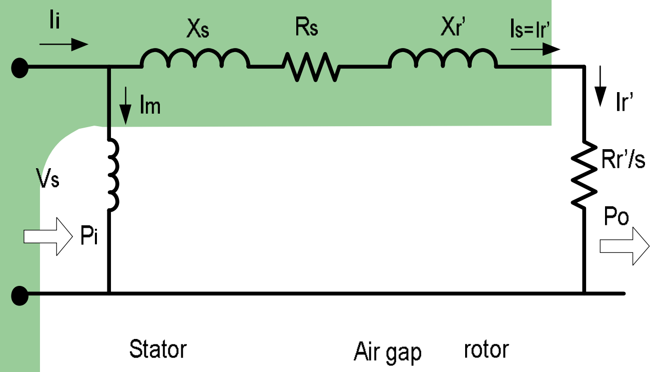
Total Impedance of this circuit is :



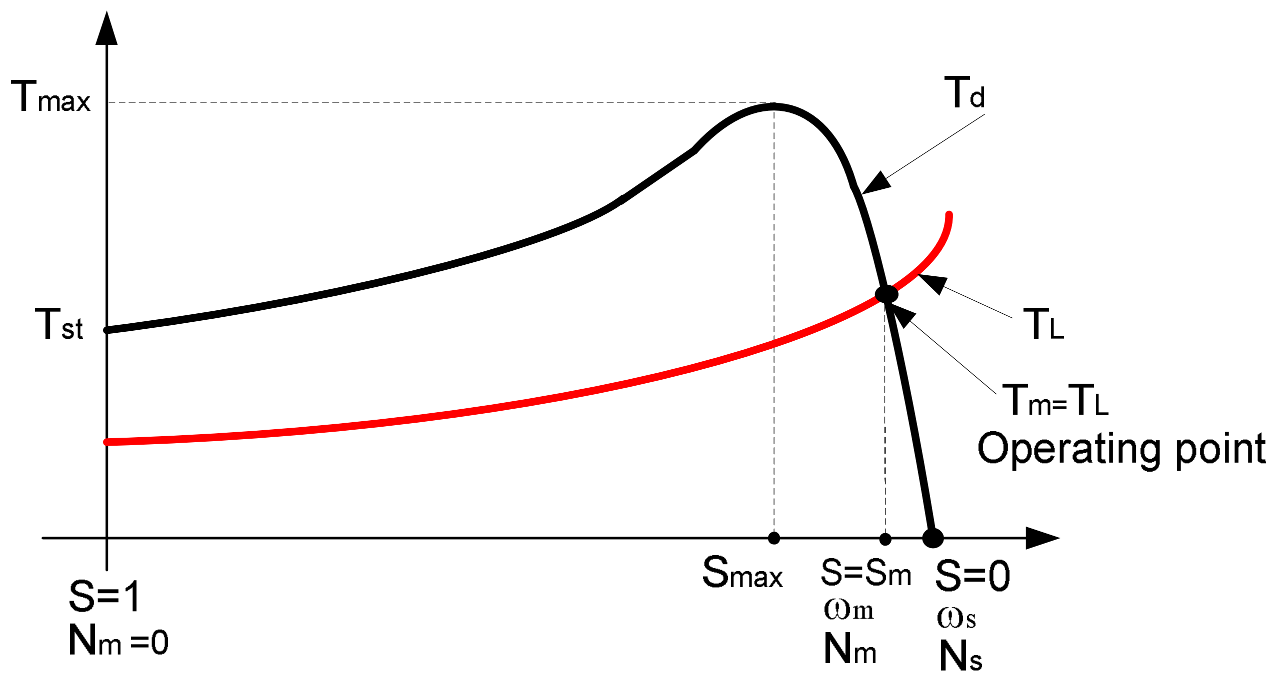
$$Z_i = \frac{-X_m(X_s + X_r') + jX_m\left(R_s + \frac{R_r'}{S}\right)}{R_s + \frac{R_r'}{S} + j(X_m + X_s + X_r')}$$

The rotor current is :

$$I_r' = \frac{V_s}{\left[\left(R_s + \frac{R_r'}{S}\right)^2 + \left(X_s + X_r'\right)^2\right]^{\frac{1}{2}}}$$



