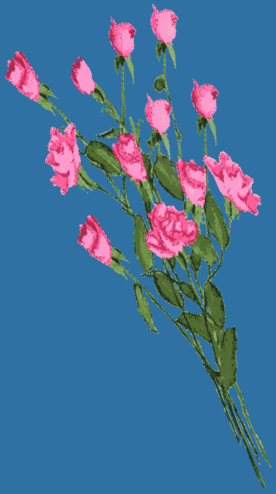
PPT ON
SOLID STATE ELECTRIC MOTOR DRIVES
VI SEM (IARE-R16)



UNIT I

CONTROL OF DC MOTORS THROUGH PHASE CONTROLLED RECTIFIERS

Introduction to thyristor controlled drives:

- Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc.

- Systems employed for motion control are called DRIVES, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control. Drives employing electric motors are known as Electrical Drives.

- An Electric Drive can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

Classification of Electric Drives

- According to Mode of Operation
  - Continuous duty drives
  - Short time duty drives
  - Intermittent duty drives According To Means of Control
  - Manual
  - Semi-automatic
  - Automatic
- According to Number of machines
  - Individual drive
  - Group drive
  - Multi-motor drive

Contd..

- According to Dynamics and Transients
  - Uncontrolled transient period
  - Controlled transient period According to Methods of Speed Control
  - Reversible and non-reversible uncontrolled constant speed.
  - Reversible and non-reversible step speed control.
- Variable position control.

Advantages of Electrical Drive

- Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
- They are available in wide range of torque, speed and power.
- They are adaptable to almost any operating conditions such as explosive and radioactive environments
- It can operate in all the four quadrants of speed-torque plane
- They can be started instantly and can immediately be fully loaded
- Control gear requirement for speed control, starting and braking is usually simple and easy to operate.

Choice (or) Selection of Electrical Drives

- Choice of an electric drive depends on a number of factors. Some of the important factors are.
  - Steady State Operating conditions requirements:
- Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc
  - Transient operation requirements:
- Values of acceleration and deceleration, starting, braking and reversing performance
  - Requirements related to the source:
- Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power
  - Capital and running cost, maintenance needs life.
  - Space and weight restriction if any.
  - Environment and location.
  - Reliability.

Single phase semi controlled converters connected to DC separately excited motors

- Here AC supply is fed to the phase controlled rectifier circuit.AC supply may be single phase or three phase. Phase controlled rectifier converts fixed AC voltage into variable DC voltage

- Here the circuit consists of SCR’s. By varying the SCR firing angle the output voltage can be controlled. This variable output voltage is fed to the DC motor. By varying the motor input voltage, the motor speed can be controlled.

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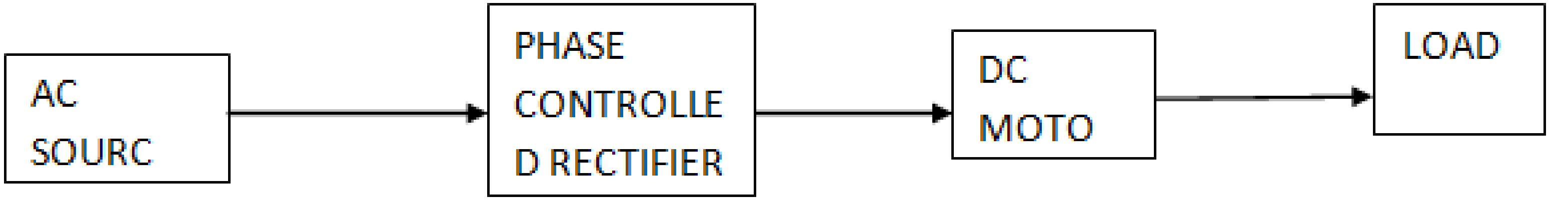
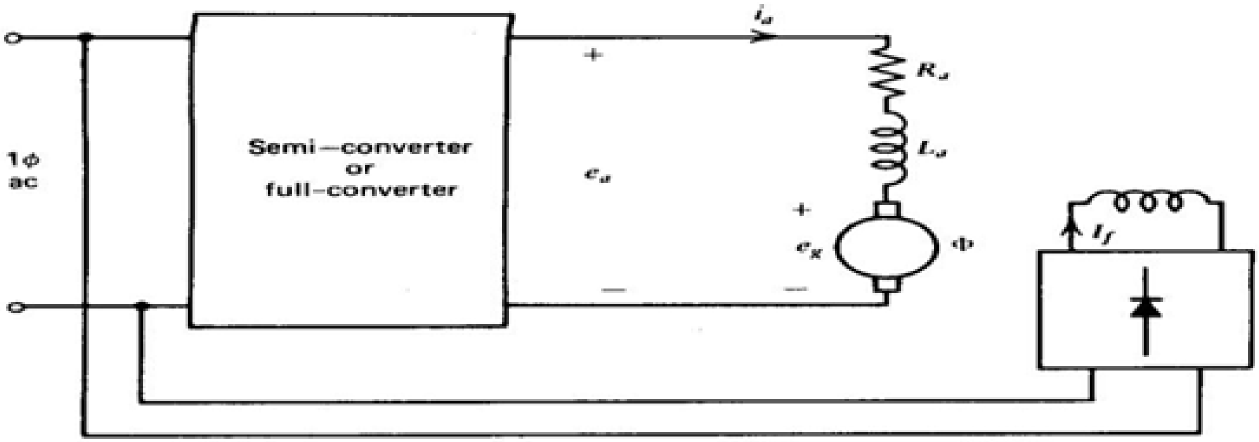


AC
SOURC

PHASE
CONTROLLE
D RECTIFIER

DC
MOTO

LOAD



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$$V_{oav} = \frac{1}{\pi}\int_{o}^{\pi} v_o \, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_i \sin\omega t \, d\omega t = \frac{\sqrt{2}V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_i}{\pi R}(1+\cos\alpha - \pi\sin\theta)$$

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_a R_a$

$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$

$N = \frac{Vm/\pi\ (1+cos\alpha)-IaRa}{Ka\emptyset}$

Single phase semi controlled converters connected to DC series motors

- The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveform respectively.

- On the other hand T1 starts conduction when it is fired in the positive half cycle of the input voltage waveform and continuous conduction till T3 is fired in the negative half cycle.

- Fig. shows the circuit diagram and the waveforms of a single phase half controlled converter supplying an R – L – E load.

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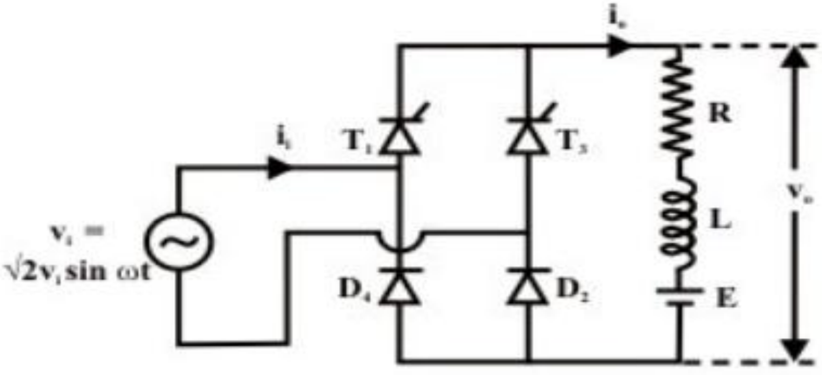
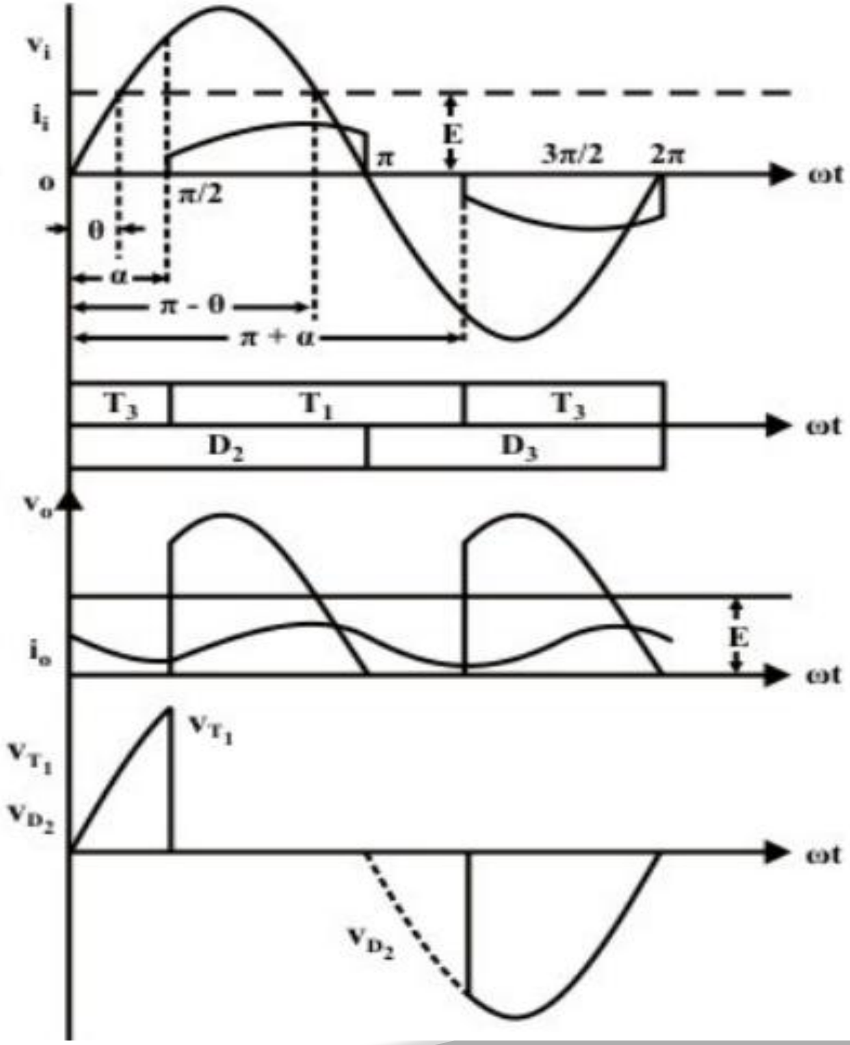


i_o
i_i
T_1
T_3
R
L
E
v_o
$v_i = \sqrt{2}v_i \sin \omega t$
D_4
D_2

(a)



v_i
i_i
o
E
π
$3\pi/2$
2π
ωt
$\pi/2$
θ
α
$\pi - \theta$
$\pi + \alpha$
T_3
T_1
T_3
D_2
D_3
ωt
v_o
i_o
E
ωt
v_{T_1}
v_{T_1}
v_{D_2}
ωt
v_{D_2}

Contd..

$$V_{oav} = \frac{1}{\pi}\int_{o}^{\pi} v_o \, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_i \sin \omega t \, d\omega t = \frac{\sqrt{2}V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_i}{\pi R}(1+\cos\alpha - \pi\sin\theta)$$

The back emf equation of DC series motor is $E_b = K_a\phi N = K_a I_a N$

$T = K_a I_a^2$

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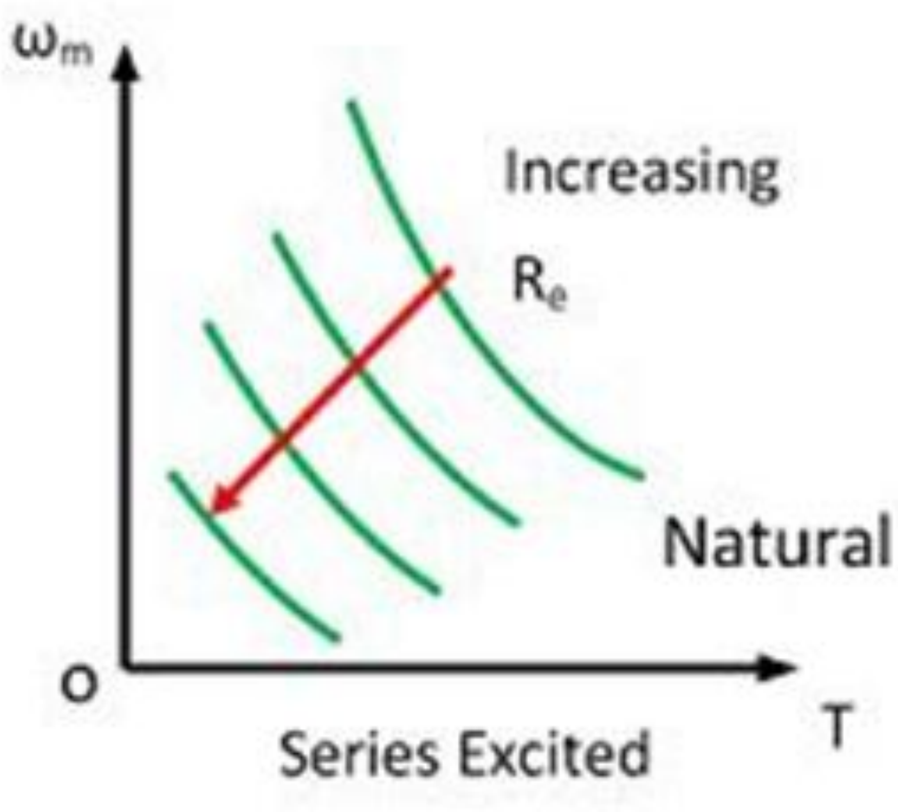
$$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$$

$$N = \frac{Vm/\pi\,(1+cos\alpha) - IaRa}{KaIa}$$

Torque speed characteristics of DC series motor



Numerical problems on Single phase semi controlled converters fed DC motors

1. The speed of a 10 HP, 210V, 1000rpm separately excited dc motors is controlled by a single phase semi converter. The rated motor armature current is 30A and the armature resistance is 0.25Ω. the AC supply voltage is 230V, the motor voltage constant is 0.172V/rpm. Assume continuous armature current. For a firing angle of 45^0 and rated armature current determine

i. the motor torque

ii. speed of the motor

Contd..

ANS:

i. $K_a\phi = 0.172\text{V/rpm} = 0.172*60/2\pi = 1.64\text{V-S/ rad}$

$T = K_a\phi I_a = 1.64*30 = 49.2\text{Nm}$

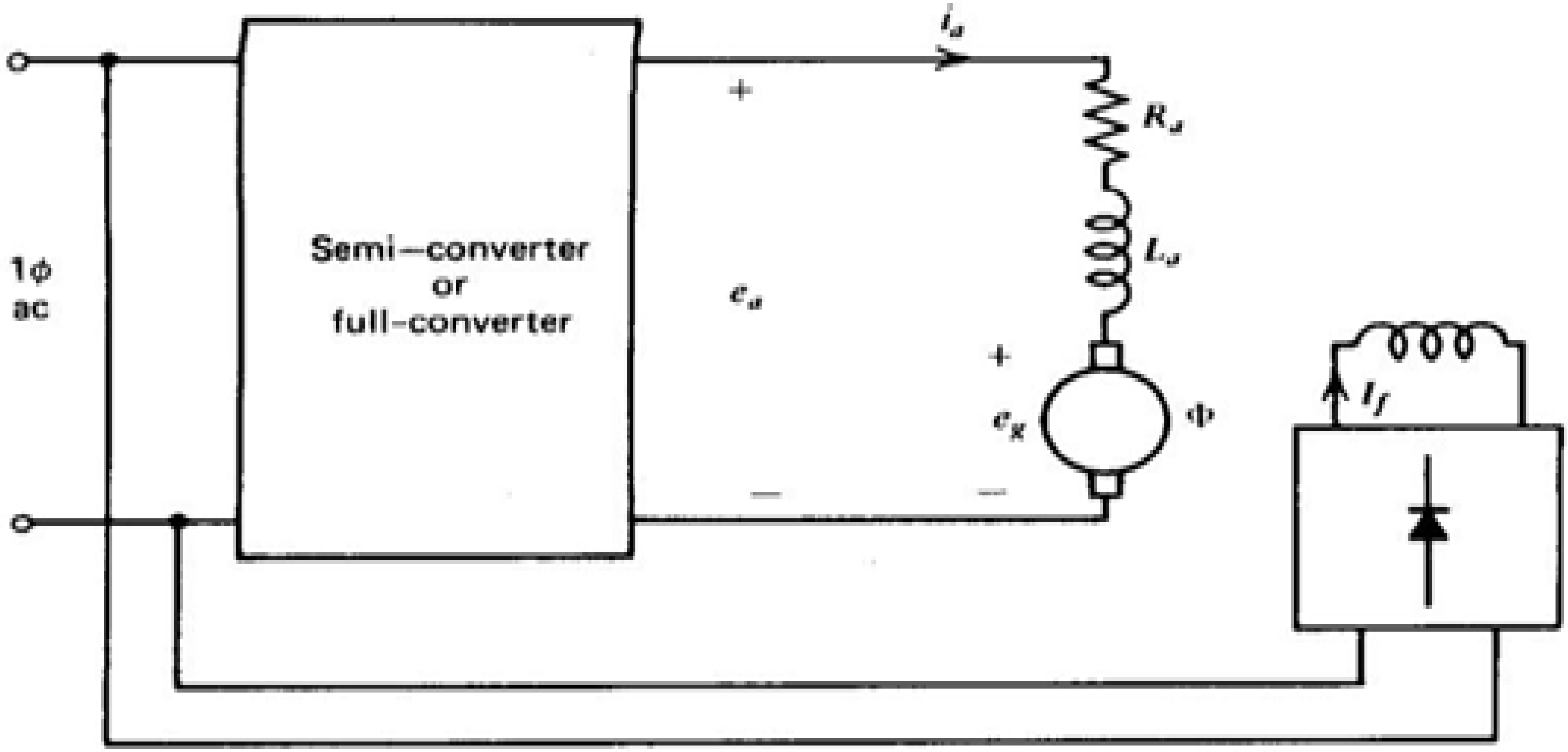
ii. $V_t = \frac{V_m}{\pi}(1+\cos\alpha) = \frac{\sqrt{2}*230}{\pi}(1+\cos 45) = 176.724\text{V}$

$E_b = V_t - I_aR_a = 168.5\text{V}$

$N = E_b/K_a\phi = 168.5/0.172 = 980 \text{ rpm}$

2. The speed of a 15hp, 220V, 1000 rpm dc series motor is controlled using a single-phase half controlled bridge rectifier. The combined armature and field resistance is 0.2 Ω. Assuming continuous and ripple free motor current and speed of 1000 rpm and K=0.03 Nm/Amp2 determine a) motor current, b) motor torque for a firing angle α=30° AC source voltage is 250 V.