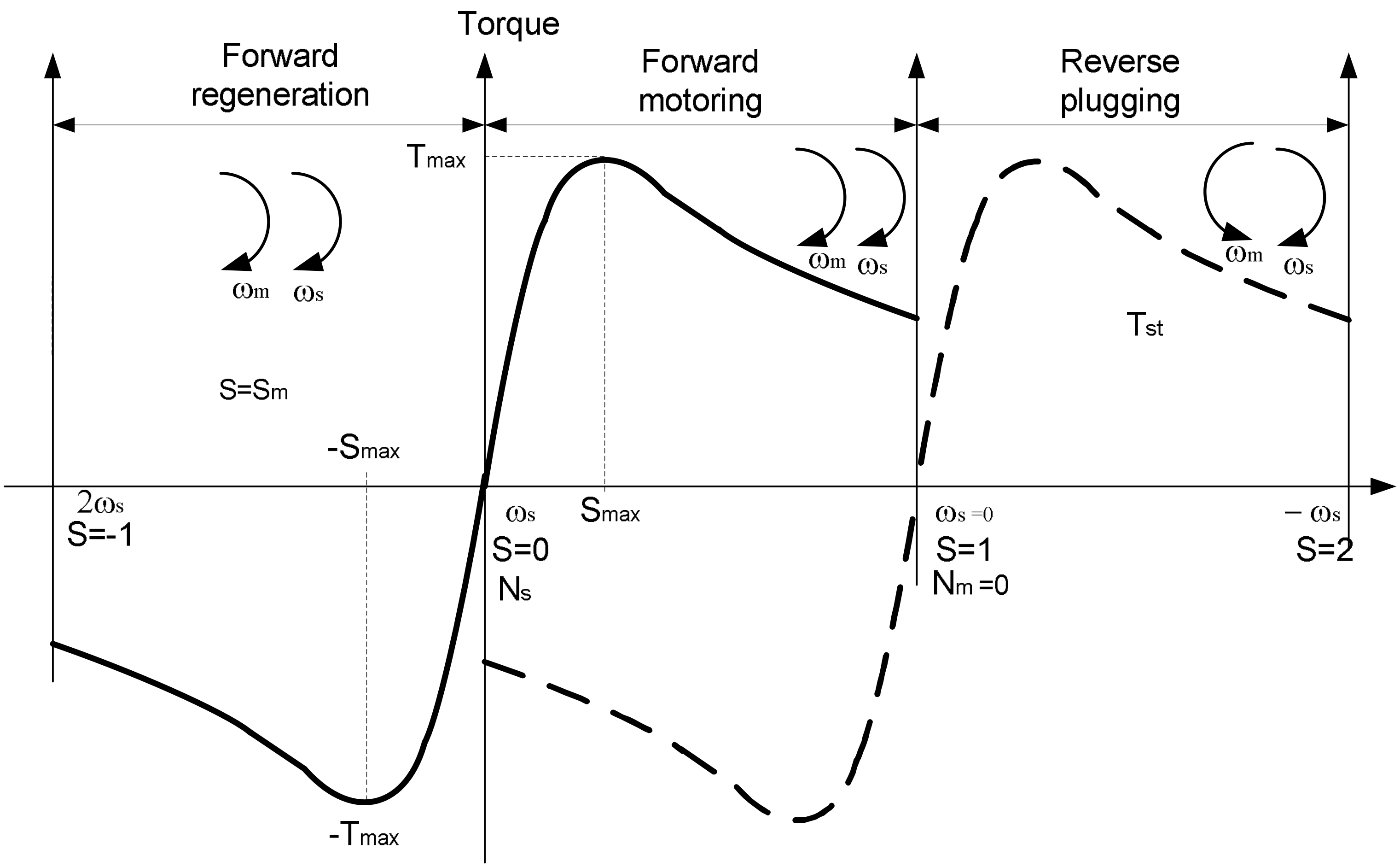
$$T_d = \frac{3 R_r' V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$



Torque – speed Characteristic

Three region operation :

1. **Motoring :** $0 \leq S \leq 1$
2. **Regenerating :** $S < 0$
3. **Plugging :** $1 \leq S \leq 2$



Performance Characteristic of Induction Motor

Starting speed of motor is $\omega_m = 0$ or $S = 1$,

Starting torque of motor is : $$T_{st} = \frac{3 R_r^{'} V_s^2}{\omega_s \left[\left(R_s + \frac{R_r^{'}}{S} \right)^2 + \left(X_s + X_r^{'} \right)^2 \right]}$$

Slip for the maximum torque S_{max} can be found by setting : $$\frac{d T_d}{dS} = 0$$

So, the slip on maximum torque is : $$S_{\max} = \pm \frac{R_r^{'}}{\left[(R_s)^2 + \left(X_s + X_r^{'} \right)^2 \right]^{\frac{1}{2}}}$$

Performance Characteristic of Induction Motor

Torque maximum is :

$$T_{\max} = \frac{3V_s^2}{2\omega_s\left[R_s + \sqrt{R_s^{\,2} + \left(X_s + X_r^{'}\right)^2}\right]}$$

And the maximum regenerative torque can be found as :

$$T_{\max} = \frac{3V_s^2}{2\omega_s\left[-R_s + \sqrt{R_s^{\,2} + \left(X_s + X_r^{'}\right)^2}\right]}$$

Where the slip of motor $s = -S_m$

Speed-Torque Characteristic :

$$T_d = \frac{3 R_r^{'} V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r^{'}}{S} \right)^2 + \left(X_s + X_r^{'} \right)^2 \right]}$$

For the high Slip S. (starting)

$$\left(X_s + X_r^{'} \right)^2 >> \left(R_s + \frac{R_r^{'}}{S} \right)^2$$

So, the torque of motor is :

$$T_d = \frac{3 R_r^{'} V_s^2}{S\,\omega_s \left(X_s + X_r^{'} \right)^2}$$

And starting torque (slip S=1) is :

$$T_{st} = \frac{3 R_r^{'} V_s^2}{\omega_s \left(X_s + X_r^{'} \right)^2}$$

For low slip S region, the motor speed near unity or synchronous speed, in this region the impedance motor is :

$$\left(X_s + X_r^{'}\right)^2 << \frac{R'_r}{S} >> R_s$$

So, the motor torque is :

$$T_d = \frac{3V_s^2\, S}{\omega_s\; R'_r}$$

And the slip at maximum torque is :

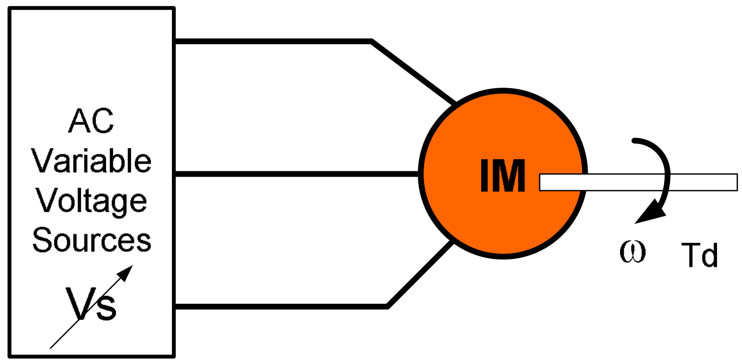
$$S_{\max} = \pm \frac{R_r^{'}}{\left[\left(R_s\right)^2 + \left(X_s + X_r^{'}\right)^2\right]^{\frac{1}{2}}}$$

The maximum motor torque is :

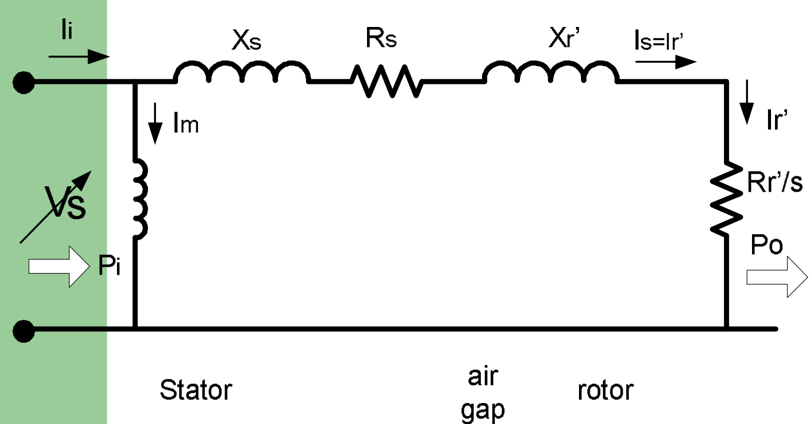
$$T_d = \frac{3\, R_r^{'}\, V_s^2}{S\,\omega_s\left[\left(R_s + \frac{R_r^{'}}{S}\right)^2 + \left(X_s + X_r^{'}\right)^2\right]}$$