Single phase fully controlled converters connected to DC separately excited motors



Contd..

- The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS (Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply).
- All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for duration equal to the turn-off time of the device specified in the data sheet.
- In positive half cycle Thyristors T1 & T2 are fired at an angle α .
- When T1 & T2 conducts
  Vo=Vs
  IO=is=Vo/R=Vs/R

Contd..

- In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)
- Here output current & supply current are in opposite direction

∴ is=-io

T3 & T4 becomes off at 2π.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\, d(wt) = \frac{2Vm}{\pi}\, cos\alpha$$

Contd..

$$V_0 = \frac{2vm}{\pi} \cos\alpha$$

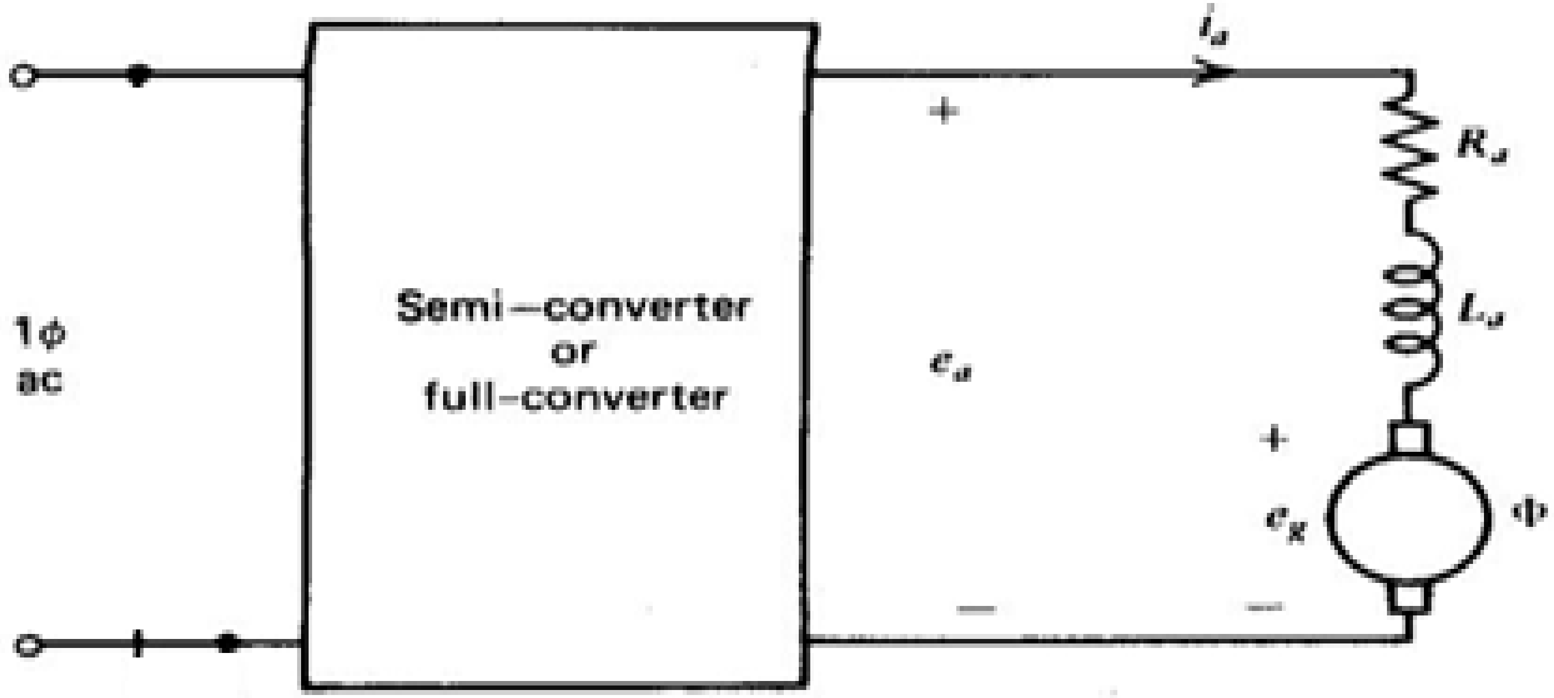
The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$$E_b = \frac{2vm}{\pi} \cos\alpha - IaRa$$

$$N = \frac{\frac{2vm}{\pi}\cos\alpha - IaRa}{Ka\emptyset}$$

Single phase full controlled converters connected to DC series motors



Contd..

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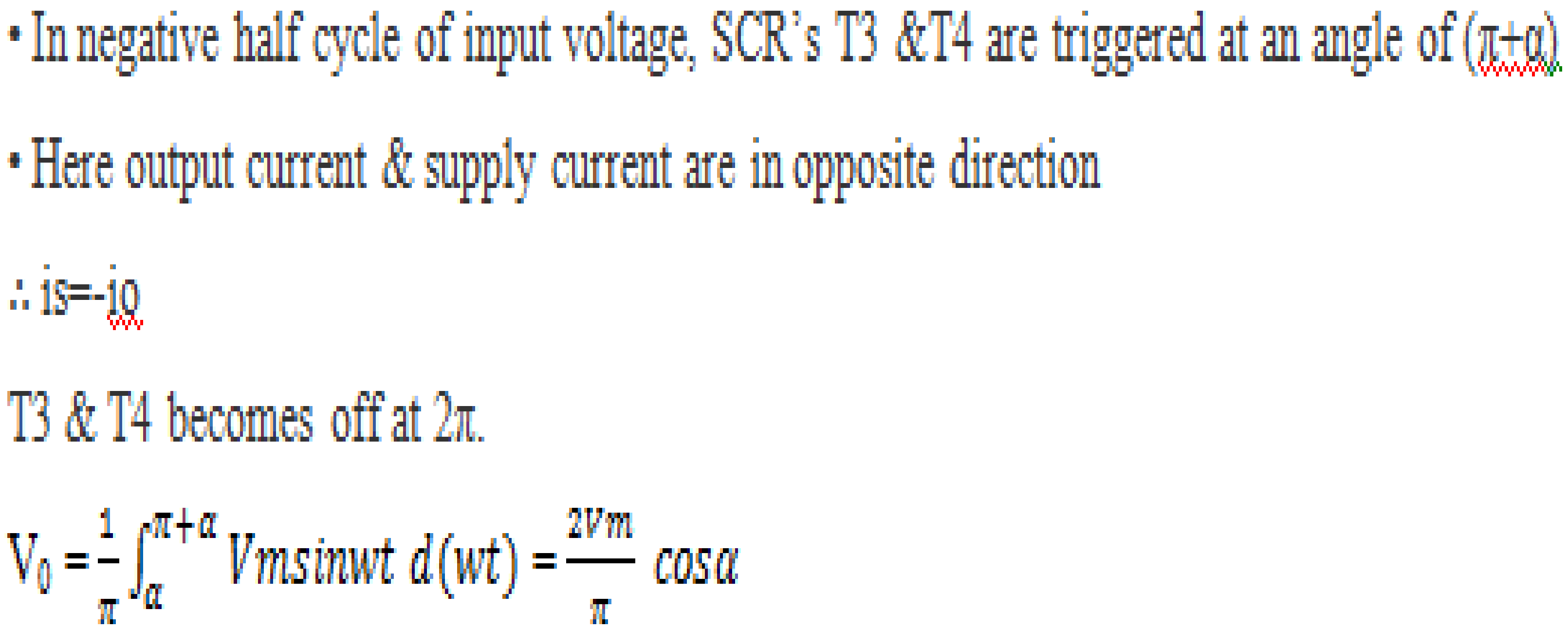
  • When T1 & T2 conducts
  Vo=Vs

Contd..



- In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)
- Here output current & supply current are in opposite direction

∴ is=-io

T3 & T4 becomes off at 2π.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vm\sin wt \, d(wt) = \frac{2Vm}{\pi} \cos\alpha$$

Contd..

The back emf equation of DC series motor is $E_b = K_a \phi N = K_a I_a N$

$$T = K_a I_a^2$$

$$E_b = V_t - I_a R_a$$

$$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$$

$$N = \frac{Vm/\pi\,(1+cos\alpha) - IaRa}{KaIa}$$

Numerical problems on Single phase full controlled converters fed DC motors

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i. the motor torque

ii. speed of the motor

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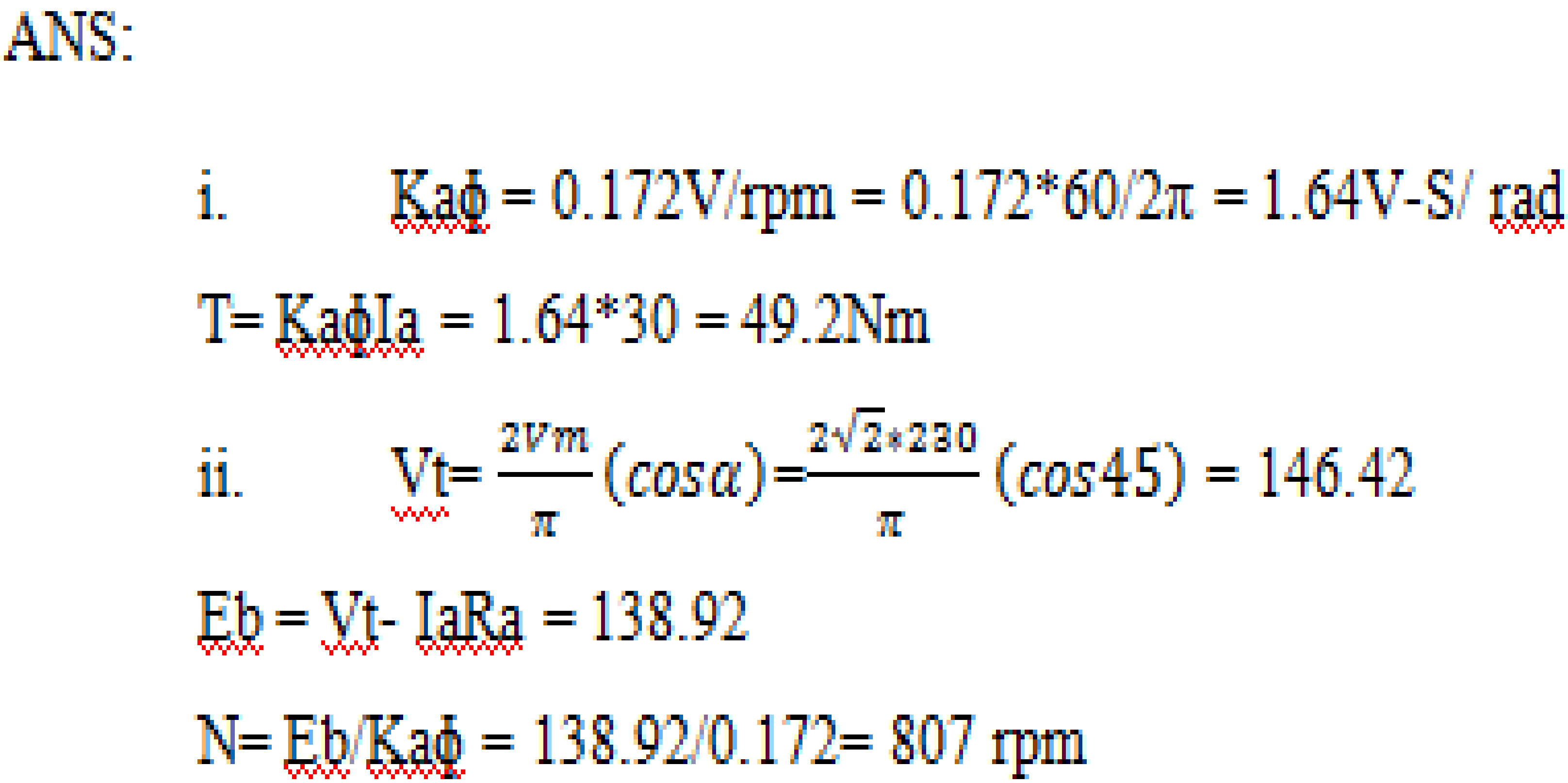


ANS:

i. Kaϕ = 0.172V/rpm = 0.172*60/2π = 1.64V-S/ rad

T= KaϕIa = 1.64*30 = 49.2Nm

ii. $Vt= \frac{2Vm}{\pi}(cos\alpha)=\frac{2\sqrt{2}*230}{\pi}(cos45) = 146.42$

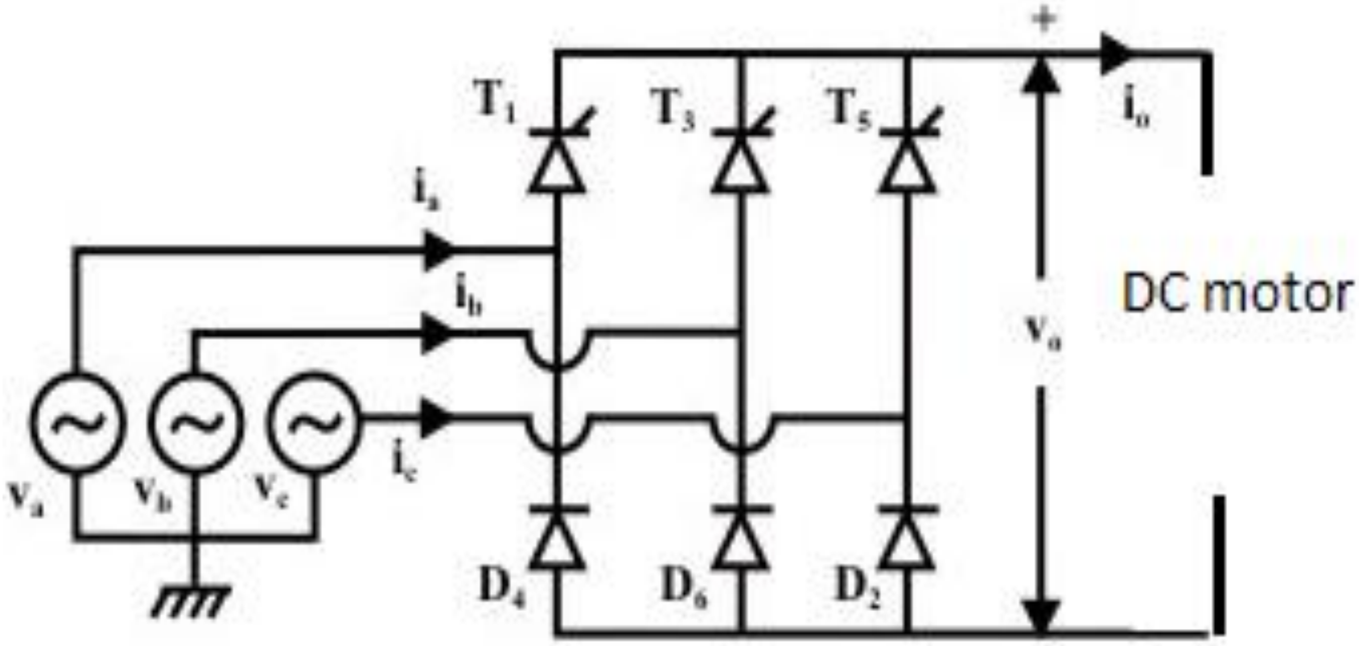
Eb = Vt- IaRa = 138.92

N= Eb/Kaϕ = 138.92/0.172= 807 rpm

Contd..

2. A single phase full converter connected to 220 V, 50 Hz at supply is supplying power to a dc series motor. The combined armature resistance and field resistance is 0.5 Ω. The firing angle os the converter is 45°. The back emf is 100 V. The average current drawn by the motor is

Three phase semi controlled converters connected to DC separately excited motors



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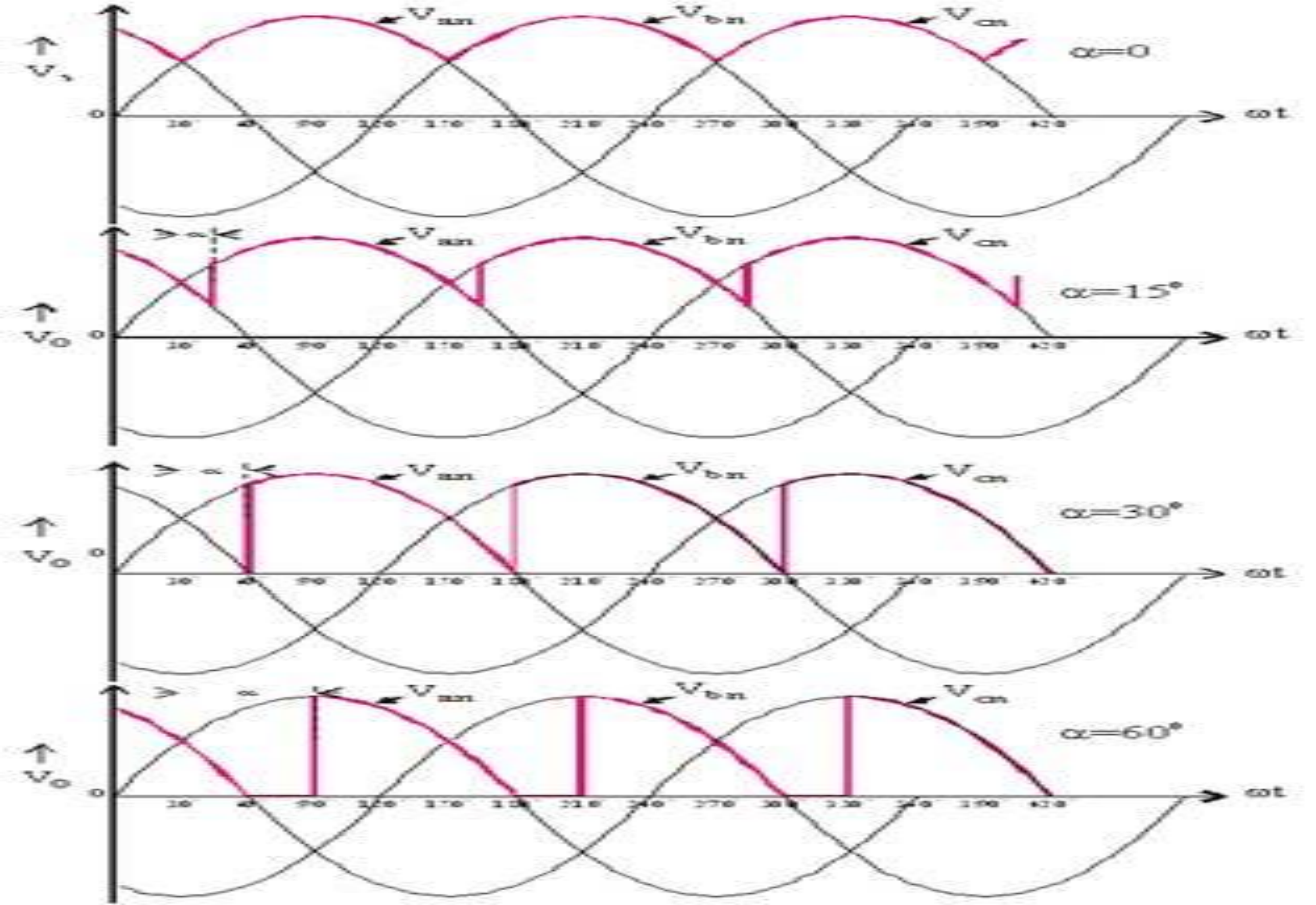


Van
Vbn
Vcn
α=0
α=15°
α=30°
α=60°
Vo
0
ωt
30
60
90
120
150
180
210
240
270
300
330
360
390
420

Contd..

The average output voltage $V_{avg} = \frac{3}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \text{Vmlsinwt d(wt)} + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \text{Vmlsinwt d(wt)}$

$$= \frac{3Vml}{2\pi}(1 + cos\alpha)$$

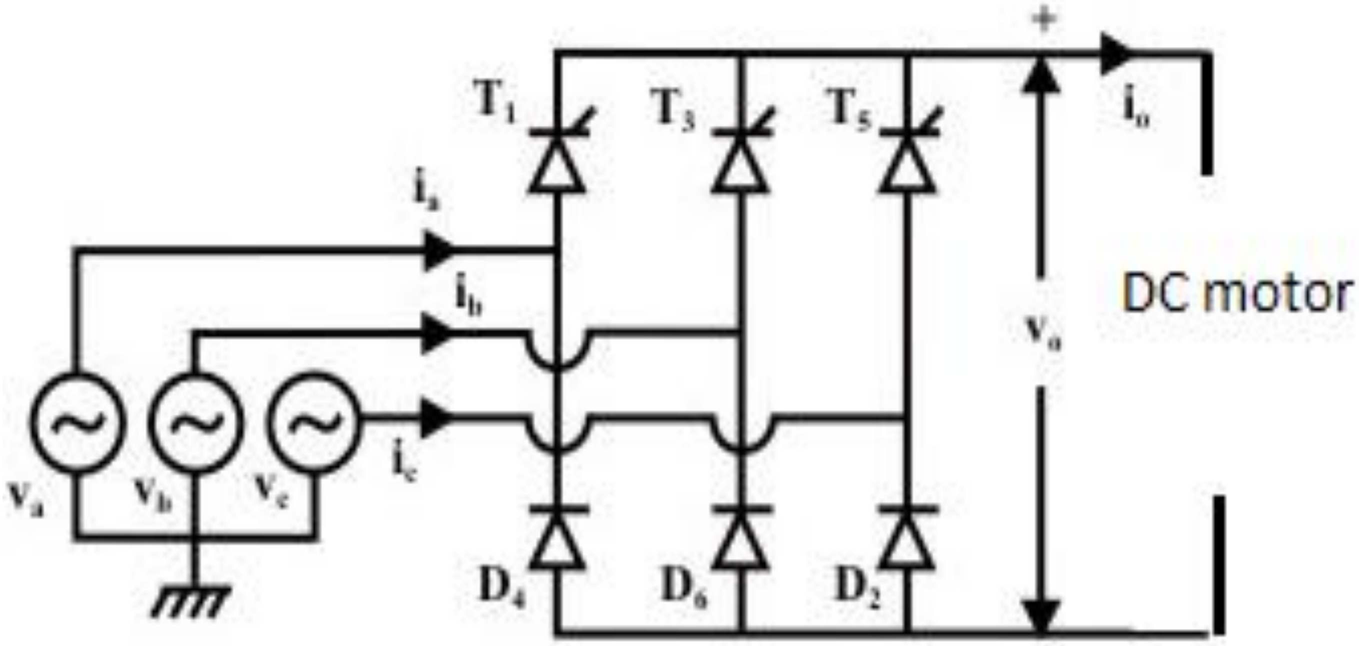
The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$E_b = \frac{Vm}{\pi}(1 + cos\alpha) - IaRa$

$N = \frac{Vm/\pi\,(1+cos\alpha) - IaRa}{Ka\phi}$

Three phase semi controlled converters connected to DC series motors



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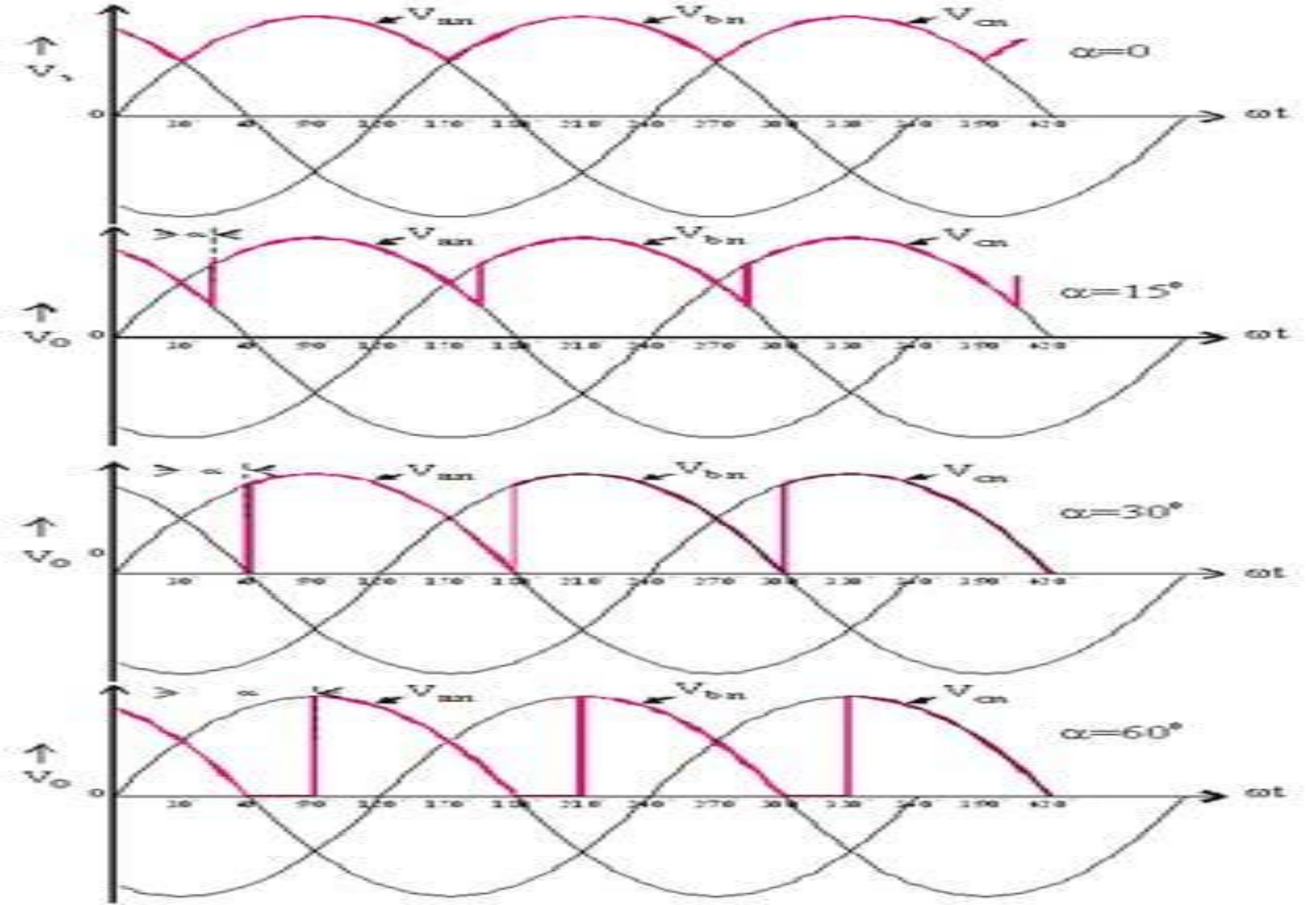

Vs
Van
Vbn
Vcn
α=0
0
ωt
30
60
90
120
150
180
210
240
270
300
330
360
390
420
Vo
α
Van
Vbn
Vcn
α=15°
0
ωt
Vo
α
Van
Vbn
Vcn
α=30°
0
ωt
Vo
α
Van
Vbn
Vcn
α=60°
0
ωt

Contd..

The average output voltage $V_{avg} = \frac{3}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \text{Vmlsinwt}\, d(wt) + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \text{Vmlsinwt}\, d(wt)$

$$= \frac{3Vml}{2\pi}(1 + cos\alpha)$$

The back emf equation of DC series motor is $E_b = K_a\phi N = K_a I_a N$

$T = K_a I_a^2$

$E_b = V_t - I_a R_a$

$E_b = \frac{3Vml}{2\pi}(1 + cos\alpha) - IaRa$

$N = \frac{\frac{3Vml}{2\pi}(1 + cos\alpha) - IaRa}{KaIa}$

Numerical problems on three phase semi converters fed DC motors

1. The speed of a separately excited dc motors is controlled by a three phase semi converter from a three phase 415V 50Hz supply. The motor constants are inductance 10mH, resistance 0.9Ω and armature constant 1.5 v-s/rad. Calculate the speed of the motor at a torque of 50Nmwhen converter is fired at 45^0. Neglect losses in the converter

Contd..

$K_a\phi = 1.5$ v-s/rad

$T = K_a\phi I_a = 50$ Nm

$I_a = 50/1.5 = 33.33$ A

$3V_{ml}\cos\alpha/2\pi = E_b + I_aR_a$

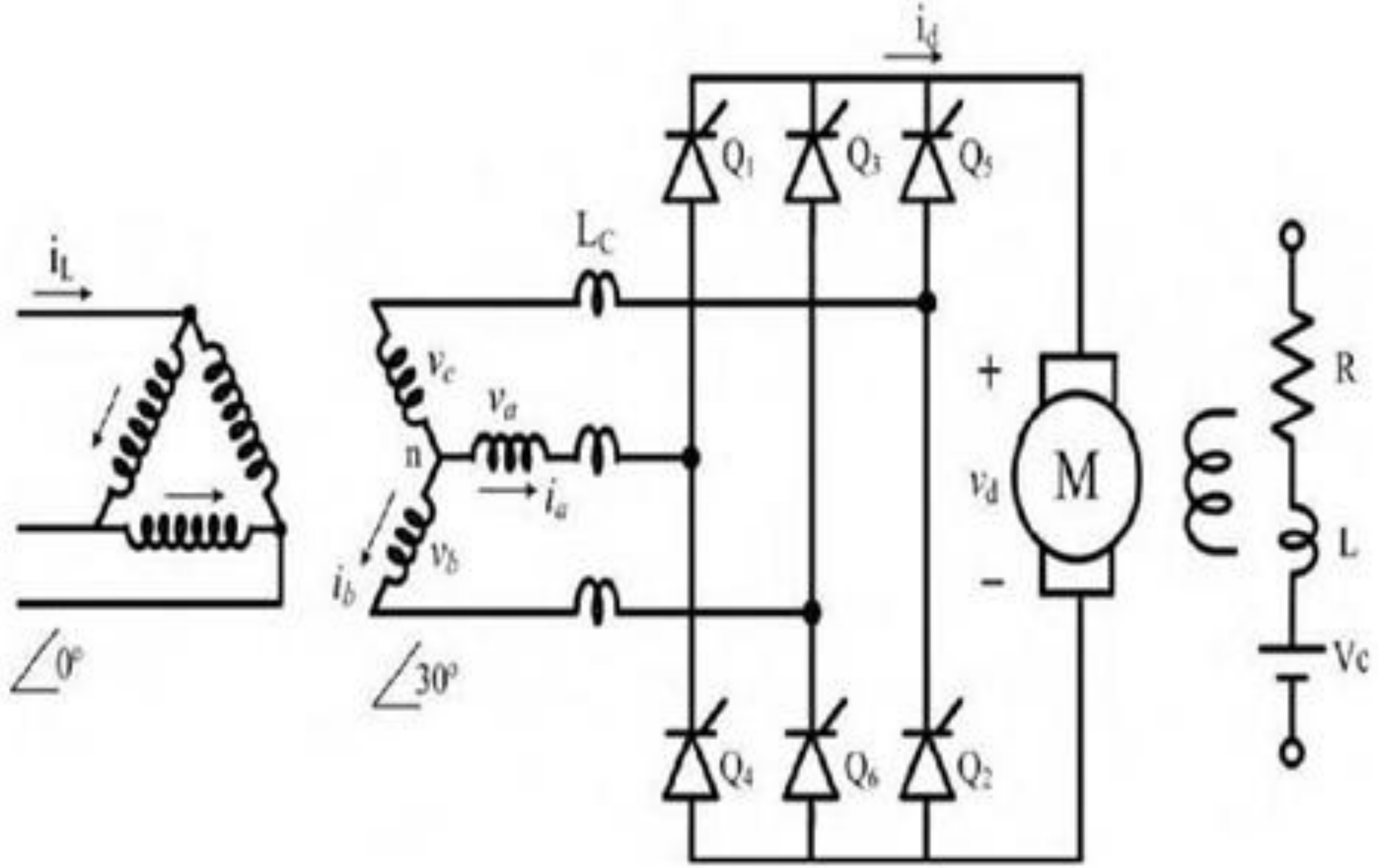
$$\frac{3\sqrt{2}415}{2\pi}\cos 45 = 1.5 * w + 33.33 * 0.9$$

$198.147 = 1.5w + 30$

$W = 168.147/1.5 = 112$ rps $= 1069$ rpm

2. A 600V, 1500rpm, 80A separately excited dc motor is fed through a three- phase semi converter from 3-phase400supply. Motor armature resistance is 1 Ω the armature current assumed constant. For a firing angle of 450 at 1200rpm ,compute the rms value of source and thyristor currents, average value of thyristor current and the input supply power factor

Three phase full controlled converters connected to DC separately excited motors



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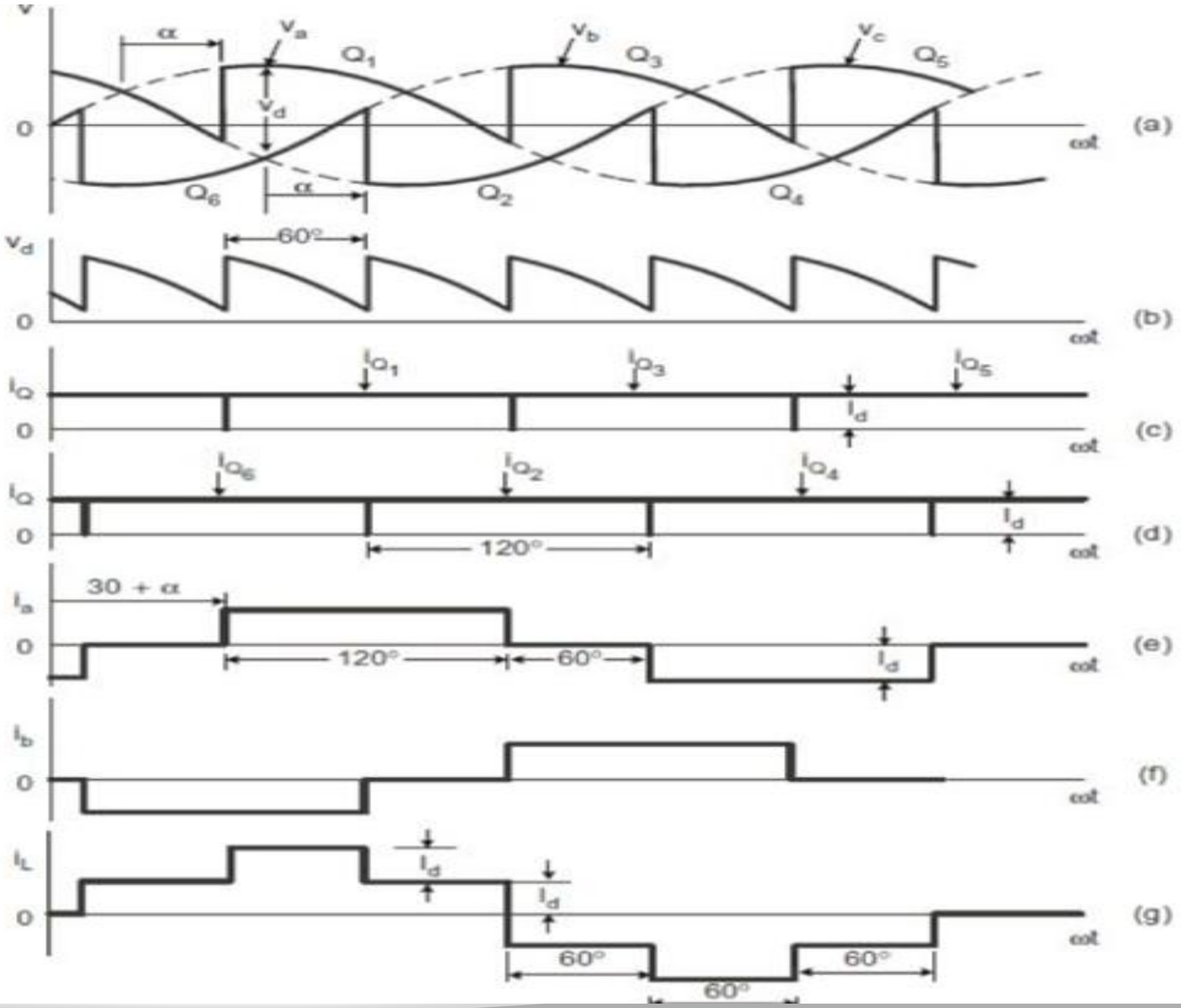

v
α
v_a
Q_1
v_d
v_b
Q_3
v_c
Q_5
0
(a)
ωt
Q_6
α
Q_2
Q_4
v_d
60°
0
(b)
ωt
i_Q
i_{Q_1}
i_{Q_3}
i_{Q_5}
I_d
0
(c)
ωt
i_Q
i_{Q_6}
i_{Q_2}
i_{Q_4}
I_d
0
120°
(d)
ωt
i_a
30 + α
0
120°
60°
I_d
(e)
ωt
i_b
0
(f)
ωt
i_L
I_d
I_d
0
(g)
ωt
60°
60°
60°

Contd..