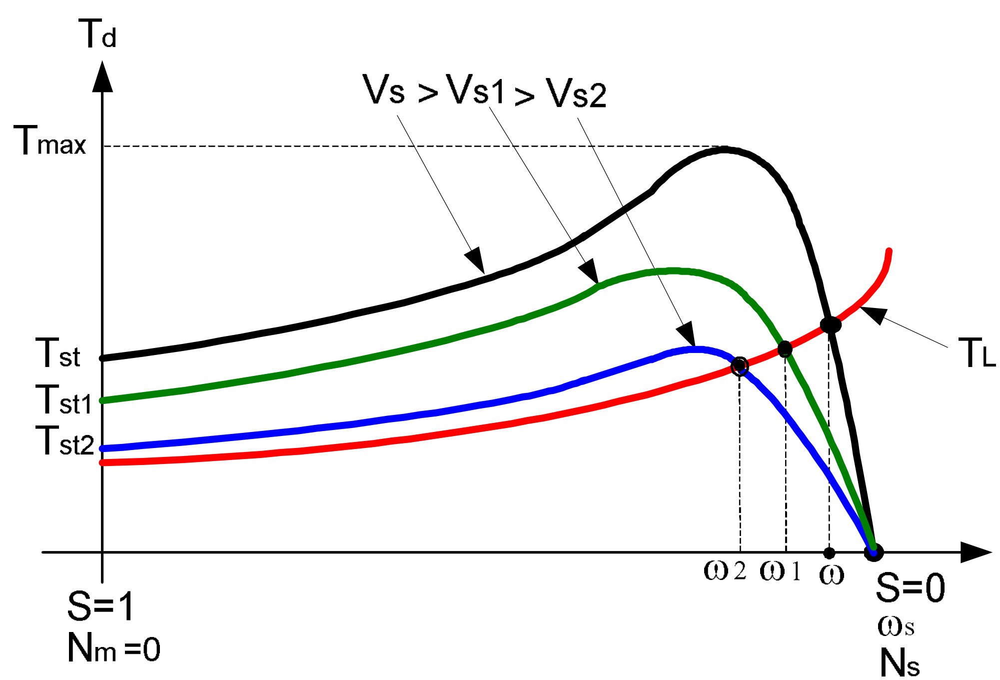
Stator Voltage Control

Controlling Induction Motor Speed by Adjusting The Stator Voltage



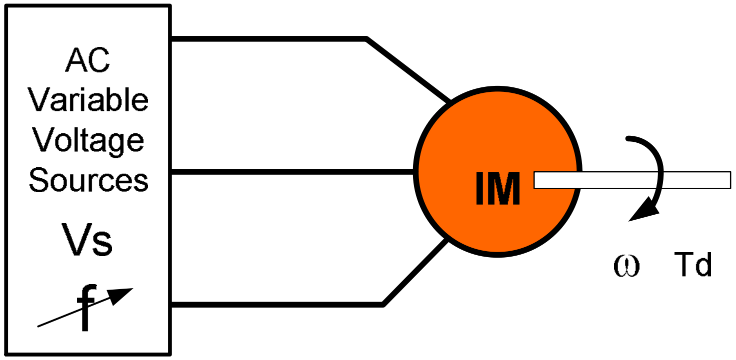
$$T_d = \frac{3 R_r' V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$



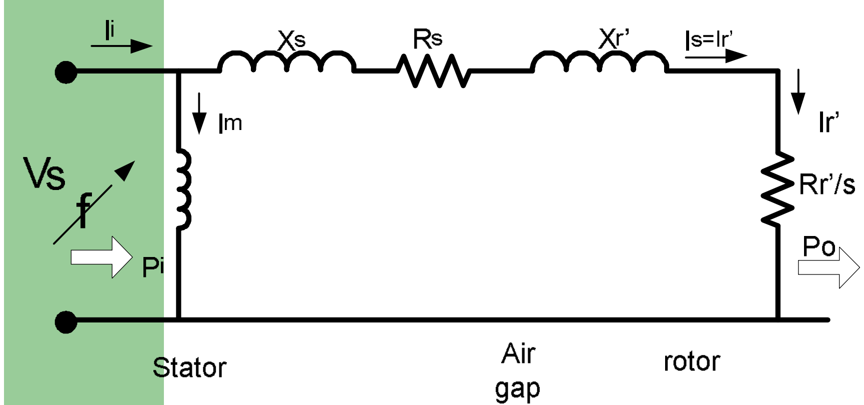


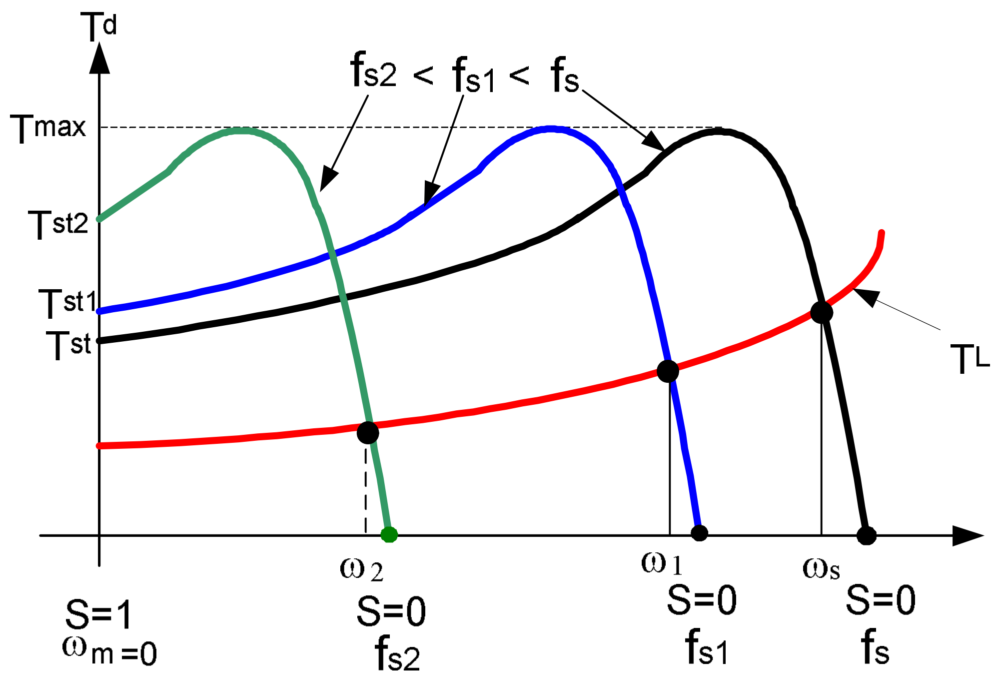
Frequency Voltage Control

Controlling Induction Motor Speed by Adjusting The Frequency Stator Voltage



$$T_d = \frac{3 R_r^{'} V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r^{'}}{S} \right)^2 + \left(X_s + X_r^{'} \right)^2 \right]}$$





If the frequency is increased above its rated value, the flux and torque would decrease. If the synchronous speed corresponding to the rated frequency is call the base speed $\omega_{b,}$ the synchronous speed at any other frequency becomes:

$$\omega_s = \beta\, \omega_b$$

And :

$$S = \frac{\beta\omega_b - \omega_m}{\beta\omega_b} = 1 - \frac{\omega_m}{\beta\omega_b}$$