The back emf equation of DC separately excited motor is $E_b = K_a\phi N$

$E_b = V_t - I_aR_a$

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vod\,(wt)$$

$$V_o = V_{ab} = \sqrt{3}\ Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\ Vm \sin\left(wt + \frac{\pi}{6}\right) d(wt)$$

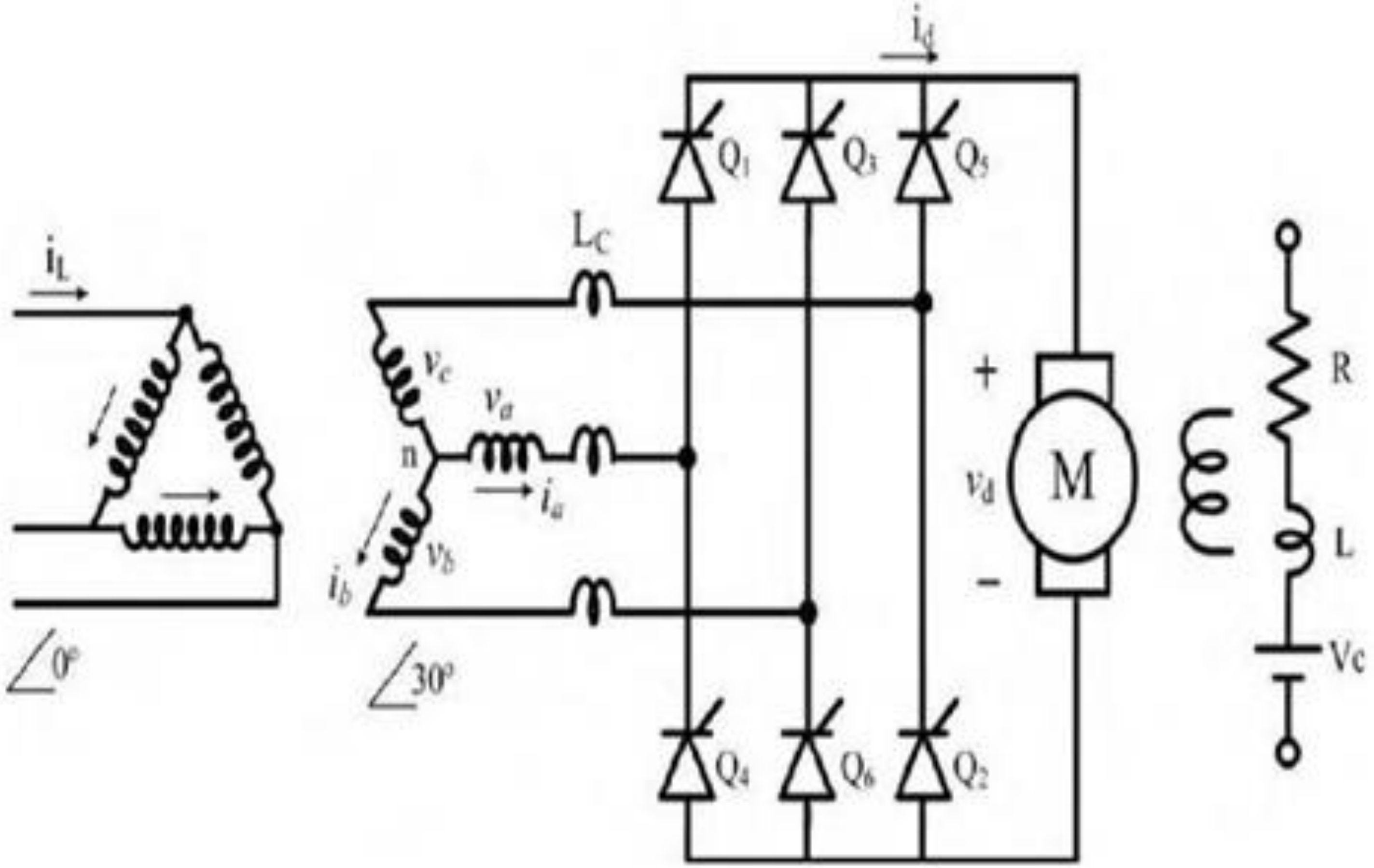
$$= \frac{3\sqrt{3}Vm}{\pi}\ cos\alpha$$

$$= \frac{3Vml}{\pi}\ cos\alpha$$

$$E_b = \frac{3Vml}{\pi}\ cos\alpha\ -\ I_aR_a$$

$N = Eb/\ Ka\phi$

Three phase full controlled converters connected to DC series motors



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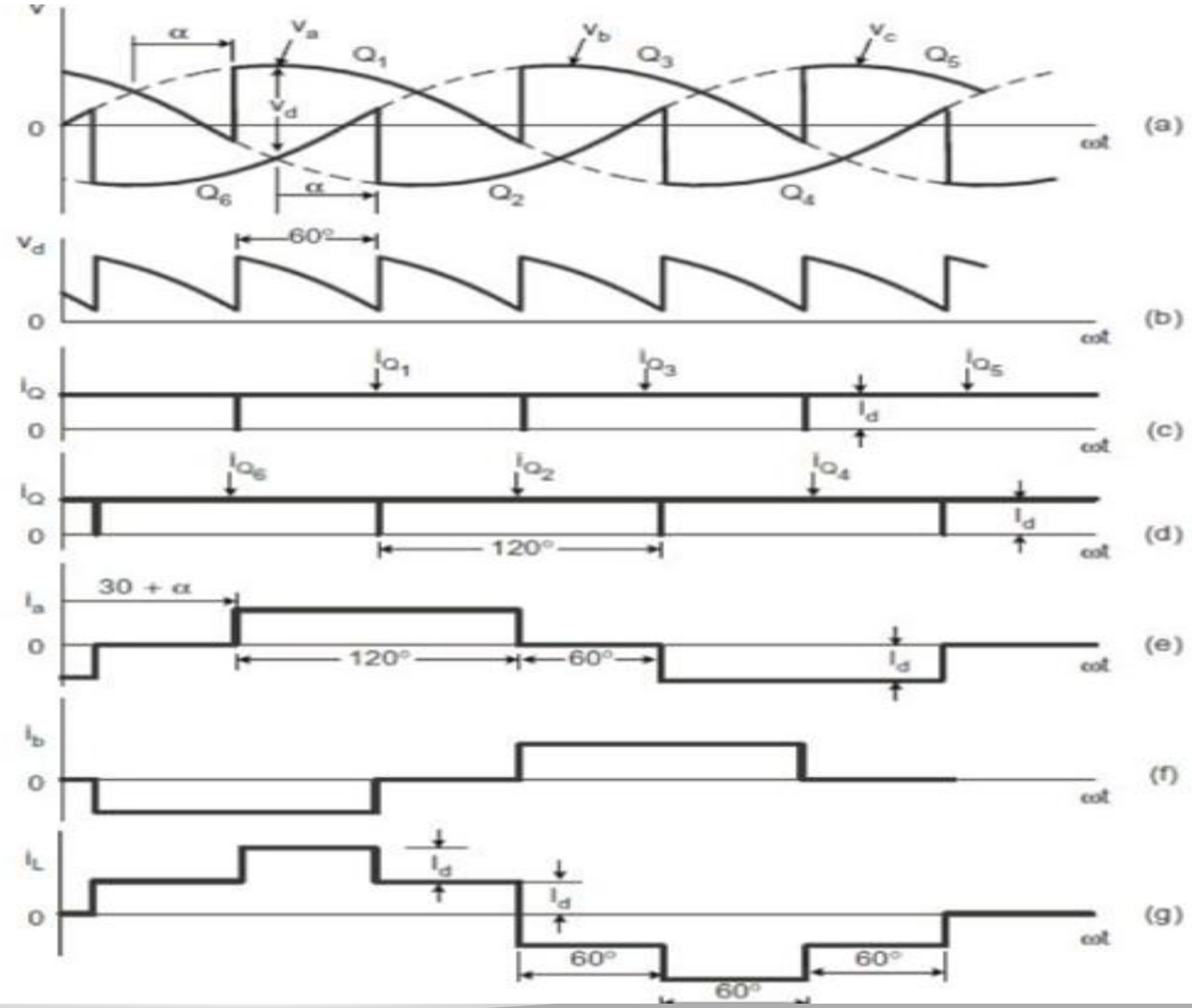
v
α
v_a
Q_1
v_b
Q_3
v_c
Q_5
0
v_d
(a)
ωt
Q_6
Q_2
Q_4
α
v_d
60°
0
(b)
ωt
i_Q1
i_Q3
i_Q5
i_Q
0
I_d
(c)
ωt
i_Q6
i_Q2
i_Q4
i_Q
0
I_d
(d)
ωt
120°
i_a
30 + α
0
120°
60°
I_d
(e)
ωt
i_b
0
(f)
ωt
i_L
I_d
I_d
0
(g)
ωt
60°
60°
60°

Contd..

The back emf equation of DC series motor is $E_b = K_a IaN$

$E_b = V_t - I_a R_a$

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vod\,(wt)$$

$$V_o = V_{ab} = \sqrt{3}\ Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\ Vm \sin\left(wt + \frac{\pi}{6}\right) d(wt)$$

$$= \frac{3\sqrt{3}Vm}{\pi} \cos\alpha$$

$$= \frac{3Vml}{\pi} \cos\alpha$$

$$E_b = \frac{3Vml}{\pi} \cos\alpha - I_a R_a$$

$N = Eb / KaIa$

Numerical problems on three phase fully controlled converters fed DC motors

1. The speed of a separately excited dc motors is controlled by a three phase semi converter from a three phase 415V 50Hz supply. The motor constants are inductance 10mH, resistance 0.9Ω and armature constant 1.5 v-s/rad. Calculate the speed of the motor at a torque of 50Nmwhen converter is fired at 45^0. Neglect losses in the converter

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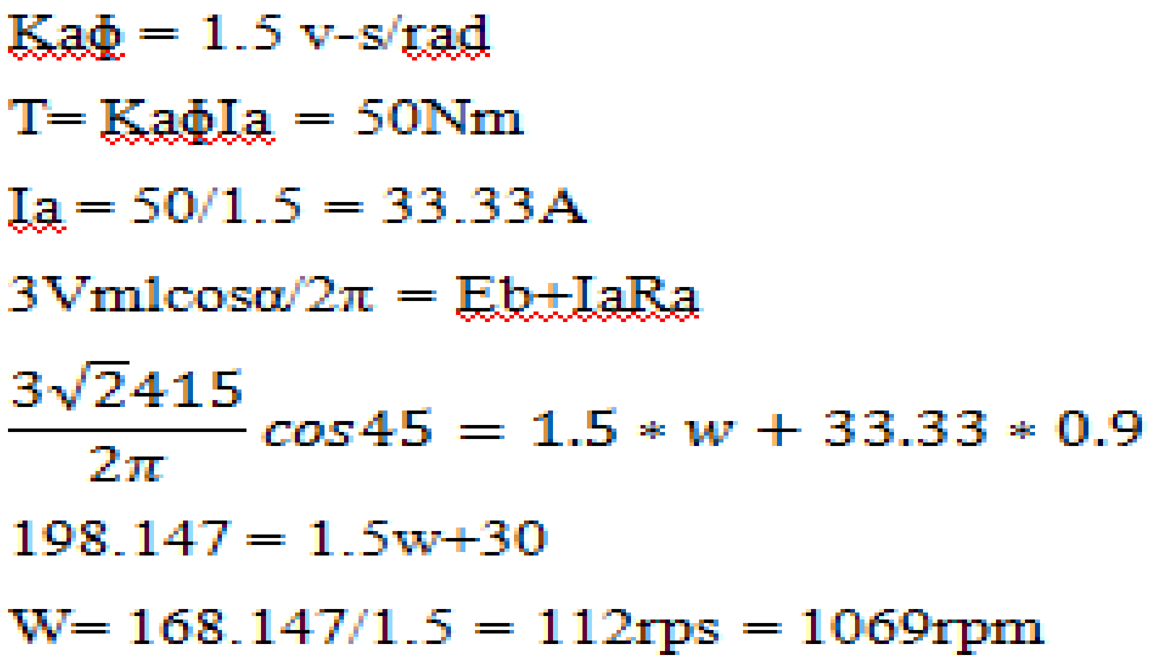

$K_a\phi$ = 1.5 v-s/rad

$T = K_a\phi I_a = 50Nm$

$I_a = 50/1.5 = 33.33A$

$3V_m I \cos\alpha/2\pi = E_b + I_a R_a$

$$\frac{3\sqrt{2}415}{2\pi} cos45 = 1.5 * w + 33.33 * 0.9$$

$198.147 = 1.5w + 30$

$W = 168.147/1.5 = 112rps = 1069rpm$

Contd..

2. A 100kW, 500 V, 2000 rpm separately excited dc motor is energized from 400 V, 50Hz, 3-phase source through a 3-phase full converter. The voltage drop in conducting thyristors is 2V. The dc motor parameters are as under: Ra =0.1Ω,Km=1.6V-s/rad, La=8mH. Rated armature current=21A. No-load armature current = 10% of rated current. Armature current is continuous and ripple free.

i. Find the no-load speed at firing angle of 30^0

ii. Find the firing angle for a speed of 2000 rpm at rated armature current. Determine also the supply power factor.

UNIT-II

SPEED CONTROL OF DC MOTORS

Introduction to four quadrant operation: Motoring operations

- For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.
- A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion.
- Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B.
- Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B
- Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative.

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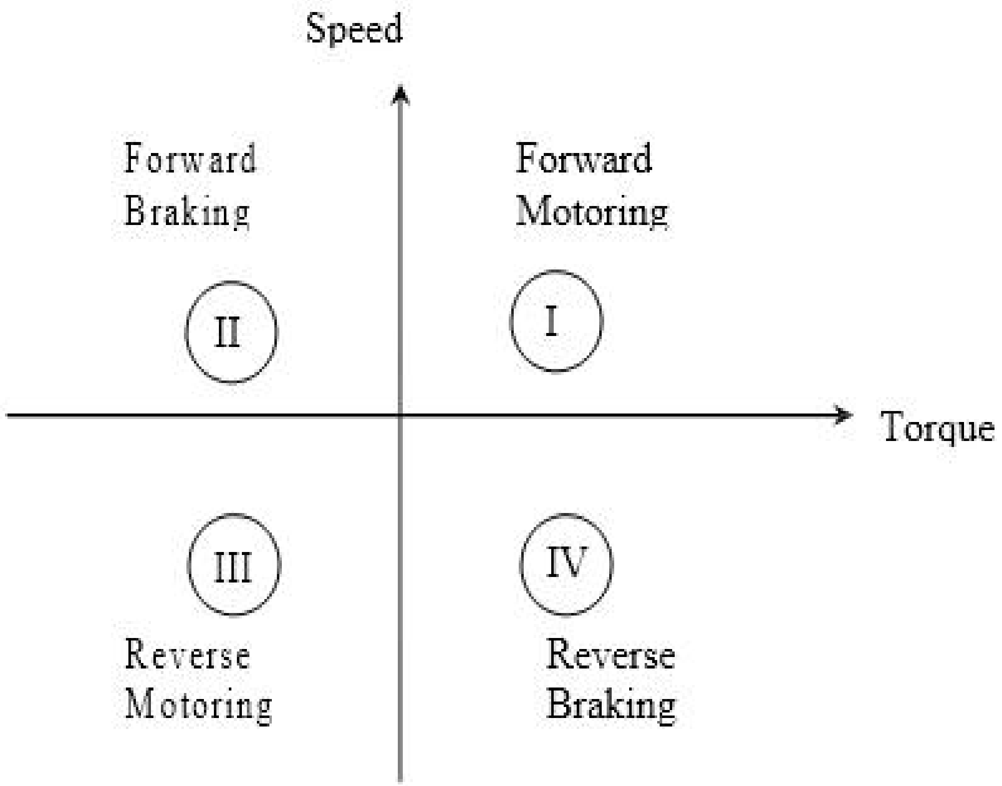
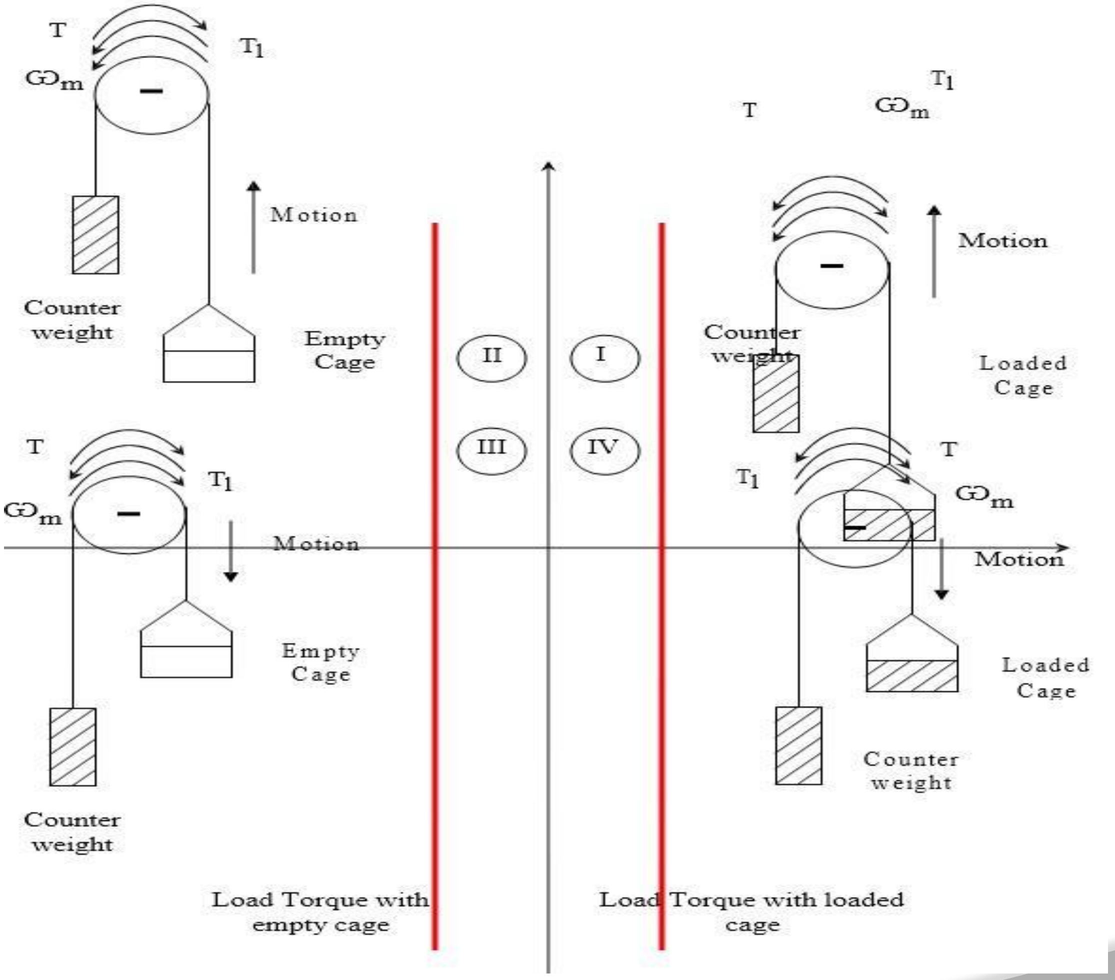

Speed
Forward Braking
Forward Motoring
II
I
Torque
III
IV
Reverse Motoring
Reverse Braking

Contd..


T
T_1
ω_m
Motion
Counter weight
Empty Cage
T_1
T
ω_m
Motion
Counter weight
Loaded Cage
II
I
III
IV
T
T_1
ω_m
Motion
Empty Cage
Counter weight
T_1
T
ω_m
Motion
Loaded Cage
Counter weight
Load Torque with empty cage
Load Torque with loaded cage

Contd..

- For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction of motor and load torques and direction of speed are marked by arrows.
- A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty cage but lower than of a fully loaded cage.

Electric braking operations plugging, dynamic braking

Types of Braking

- Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

  i) Regenerative Braking

  ii) Plugging type braking

  iii) Dynamic braking

Dynamic Braking

- Another method of reversing the direction of torque and braking the motor is dynamic braking. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self –excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.

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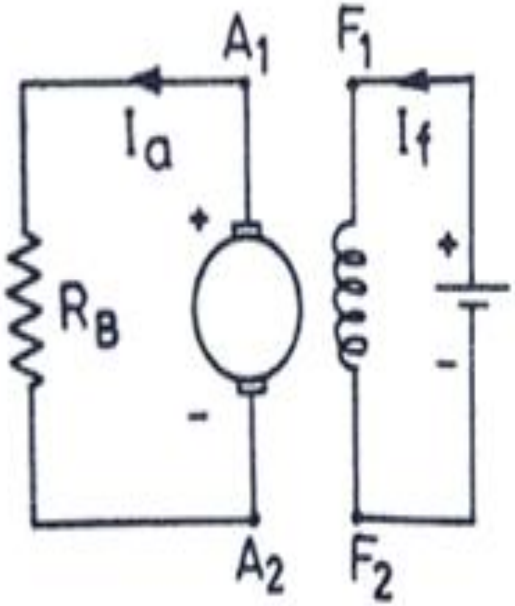
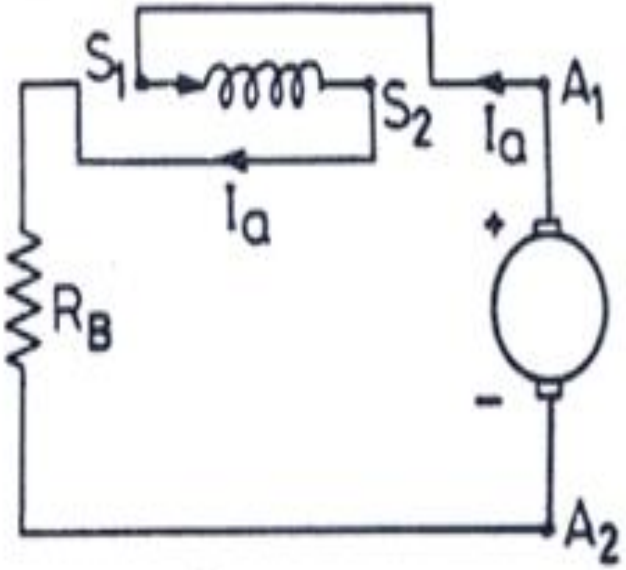
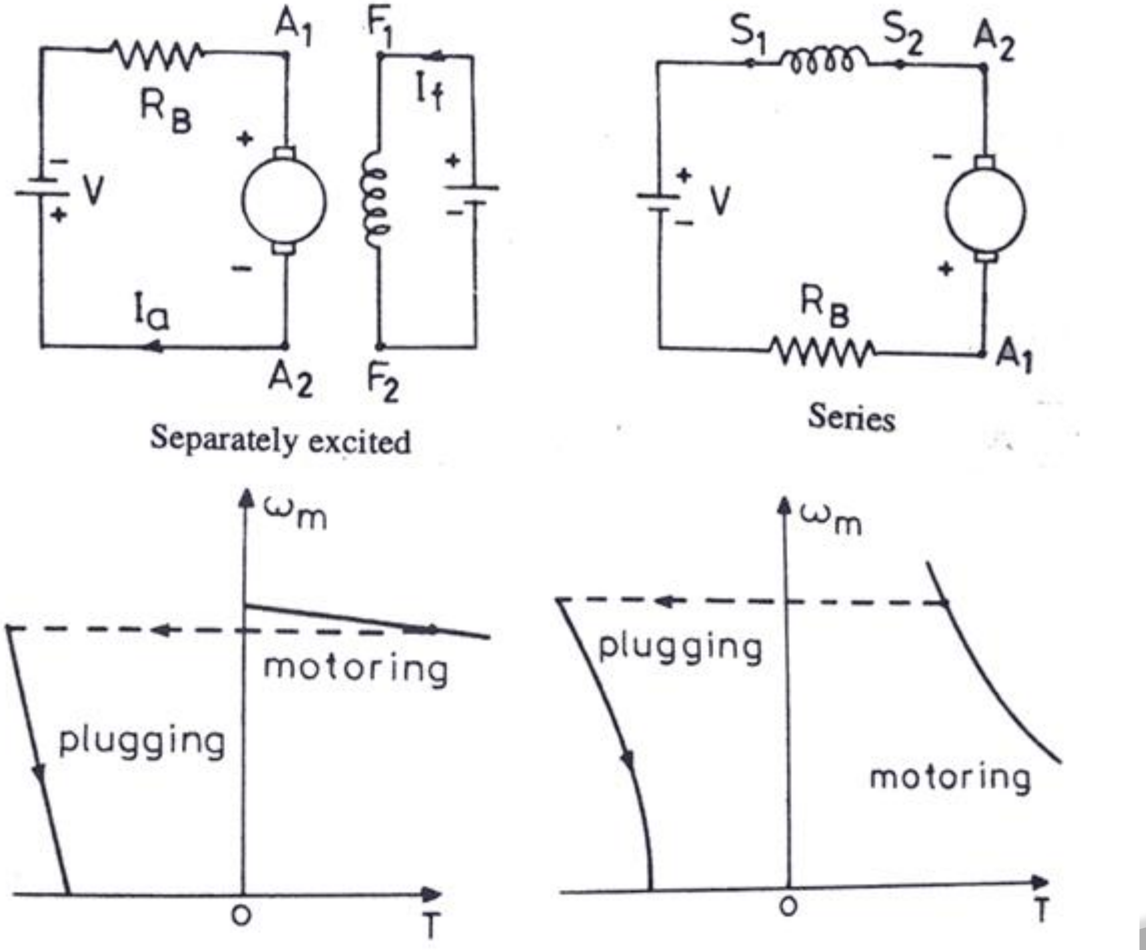




Plugging Type Braking

- Another type of braking is plugging type braking. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.

Contd..



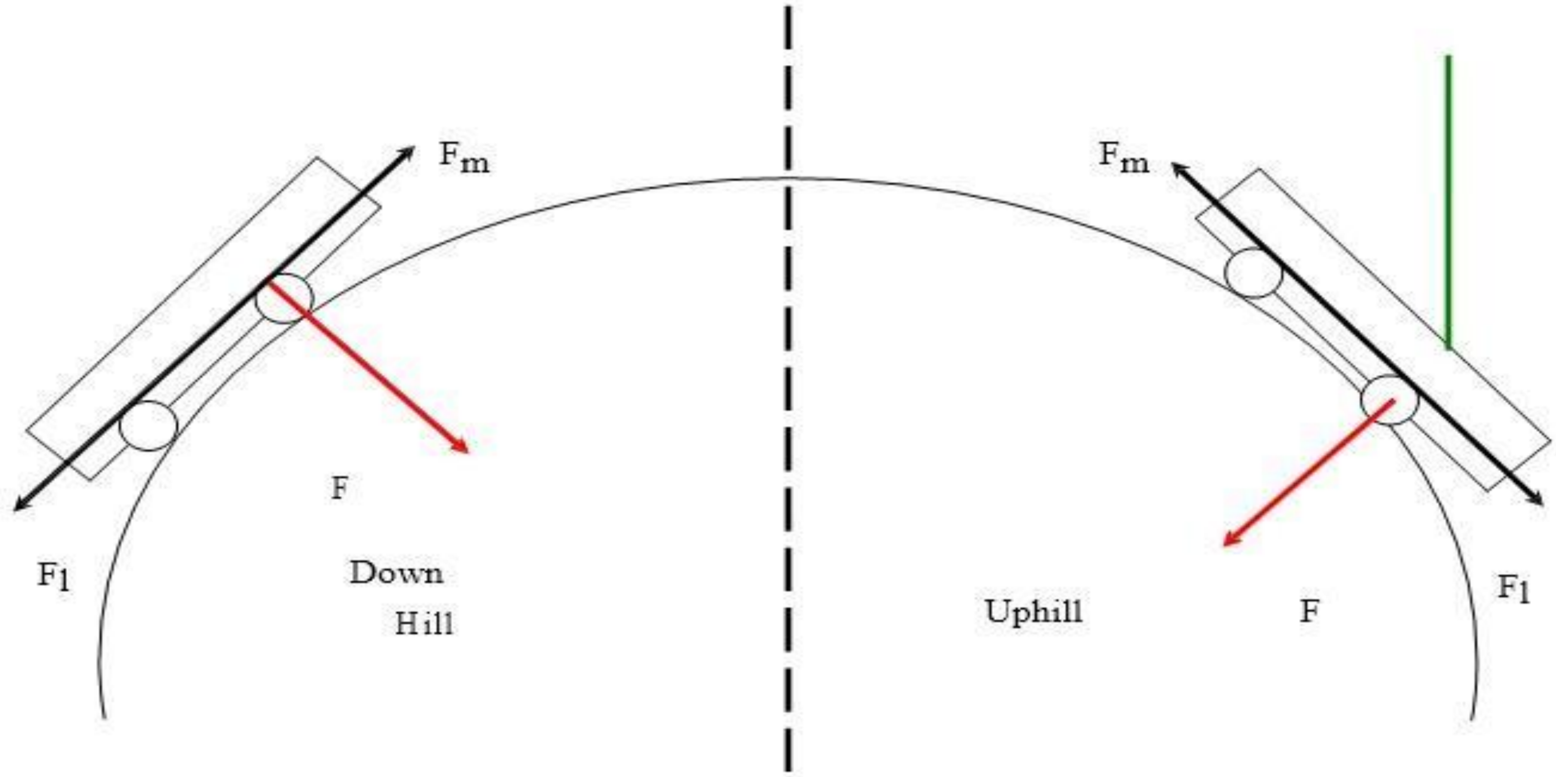
Separately excited

Series

Regenerative braking operations

- Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place.

Contd..



Regenerative braking of electric vehicle

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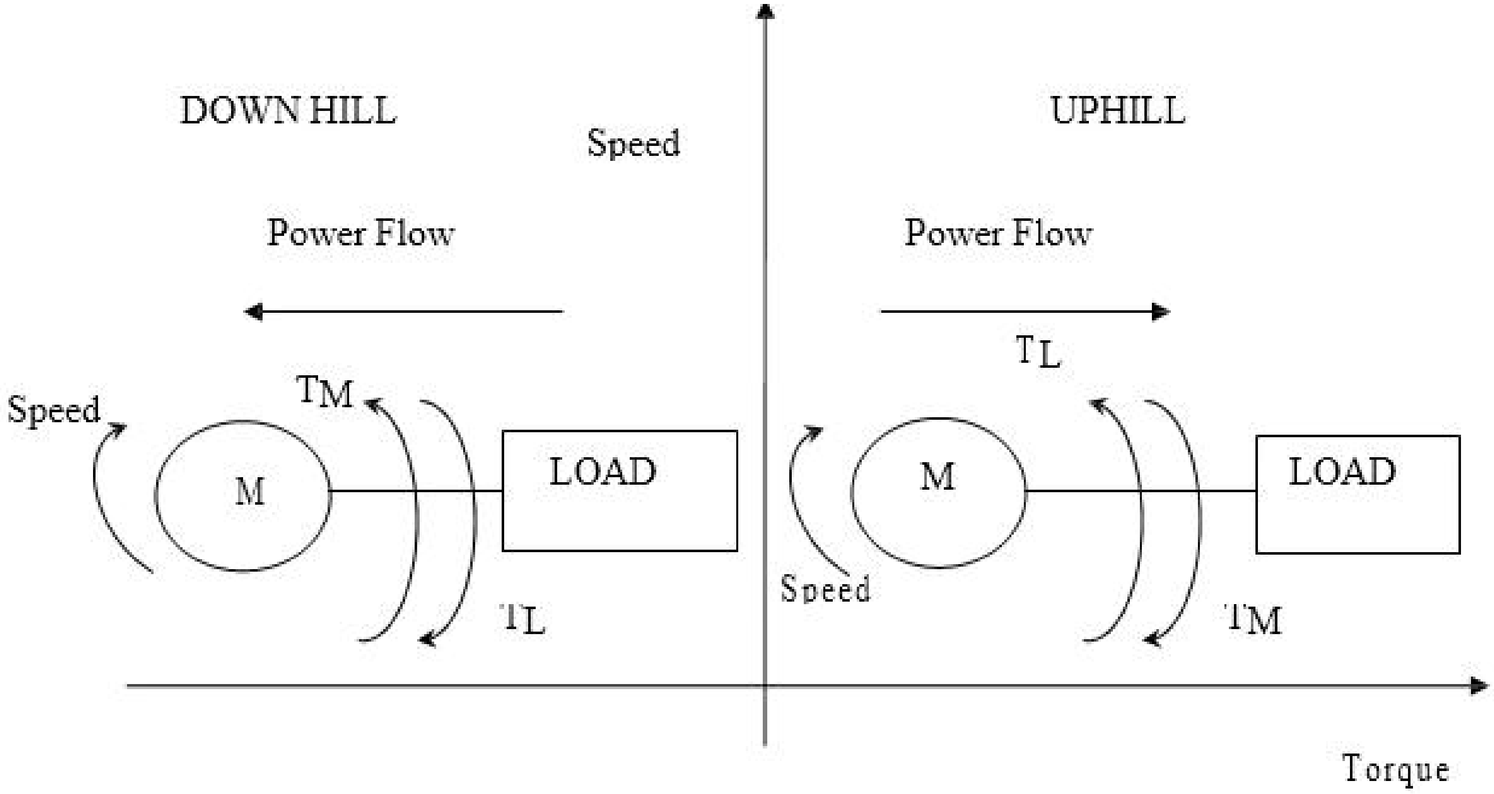
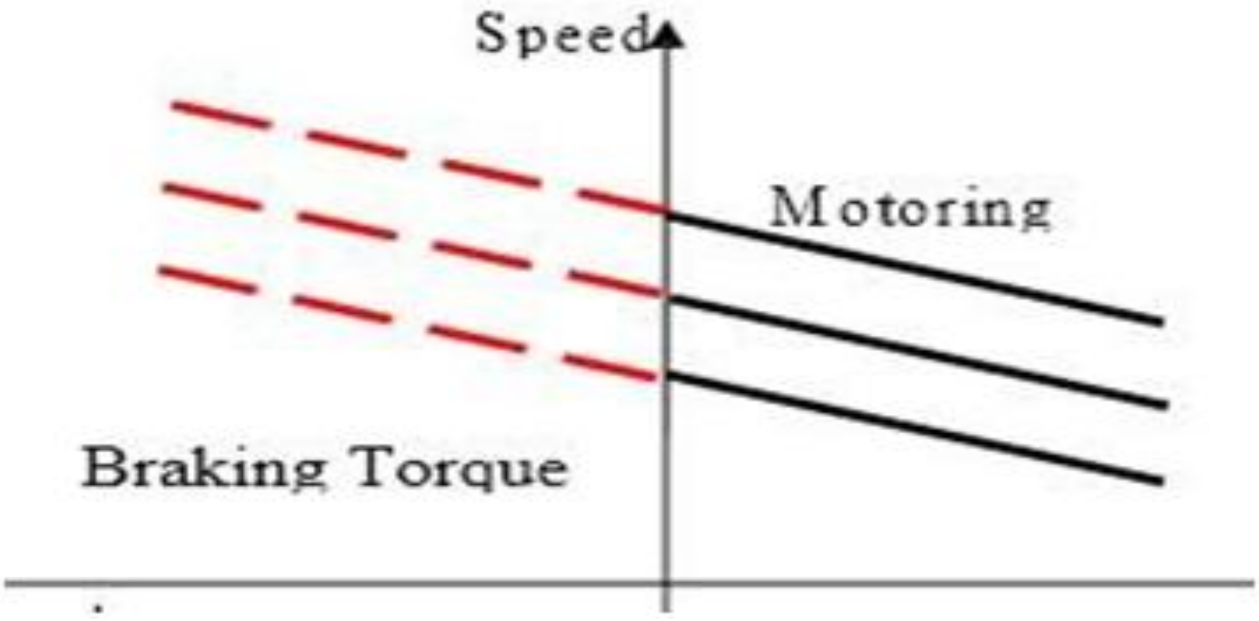

DOWN HILL
Speed
UPHILL
Power Flow
Power Flow
TL
Speed
TM
M
LOAD
M
LOAD
Speed
TL
TM
Torque

Contd..

- Regenerative Braking for DC motor:
- In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.
- $E > V$ and I_a should be negative

Contd..