The motor torque :

$$T_d = \frac{3 R_r' V_s^2}{S\, \omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$

$$T_d = \frac{3 R_r' V_s^2}{S\, \beta\omega_b \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(\beta X_s + \beta X_r' \right)^2 \right]}$$

If R_s is negligible, the maximum torque at the base speed as :

$$T_{mb} = \frac{3\,V_s^2}{2S\,\omega_b\left(X_s + X_r^{'}\right)}$$

And the maximum torque at any other frequency is :

$$T_m = \frac{3}{2S\,\omega_b\left(X_s + X_r^{'}\right)}\frac{V_s^{\,2}}{\beta^2}$$

At this maximum torque, slip S is :

$$S_m = \frac{R_r'}{\beta\left(X_s + X_r^{'}\right)}$$

Normalizing :

$$\frac{T_m = \dfrac{3}{2S\,\omega_b\left(X_s + X_r^{'}\right)}\dfrac{V_s^{\,2}}{\beta^2}}{T_{mb} = \dfrac{3\,V_s^2}{2S\,\omega_b\left(X_s + X_r^{'}\right)}} \Rightarrow \boxed{\frac{T_m}{T_{mb}} = \frac{1}{\beta^2}}$$

And

$$T_m\,\beta^2 = T_{mb}$$

Example :

A three-phase , 11.2 kW, 1750 rpm, 460 V, 60 Hz, four pole, Y-connected induction motor has the following parameters : Rs = 0.1Ω, Rr' = 0.38Ω, Xs = 1.14Ω, Xr' = 1.71Ω, and Xm = 33.2Ω. If the breakdown torque requiretment is 35 Nm, Calculate : a) the frequency of supply voltage, b) speed of motor at the maximum torque

Solution :

Input voltage per-phase : $V_s = \frac{460}{\sqrt{3}} = 265\, volt$

Base frequency : $\omega_b = 2\pi\, f = 2\, x\, 3.14\, x\, 60 = 377\, rad/s$

Base Torque : $T_{mb} = \frac{60 P_o}{2\pi\, N_m} = \frac{60\, x\, 11200}{2\, x\, 3.14\, x\, 1750} = 61.11\, Nm$

Motor Torque : $T_m = 35\, Nm$

a) the frequency of supply voltage :

$$\frac{T_m}{T_{mb}} = \frac{1}{\beta^2} \Rightarrow \beta = \sqrt{\frac{T_{mb}}{T_m}} = \sqrt{\frac{61.11}{35}} = 1.321$$

Synchronous speed at this frequency is :

$$\omega_s = \beta\, \omega_b$$

$$\omega_s = 1.321\, x\, 377 = 498.01\, rad\, /\, s$$

or

$$N_s = \beta\, N_b = \frac{60\, x\, 498.01}{2\, x\, \pi} = 4755.65\ rpm$$

So, the supply frequency is : $f_s = \frac{p\ N_S}{120}_b = \frac{4\, x\, 4755.65}{120} = 158.52\, Hz$

b) speed of motor at the maximum torque :

At this maximum torque, slip S_m is : $S_m = \frac{R_r'}{\beta\left(X_s + X_r'\right)}$

Rr' = 0.38Ω, Xs = 1.14Ω, Xr' = 1.71Ω and $\beta = 1.321$

So,

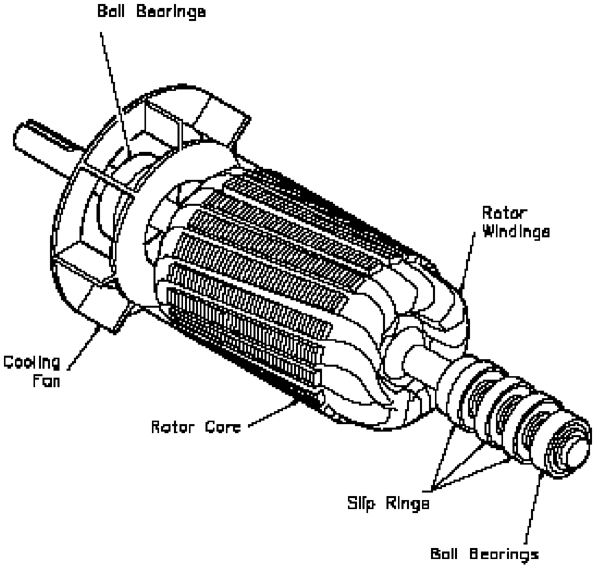
$$S_m = \frac{0.38}{1.321(1.14 + 1.71)} = 0.101$$

or,

$$N_m = N_S\,(1 - S) = 4755.65\,(1 - 0.101) = 4275\, rpm$$

CONTROLLING INDUCTION MOTOR SPEED USING ROTOR RESISTANCE

(Rotor Voltage Control)