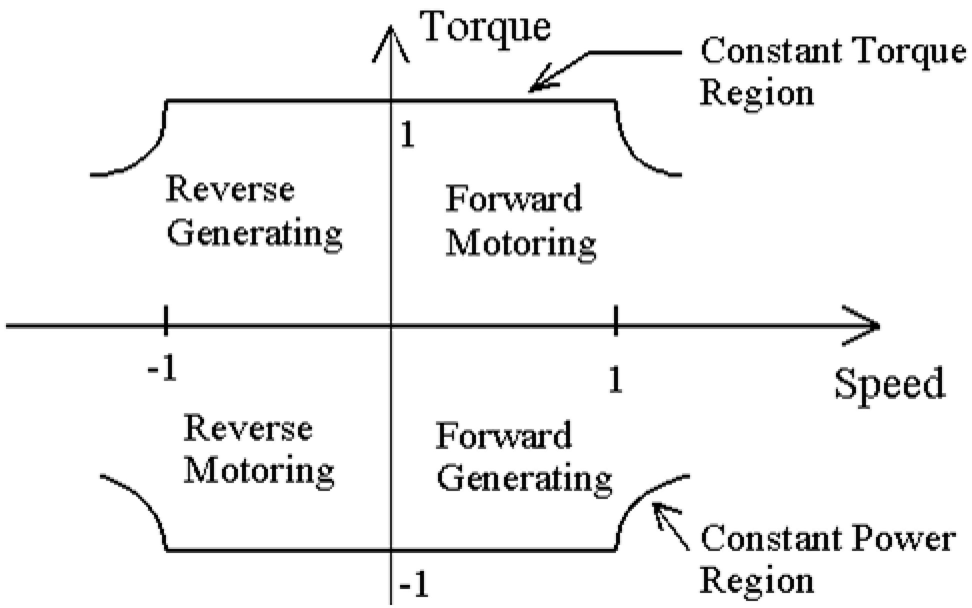


Regenerative braking speed torque characteristics of dc shunt motor

Four quadrant operation of DC motors by dual converters

- Separately-excited dc shunt motor can be operated in either direction in either of the two modes, the two modes being the motoring mode and the regenerating mode.
- It can be seen that the motor can operate in any of the four quadrants and the armature of the dc motor in a fast four-quadrant drive is usually supplied power through a dual converter. The dual converter can be operated with either circulating current or without circulating current.
- If both the converters conduct at the same time, there would be circulating current and the level of circulating current is restricted by provision of an inductor.

Contd..



Four quadrant operations

Contd..

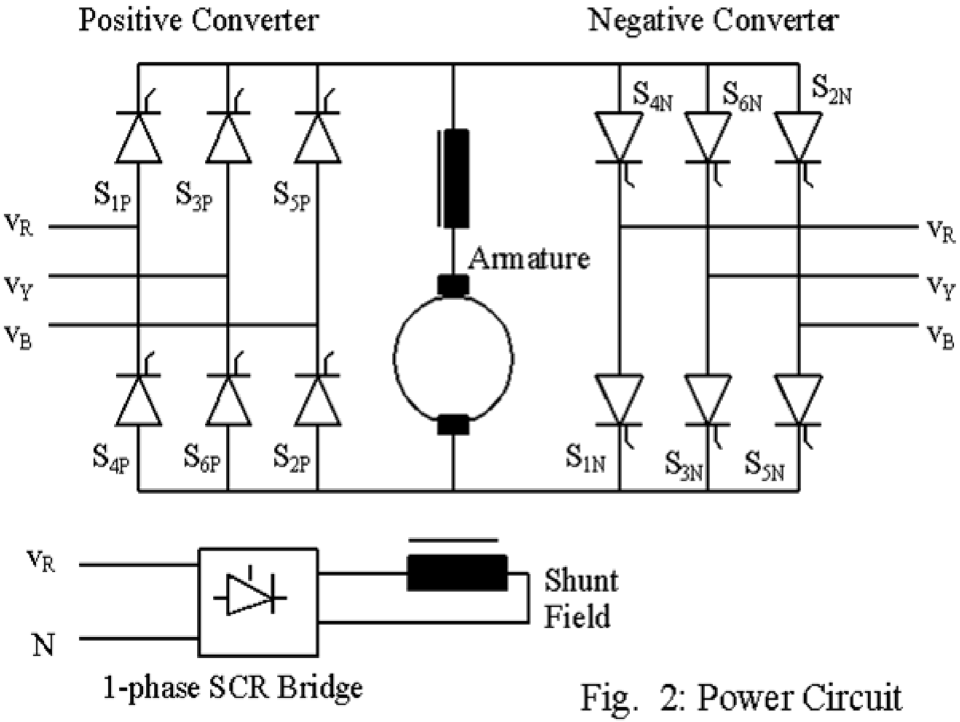
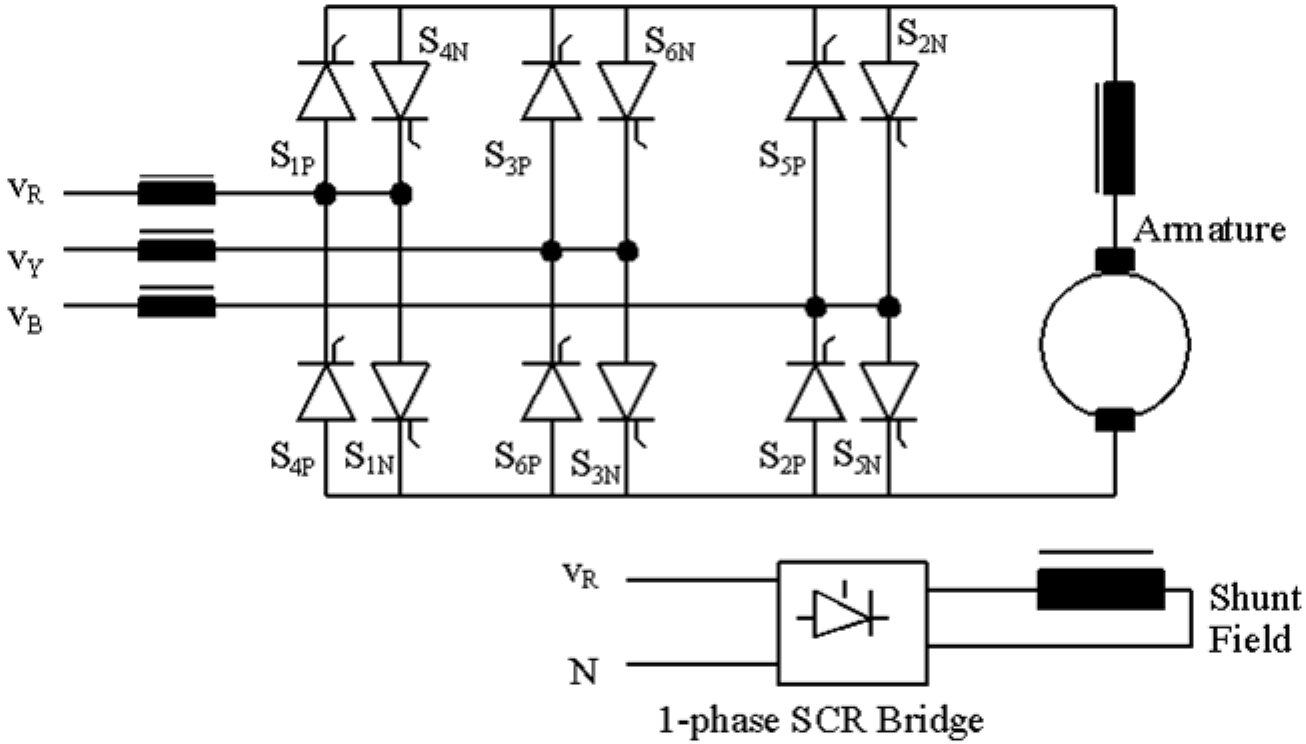


Fig. 2: Power Circuit

Dual converter fed DC motor

closed loop operation of DC motor with four quadrant operations



Dual converter fed DC separately excited motor

Contd..

- The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled.
- To control the motor in the reverse direction, the negative converter is controlled. When the motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter.

Contd..

$$\frac{3U}{\pi} \times \cos(\alpha_P) = -\frac{3U}{\pi} \times \cos(\alpha_N) \quad (1)$$

$$\cos(\alpha_P) = \cos(\pi - \alpha_N) \quad (2)$$

$$\alpha_P + \alpha_N = \pi \quad (3)$$

Contd..

- In a dual-converter, the firing angles for the converter are changed according to equation (3). But it needs to be emphasized that only one converter operates at any instant.
- When the speed of the motor is to be increased above its base speed, the voltage applied to the armature is kept at its nominal value and the phase-angle of the single phase bridge is varied such that the field current is set to a value below its nominal value.
- If the nominal speed of the motor is 1500 rpm, then the maximum speed at which it can run cannot exceed a certain value, say 2000 rpm. Above this speed, the rotational stresses can affect the commutator and the motor can get damaged.

Single quadrant chopper fed DC separately excited and series motors with continuous current operation

- Time Ratio Control (TRC)
- In this control scheme, time ratio Ton/T (duty ratio) is varied. This is realized by two different ways called Constant Frequency System and Variable Frequency System as described below:
- Constant Frequency System
- In this scheme, on-time is varied but chopping frequency f is kept constant. Variation of Ton means adjustment of pulse width, as such this scheme is also called pulse-width-modulation scheme.
- Variable Frequency System
- In this technique, the chopping frequency f is varied and either (i) on-time Ton is kept constant or

  (ii) off-time Toff is kept constant. This method of controlling duty ratio is also called Frequency- modulation scheme.

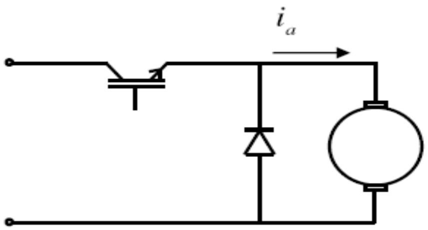
Contd..

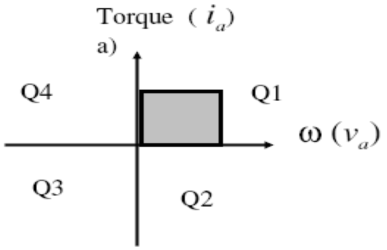
- Current- Limit Control
- In this control strategy, the on and off of chopper circuit is decided by the previous set value of load current. The two set values are maximum load current and minimum load current.
- When the load current reaches the upper limit, chopper is switched off. When the load current falls below lower limit, the chopper is switched on. Switching frequency of chopper can be controlled by setting maximum and minimum level of current.
- Current limit control involves feedback loop, the trigger circuit for the chopper is therefore more complex. PWM technique is the commonly chosen control strategy for the power control in chopper circuit

Contd..

Single-quadrant drive

- Unidirectional speed. Braking not required.





For $0 < t < T$,

The armature voltage at steady state :

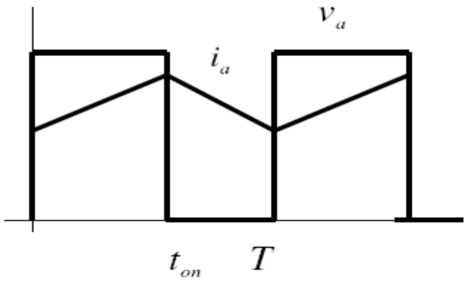
$$V_a = \frac{1}{T}\int_0^{t_{on}} V dt = \frac{t_{on}}{T} = DV$$

Armature (DC) current is :

$$I_a = \frac{V_a - E_g}{R_a};$$

and speed can be approximated as :

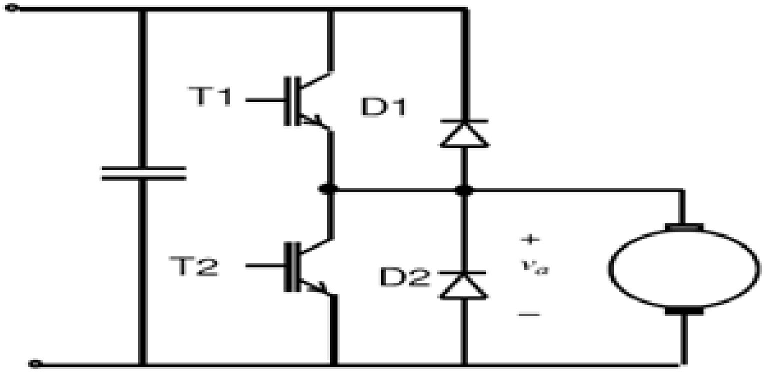
$$\omega = \frac{V_a}{K_v I_f}$$

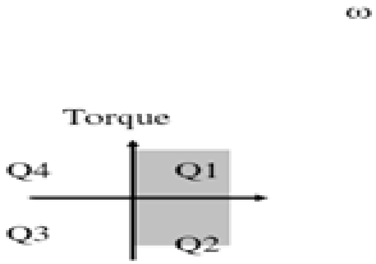


Two quadrant chopper fed DC separately excited and series motors with continuous current operation

- FORWARD MOTORING (T1 and D2 operate)
  - T1 on: The supply is connected to motor terminal.
  - T1 off: The armature current freewheels through D2.
  - V*a* (hence speed) is determined by the duty ratio.

- REGENERATION (T2 and D1 operate)
  - T2 on: motor acts as a generator
  - T2 off:, the motor acting as a generator returns energy to the supply through D2.





Contd..

- Class C Chopper can be used as a step-up or step-down chopper
- Class C Chopper is a combination of Class A and Class B Choppers.
- For first quadrant operation, CH1 is ON or D2 conducts.
- For second quadrant operation, CH2 is ON or D1 conducts.
- When CH1 is ON, the load current is positive.
- The output voltage is equal to ‘V’ & the load receives power from the source.
- When CH1 is turned OFF, energy stored in inductance L forces current to flow through the diode D2 and the output voltage is zero.

Contd..

- Current continues to flow in positive direction.
- When CH2 is triggered, the voltage E forces current to flow in opposite direction through L and CH2 The output voltage is zero.
- On turning OFF CH2 , the energy stored in the inductance drives current through diode D1 and the supply Output voltage is V, the input current becomes negative and power flows from load to source.

Contd..

- Average output voltage is positive

• Average output current can take both positive and negative values.

• Choppers CH1 & CH2 should not be turned ON simultaneously as it would result in short circuiting the supply.

• Class C Chopper can be used both for dc motor control and regenerative braking of dc motor.

Numerical problems on Chopper fed DC motors

1. A step up chopper has an input voltage of 150V. The voltage output needed is 450V. Given, that the thyristor has a conducting time of 150μseconds. Calculate the chopping frequency.

$$f = \frac{1}{T}$$

Where **T** – Chopping time period = $T_{ON} + T_{OFF}$

Given – $V_S = 150V$ $V_0 = 450V$ $T_{ON} = 150\mu sec$

$$V_0 = V_{S\left(\frac{T}{T-T_{ON}}\right)}$$

$$450 = 150\frac{T}{T-150^{-6}} \quad T = 225\mu sec$$

Therfore, $f = \frac{1}{225*10^{-6}} = 4.44KHz$

Contd..

- The new voltage output, on condition that the operation is at constant frequency after the halving the pulse width.
- Halving the pulse width gives –

$$T_{ON} = \frac{150 \times 10^{-6}}{2} = 75\mu sec$$

The frequency is constant thus,

$$f = 4.44KHz$$

$$T = \frac{1}{f} = 150\mu sec$$

The voltage output is given by –

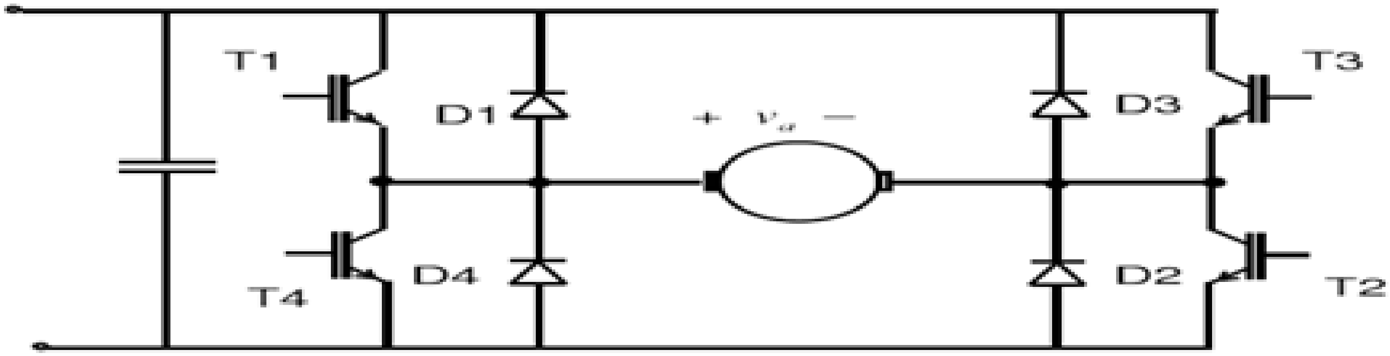
$$V_0 = V_S\left(\frac{T}{T - T_{ON}}\right) = 150 \times \left(\frac{150 \times 10^{-6}}{(150 - 75) \times 10^{-6}}\right) = 300Volts$$

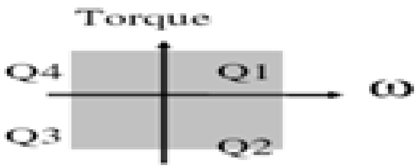
Contd..

2. A d.c. series motor, fed from 400 V dc source through a chopper, has the following parameters. Ra = 0.05 Ω, Rs = 0.07 Ω, k = 5* 10-3 Nm/amp^2 the average armature current of 200A ripple free or a chopper duty cycle of 50%. Determine Input power from the source and ii) Motor speed

Four quadrant chopper fed DC separately excited and series motors with continuous current operation:

A full-bridge DC-DC converter is used.





Contd..

- • Class E is a four quadrant chopper

  • When CH1 and CH4 are triggered, output current i_O flows in positive direction through CH1 and CH4, and with output voltage $v_O = V$.

  • This gives the first quadrant operation.

  • When both CH1 and CH4 are OFF, the energy stored in the inductor L drives i_O through D2 and D3 in the same direction, but output voltage $v_O = -V$.

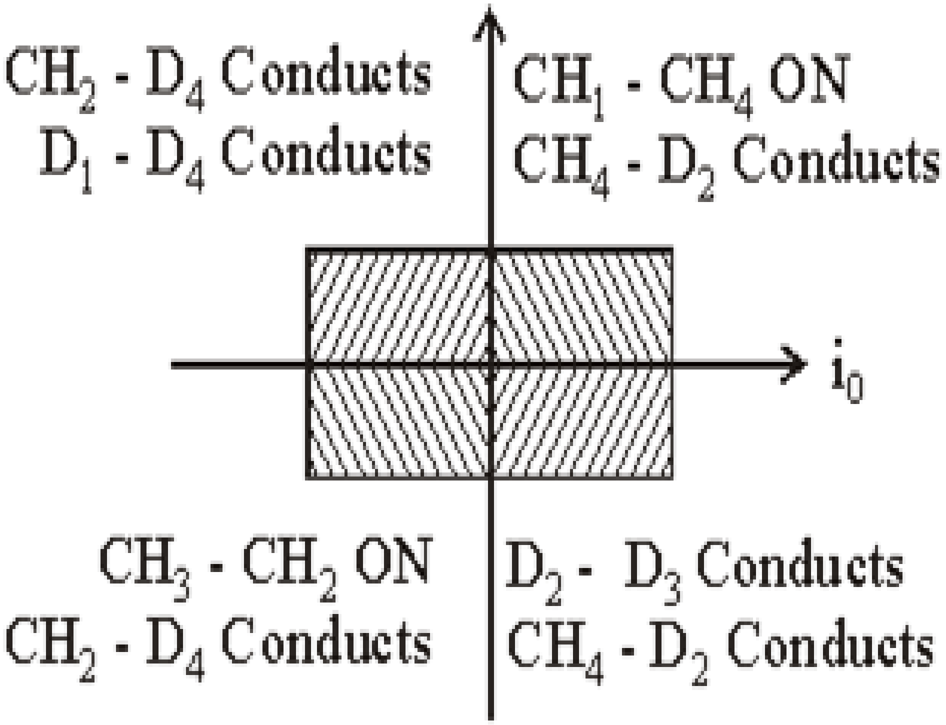
  • Therefore the chopper operates in the fourth quadrant.