Wound rotor induction motor applications

cranes

CONTROLLING INDUCTION MOTOR SPEED USING ROTOR RESISTANCE

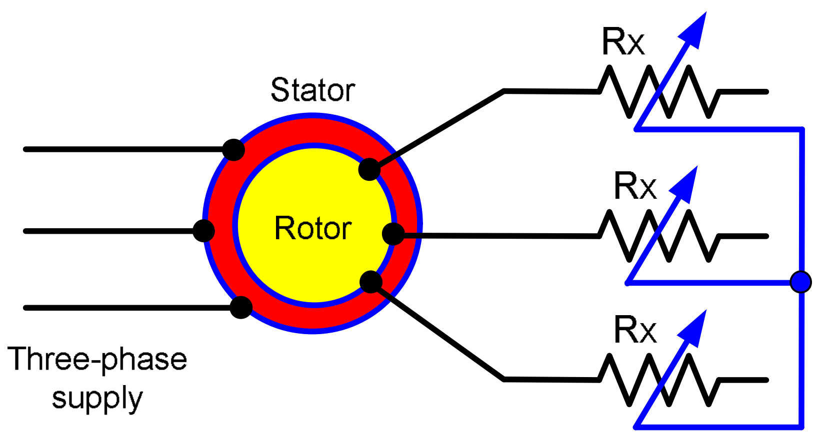
(Rotor Voltage Control)

Equation of Speed-Torque :

$$T_d = \frac{3 R_r' V_s^2}{S\,\omega_s \left[\left(R_s + \frac{R_r'}{S} \right)^2 + \left(X_s + X_r' \right)^2 \right]}$$

$$T_d = \frac{3 V_s^2 S}{\omega_s \; R'_r}$$

In a wound rotor induction motor, an external three-phase resistor may be connected to its slip rings,



These resistors Rx are used to control motor starting and stopping anywhere from reduced voltage motors of low horsepower up to large motor applications such as materials handling, mine hoists, cranes etc.

The most common applications are:

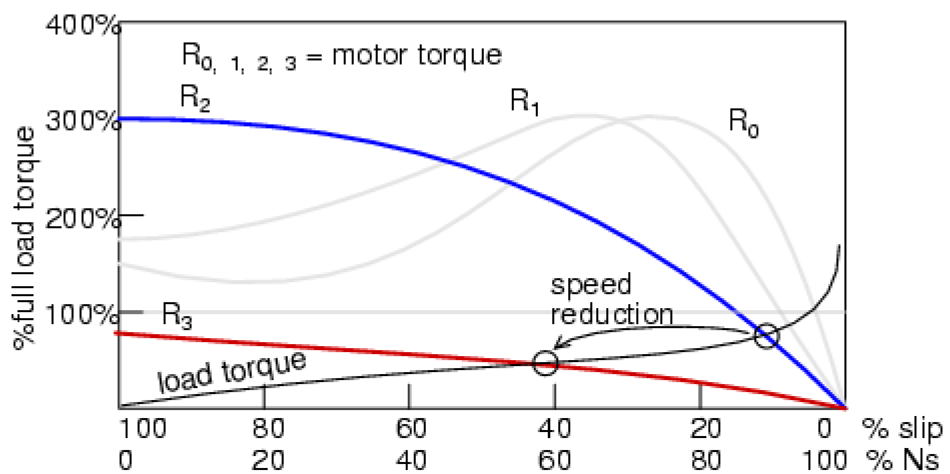
AC Wound Rotor Induction Motors – where the resistor is wired into the motor secondary slip rings and provides a soft start as resistance is removed in steps.

AC Squirrel Cage Motors – where the resistor is used as a ballast for soft starting also known as reduced voltage starting.

DC Series Wound Motors – where the current limiting resistor is wired to the field to control motor current, since torque is directly proportional to current, for starting and stopping.

The developed torque may be varying the resistance Rx

The torque-speed characteristic for variations in rotor resistance



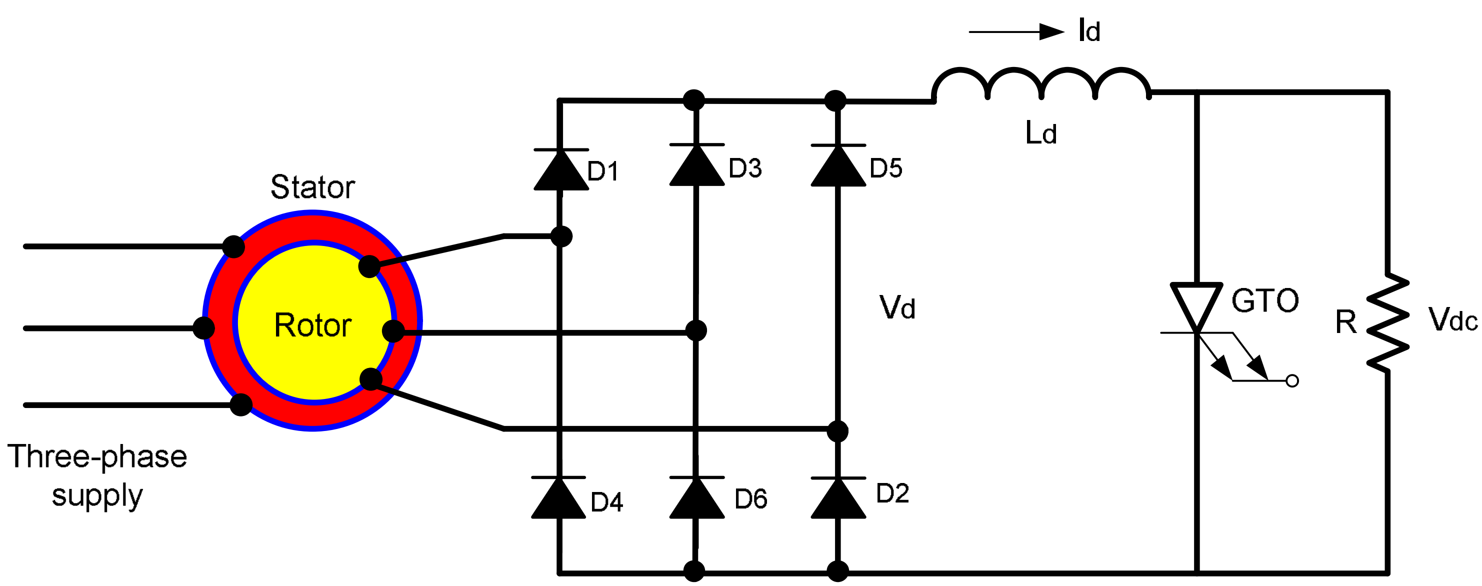
This method increase the starting torque while limiting the starting current. The wound rotor induction motor are widely used in applications requiring frequent starting and braking with large motor torque (crane, hoists, etc)

The three-phase resistor may be replaced by a three-phase diode rectifier and a DC chopper. The inductor Ld acts as a current source Id and the DC chopper varies the effective resistance:

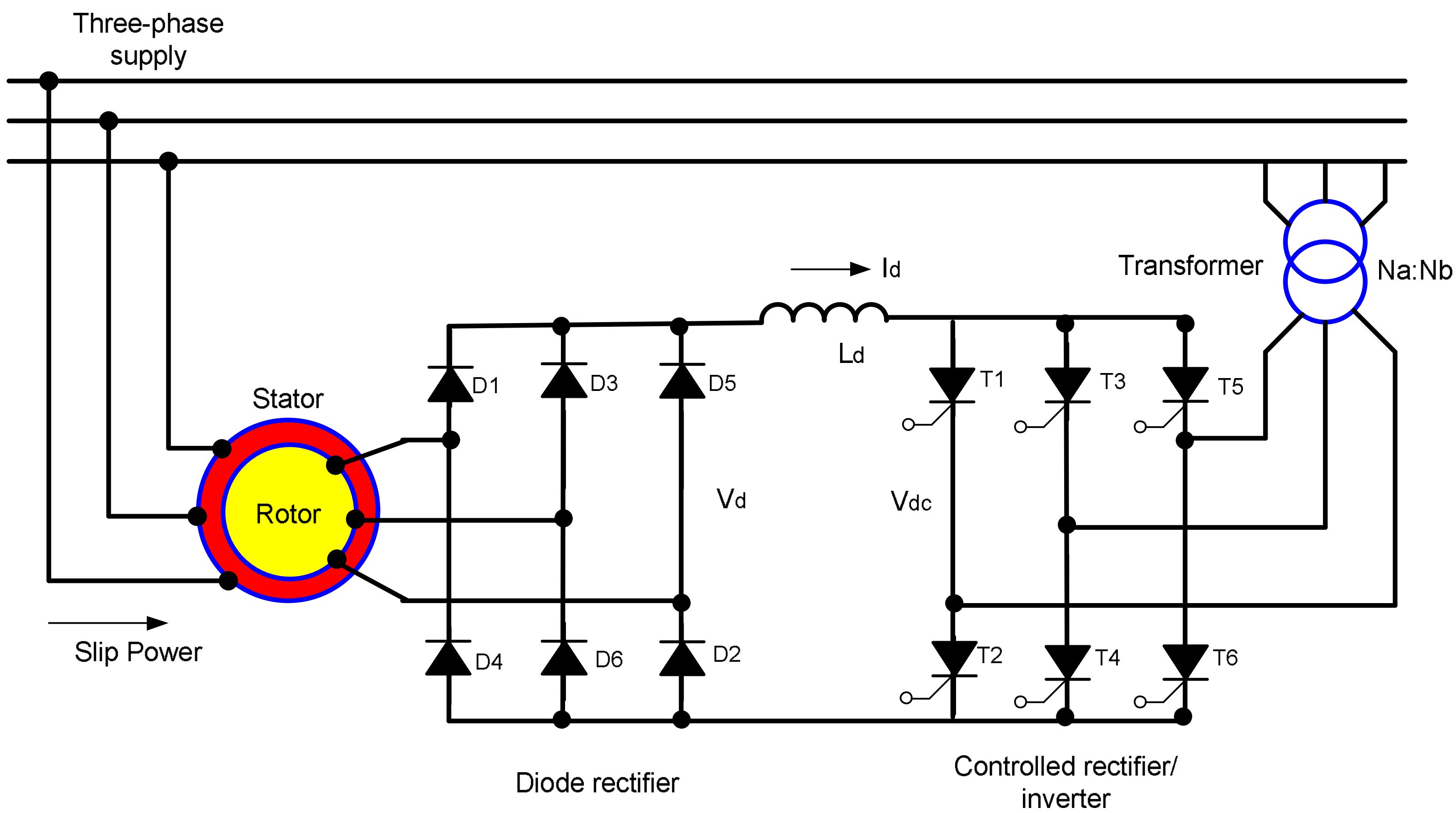
$$R_e = R(1-k)$$

Where k is duty cycle of DC chopper

The speed can controlled by varying the duty cycle k, (slip power)



The slip power in the rotor circuit may be returned to the supply by replacing the DC converter and resistance R with a three-phase full converter (inverter)



Example:

A three-phase induction motor, 460, 60Hz, six-pole, Y connected, wound rotor that speed is controlled by slip power such as shown in Figure below. The motor parameters are Rs=0.041 Ω, Rr'=0.044 Ω, Xs=0.29 Ω, Xr'=0.44 Ω and Xm=6.1 Ω. The turn ratio of the rotor to stator winding is nm=Nr/Ns=0.9. The inductance Ld is very large and its current Id has negligible ripple.

The value of Rs, Rr', Xs and Xr' for equivalent circuit can be considered negligible compared with the effective impedance of Ld. The no-load of motor is negligible. The losses of rectifier and Dc chopper are also negligible.

The load torque, which is proportional to speed square is 750 Nm at 1175 rpm.

(a) If the motor has to operate with a minimum speed of 800 rpm, determine the resistance R, if the desired speed is 1050 rpm,

(b) Calculate the inductor current Id.

(c) The duty cycle k of the DC chopper.

(d) The voltage Vd.

(e) The efficiency.

(f) The power factor of input line of the motor.

$$V_s = \frac{460}{\sqrt{3}} = 265.58\ volt$$

$$p = 6$$

$$\omega = 2\pi\ x\, 60 = 377\ rad/s$$

$$\omega_s = 2\, x\, 377/6 = 125.66\ \ rad/s$$

The equivalent circuit :

The dc voltage at the rectifier output is :

$$V_d = I_d R_e = I_d R(1-k)$$

and

$$E_r = S V_s \frac{N_r}{N_s} = S V_s n_m$$

For a three-phase rectifier, relates Er and Vd as :

$$V_d = 1.65 x \sqrt{2}\ E_r = 2.3394 E_r$$

Using : $E_r = S V_s \frac{N_r}{N_s} = S V_s n_m$

$$V_d = 2.3394 S V_s n_m$$

If Pr is the slip power, air gap power is : $P_g = \frac{P_r}{S}$

Developed power is : $P_d = 3(P_g - P_r) = 3(\frac{P_r}{S} - S) = \frac{3P_r(1-S)}{S}$

Because the total slip power is 3Pr = Vd Id and $P_d = T_L \omega_m$

So, $$P_d = \frac{(1-S)V_d I_d}{S} = T_L \omega_m = T_L \omega_m (1-S)$$

Substituting Vd from $V_d = 2.3394 S V_s n_m$ In equation Pd above, so :

Solving for Id gives : $$I_d = \frac{T_L \omega_s}{2.3394 V_s n_m}$$

Which indicates that the inductor current is independent of the speed.

From equation : $V_d = I_d R_e = I_d R(1-k)$ and equation : $V_d = 2.3394 S V_s n_m$

So, $$I_d R(1-k) = 2.3394 S V_s n_m$$

Which gives : $$S = \frac{I_d R(1-k)}{2.3394 S V_s n_m}$$

The speed can be found from equation : $S = \frac{I_d R(1-k)}{2.3394 S V_s n_m}$ as :

$$\omega_m = \omega_s(1-S) = \omega_s\left[1 - \frac{I_d R(1-k)}{2.3394 V_s n_m}\right]$$

$$\omega_m = \omega_s\left[1 - \frac{T_L \omega_s R(1-k)}{(2.3394 V_s n_m)^2}\right]$$

Which shows that for a fixed duty cycle, the speed decrease with load torque. By varying k from 0 to 1, the speed can be varied from minimum value to ωs

$$\omega_m = 180\ \pi / 30 = 83.77\ rad/s$$

From torque equation : $T_L = K_v \omega_m{}^2$

$$= 750\, x \left(\frac{800}{1175}\right)^2 = 347.67\ Nm$$

From equation : $$I_d = \frac{T_L \omega_s}{2.3394 V_s\, n_m}$$ The corresponding inductor current is :

$$I_d = \frac{347.67\ x\ 125.66}{2.3394\, x\, 265.58\ x\ 0.9} = 78.13\, A$$

The speed is minimum when the duty-cycle k is zero and equation :

$$\omega_m = \omega_s (1 - S) = \omega_s \left[1 - \frac{I_d R (1-k)}{2.3394 V_s\, n_m} \right]$$

$$83.77 = 125.66 (1 - \frac{78.13\, R}{2.3394\, x\, 265.58\, x\, 0.9})$$

And : $$R = 2.3856\, \Omega$$