  • When CH2 and CH3 are triggered, the load current i_O flows in opposite direction & output voltage $v_O = -V$.

Contd..

- Since both i_O and v_O are negative, the chopper operates in third quadrant.
- When both CH2 and CH3 are OFF, the load current i_O continues to flow in the same direction D1 and D4 and the output voltage $v_O = V$.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.

Contd..



Four quadrant operations

Numerical problems on Chopper fed DC motors

1. In a dc chopper, the average load current is 30 Amps, chopping frequency is 250 Hz. Supply voltage is 110 volts. Calculate the ON and OFF periods of the chopper if the load resistance is 2 ohms.

$$I_{dc} = 30 \text{ Amps}, \quad \text{f} = 250 \text{ Hz}, \quad \text{V} = 110 \text{ V}, \quad R = 2\Omega$$

Chopping period, $$T = \frac{1}{f} = \frac{1}{250} = 4\times10^{-3} = 4 \text{ msecs}$$

$$I_{dc} = \frac{V_{dc}}{R} \text{ and } V_{dc} = dV$$

Therefore $$I_{dc} = \frac{dV}{R}$$

$$d = \frac{I_{dc}R}{V} = \frac{30\times2}{110} = 0.545$$

Contd..

Chopper ON period, $t_{ON} = dT = 0.545 \times 4 \times 10^{-3} = 2.18 \text{ msecs}$

Chopper OFF period, $t_{OFF} = T - t_{ON}$

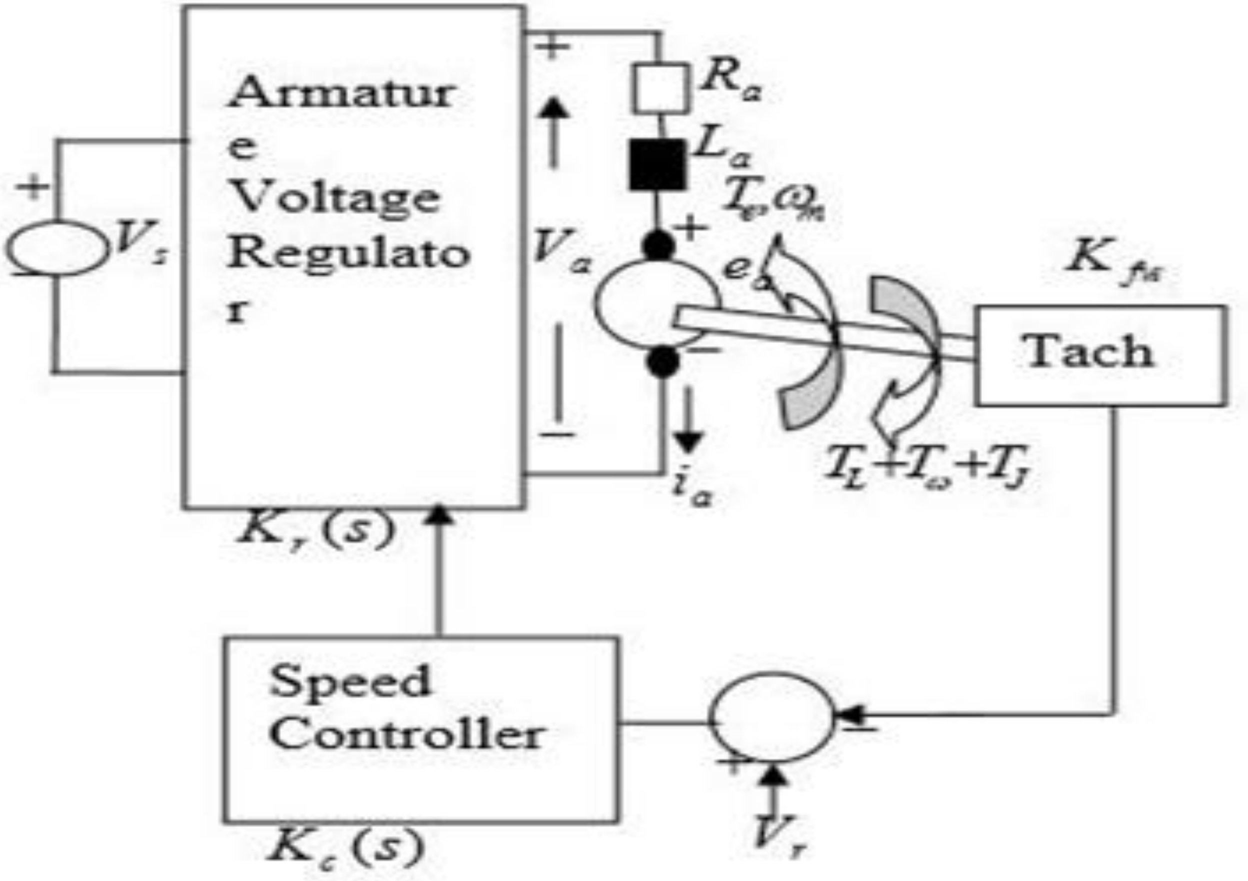
$$t_{OFF} = 4 \times 10^{-3} - 2.18 \times 10^{-3}$$

$$t_{OFF} = 1.82 \times 10^{-3} = 1.82 \text{ msec}$$

Contd..

2. A chopper used for ON and OFF control of a dc separately excited motor has supply voltage of 230Vm Ton = 10ms, Toff = 15ms. Neglecting armature inductance and assuming continuous conduction of motor current, Calculate the average load current when the motor speed is 1500 rpm, has a voltage constant Kv = 0.5 V/rad/sec. The armature resistance is 2 Ω.

Closed loop operation of chopper fed DC motors



closed loop operation of DC motor

Contd..

- Closed loop control improves on the drives performance by increasing speed of response and improving on speed regulation. So the function of closed loop control is that ωn is increased, ε is reduced, ts are reduced, and Speed Regulation (SR) is reduced. A closed loop speed control scheme is shown above
- Where, KfꞶ is the tachometer feedback gain Kc(s) is the speed controller gain
- Kr(s) is the armature voltage regulator gain

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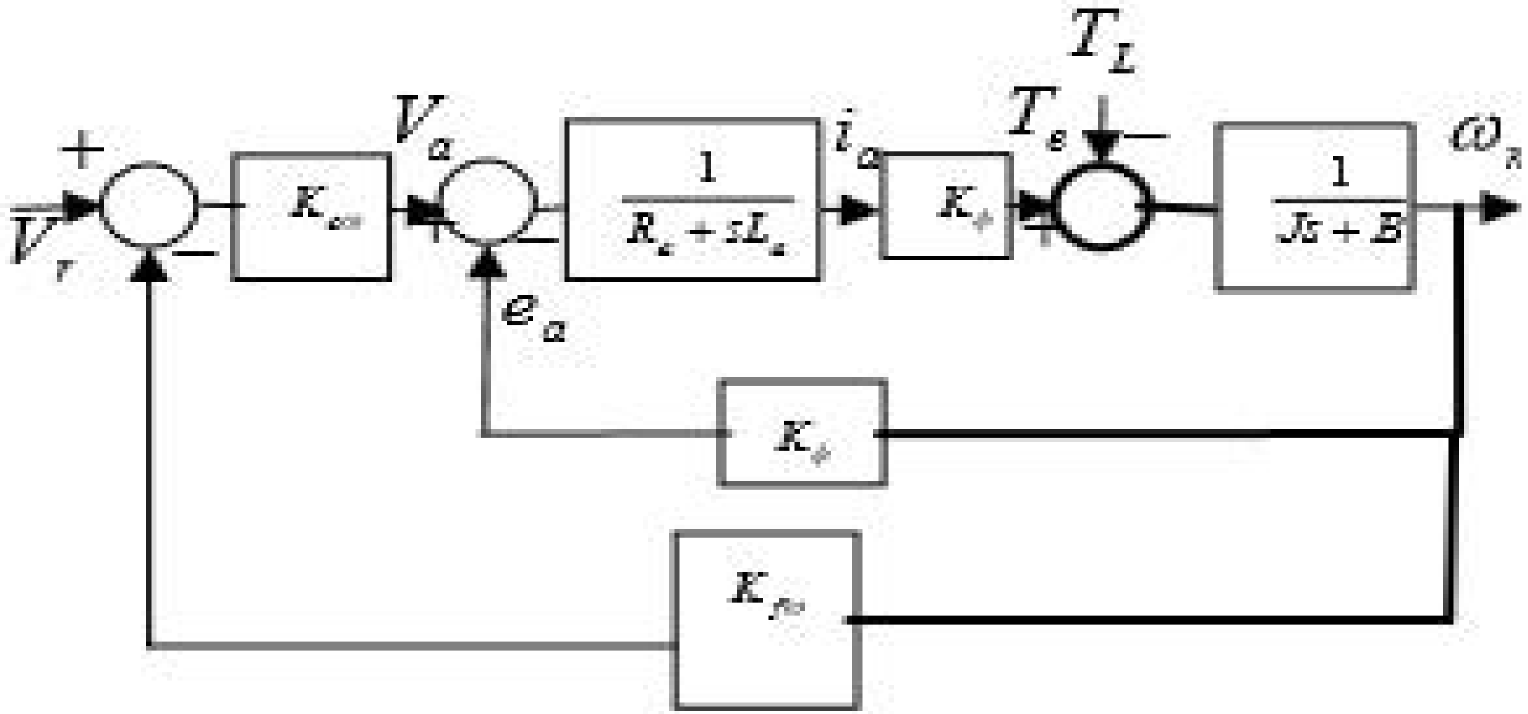

Block diagram of closed loop operation of DC motor

UNIT III

SPEED CONTROL OF INDUCTION MOTORS THROUGH VARIABLE VOLTAGE AND VARIABLE FREQUENCY

Introduction to Variable voltage characteristics of induction motor:

- A three phase induction motor is basically a constant speed motor so it’s somewhat difficult to control its speed.
- The speed control of induction motor is done at the cost of decrease in efficiency and low electrical power factor.
- Before discussing the methods to control the speed of three phase induction motor one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas

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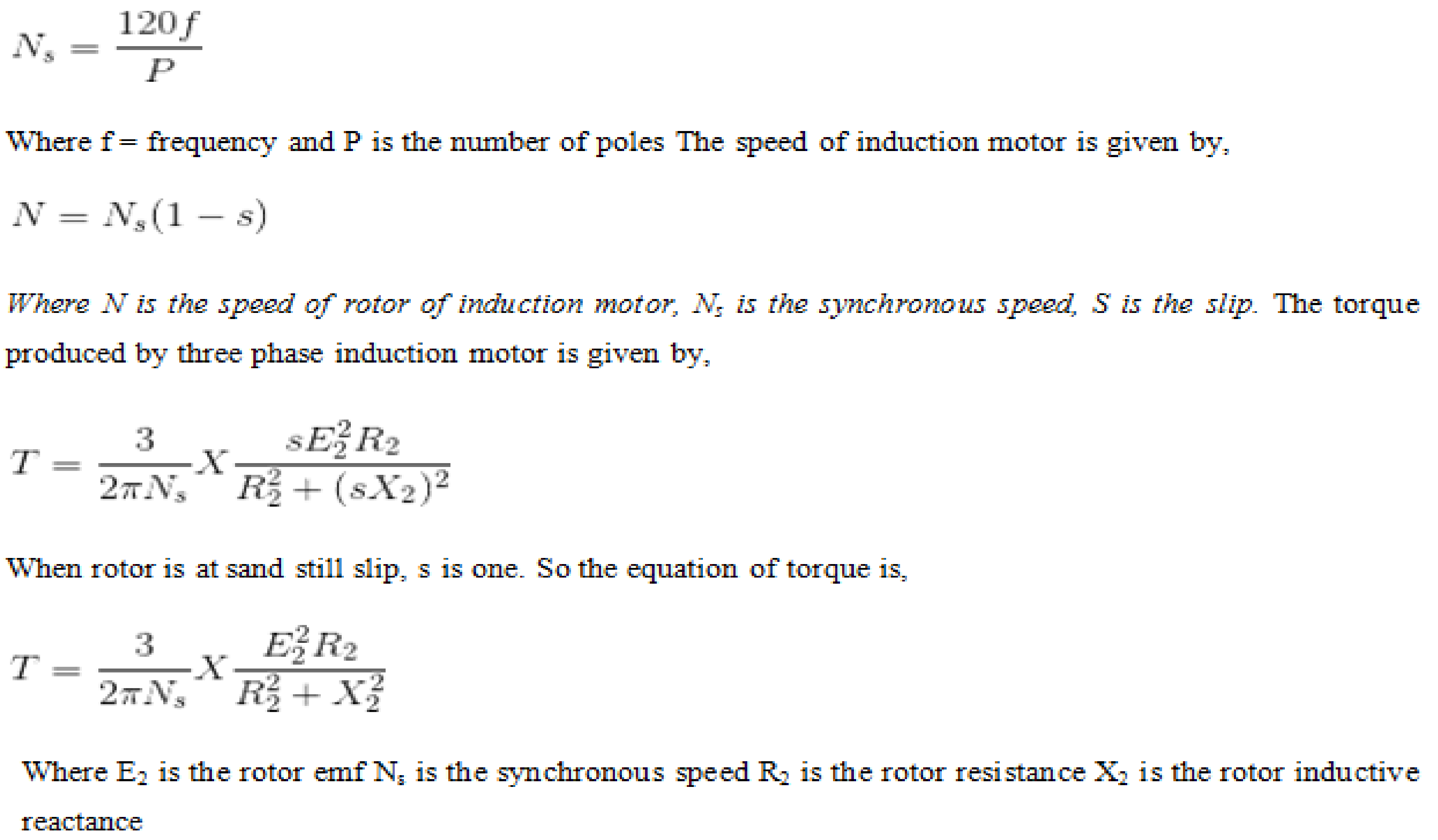

$$N_s = \frac{120f}{P}$$

Where f = frequency and P is the number of poles The speed of induction motor is given by,

$$N = N_s(1 - s)$$

Where N is the speed of rotor of induction motor, N_s is the synchronous speed, S is the slip. The torque produced by three phase induction motor is given by,

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

Contd..

The Speed of Induction Motor is changed from Both

Stator and Rotor Side

The speed control of three phase induction motor from stator

side are further classified as :

- V / f control or frequency control.
- Changing the number of stator poles.
- Controlling supply voltage.
- Adding rheostat in the stator circuit.

Contd..

The speed controls of three phase induction motor from rotor side are further classified as:

- Adding external resistance on rotor side.
- Cascade control method.
- Injecting slip frequency emf into rotor side.

Control of induction motor by AC voltage controllers:

- In this method of control, back-to-back thyristors are used to supply the motor with variable ac voltage. The analysis implies that the developed torque varies inversely as the square of the input RMS voltage to the motor.
- This makes such a drive suitable for fan- and impeller-type loads for which torque demand rises faster with speed. For other types of loads, the suitable speed range is very limited.

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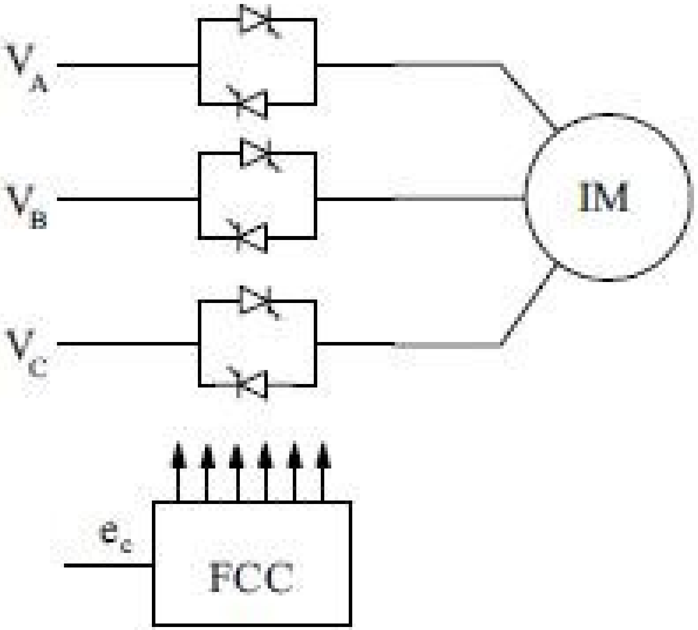
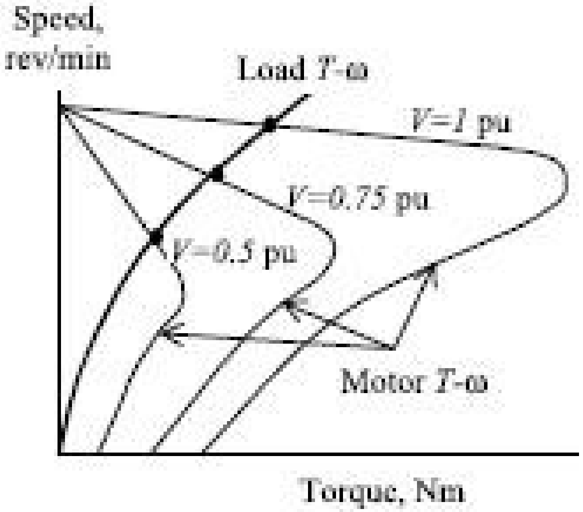


V_A
V_B
V_C
IM
e_c
FCC



Speed, rev/min
Load T-ω
V=1 pu
V=0.75 pu
V=0.5 pu
Motor T-ω
Torque, Nm

Contd..

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

Contd..

- The induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control.
- But both of these schemes result in very low efficiencies at lower speeds. The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.

Contd..

- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage

Speed torque characteristics of induction motor with variable voltage

- In this method of control, back-to-back thyristors are used to supply the motor with variable ac voltage.
- The analysis implies that the developed torque varies inversely as the square of the input RMS voltage to the motor.
- This makes such a drive suitable for fan- and impeller-type loads for which torque demand rises faster with speed.

- For other types of loads, the suitable speed range is very limited. Motors with high rotor resistance may offer an extended speed range. It should be noted that this type of drive with back-to-back thyristors with firing-angle control suffers from poor power and harmonic distortion factors when operated at low speed.
- If unbalanced operation is acceptable, the thyristors in one or two supply lines to the motor may be bypassed. This offers the possibility of dynamic braking or plugging, desirable in some applications.

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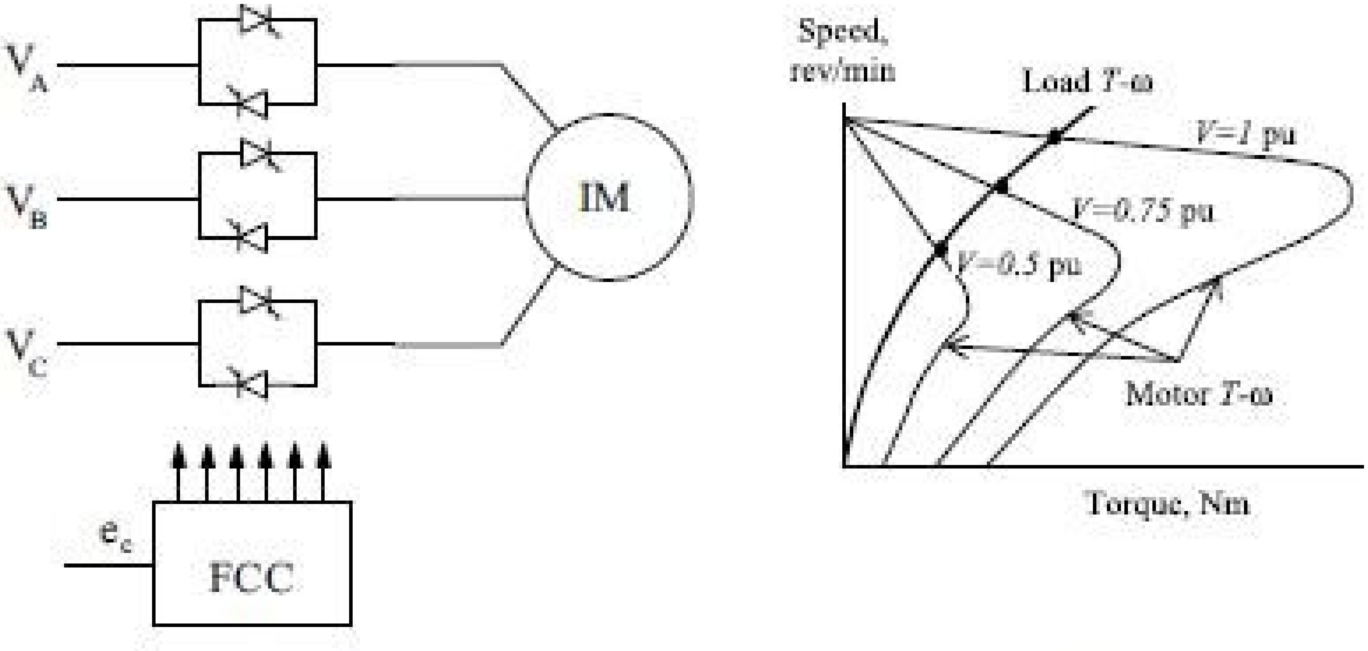

Stator voltage controller and speed characteristics under voltage

Contd..

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

Contd..

- The induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control. But both of these schemes result in very low efficiencies at lower speeds.
- The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.

Contd..

- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage

Introduction to variable frequency characteristics of induction motor

- The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.
- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.

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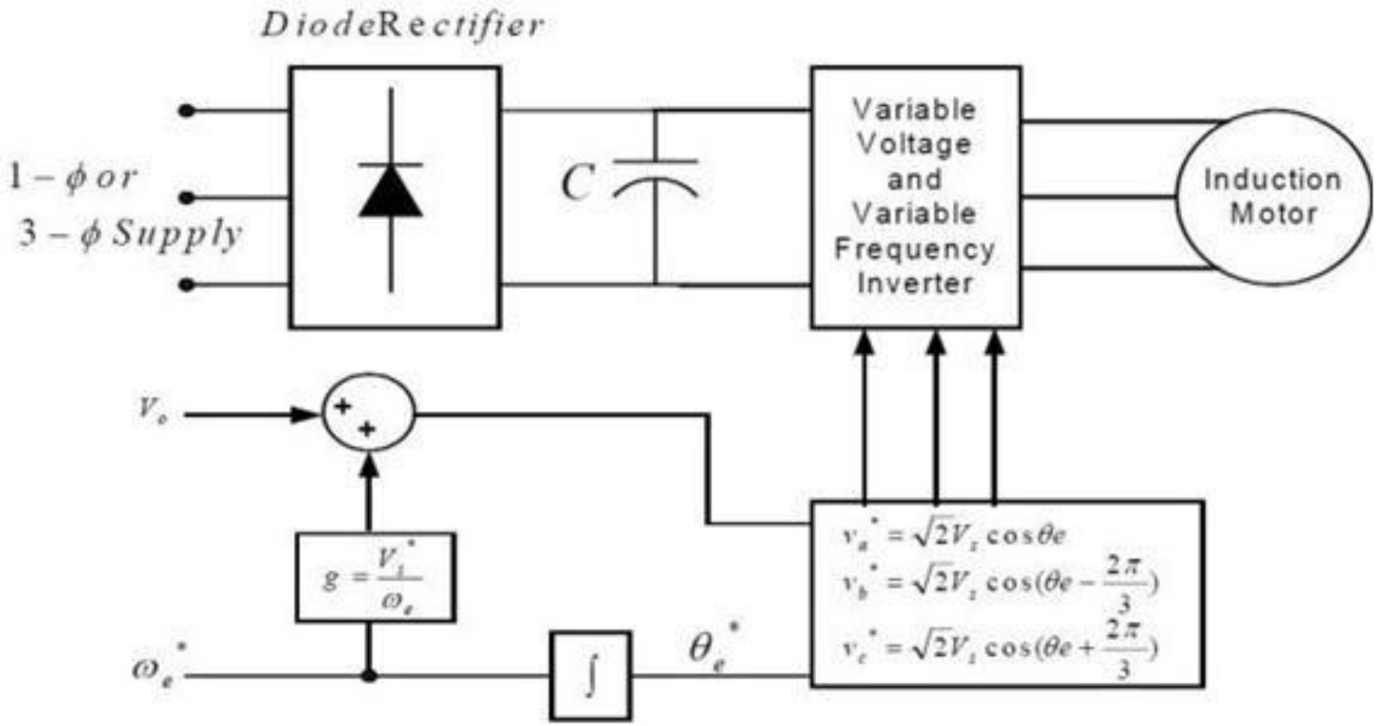

Block diagram of open loop V/F Control for an IM

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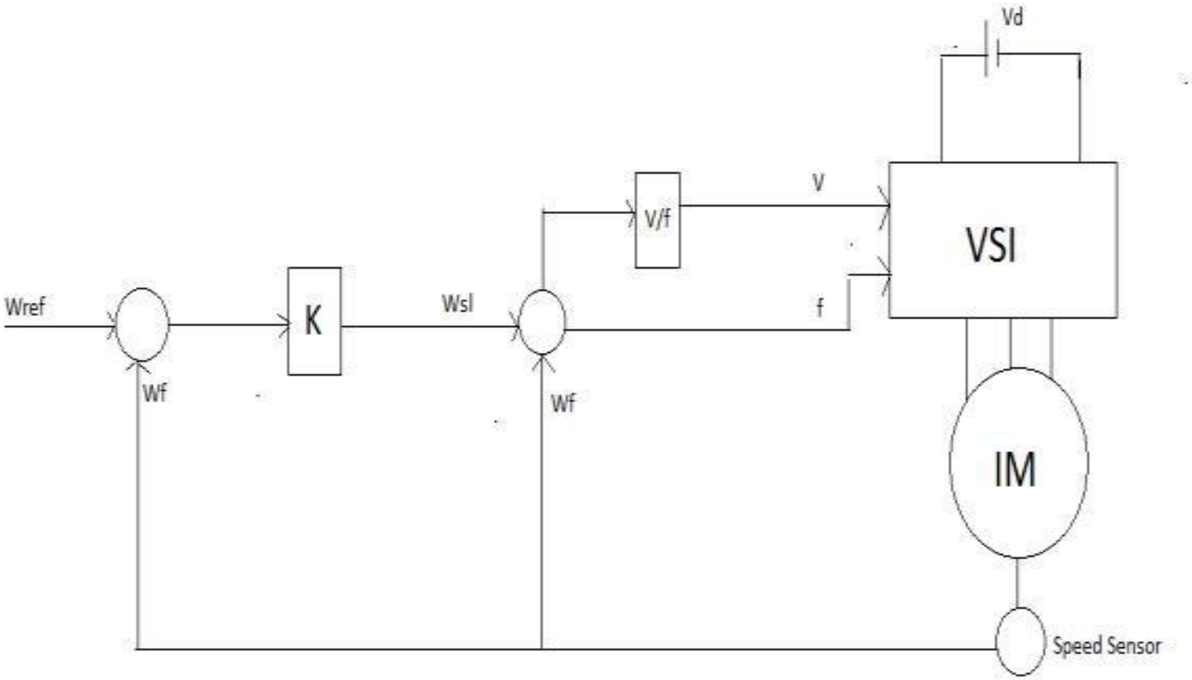

Block diagram for closed loop V/F control for an IM

Contd..

- A speed sensor or a shaft position encoder is used to obtain the actual speed of the motor. It is then compared to a reference speed. The difference between the two generates an error and the error so obtained is processed in a Proportional controller and its output sets the inverter frequency. The
- synchronous speed, obtained by adding actual speed ɷf and the slip speed ɷSI, determines the inverter frequency The reference signal for the closed-loop control of the machine terminal voltage ɷf is generated from frequency

Variable frequency control of induction motor by voltage source inverter

- The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.
- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.

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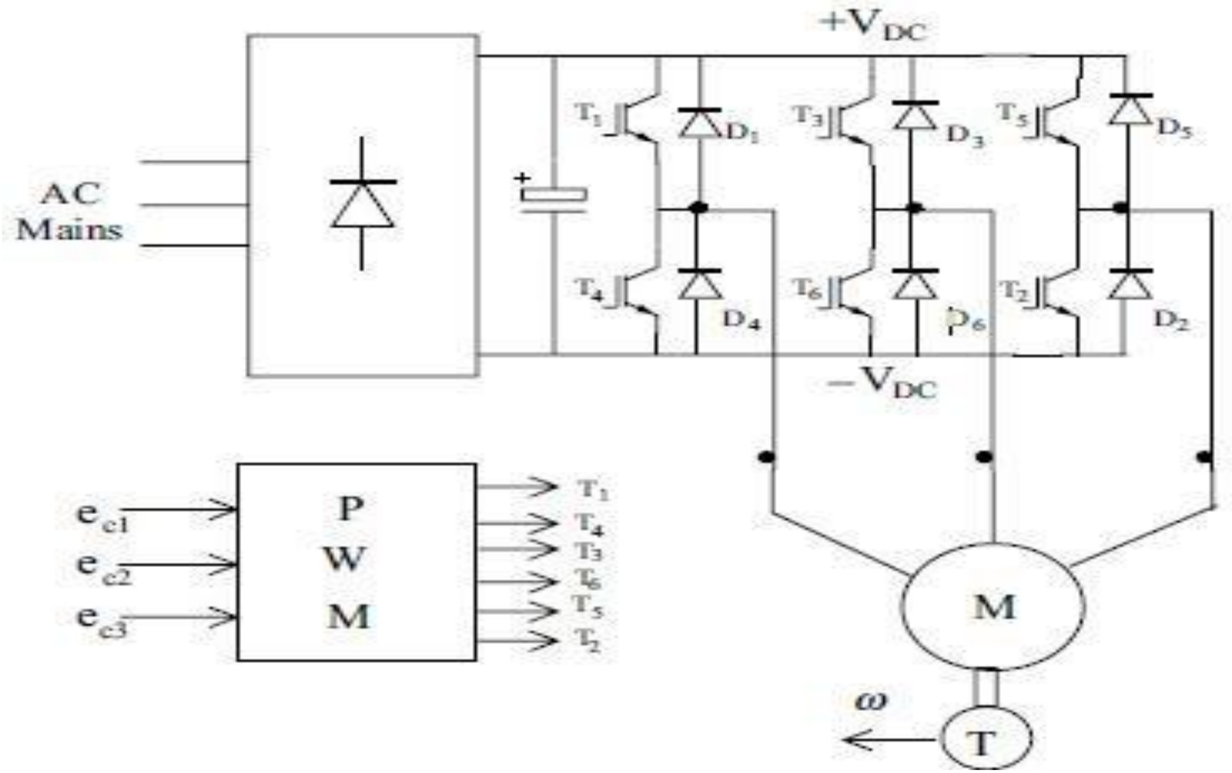

Voltage source inverter fed Induction Motor drive

Contd..

Field Weakening Mode

- The flux reference can be set according to a fixed flux- speed characteristic
- It can be calculated from simplified motor equations, which can be improved through consideration of additional variables
- It can be provided by a voltage controller, which sets the flux in such a way that the voltage required by the motor matches the voltage capability of the inverter

Variable frequency control of induction motor by current source inverter

- The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.
- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.

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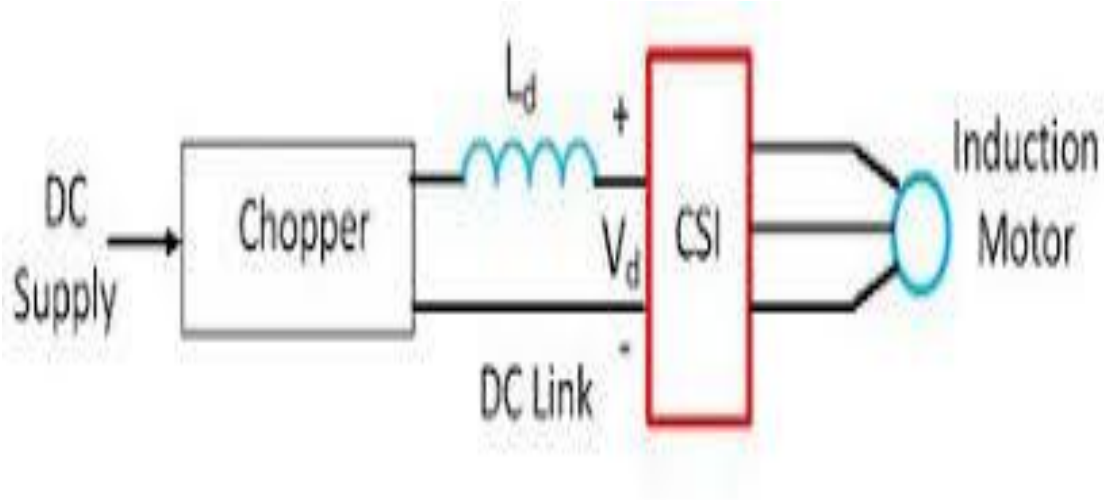

Current source inverter fed Induction Motor drive

Variable frequency control of induction motor by cycloconverter:

- The most efficient scheme for speed control of induction motor is by varying supply frequency.
- This not only results in scheme with wide speed range but also improves the starting performance.
- If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant.
- This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.

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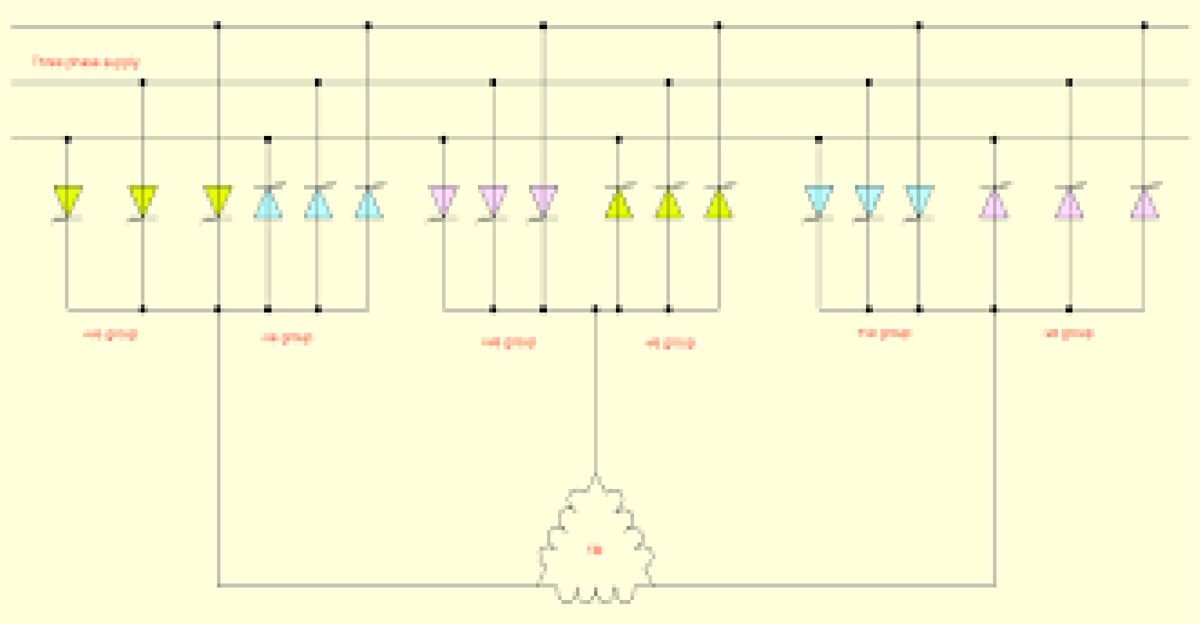

cycloconverter fed Induction Motor drive

Contd..

The open loop V/F control of an induction motor is the most common method of speed control because of its simplicity and these types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 50Hz power supplies for constant speed applications. For adjustable speed drive applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the stator flux

$\Psi s=Vs/\omega s$

Variable frequency control of induction motor by pulse with modulation control

Voltage-source Inverter-driven Induction Motor

A three-phase variable frequency inverter supplying an induction motor is shown in Figure. The power devices are assumed to be ideal switches. There are two major types of switching schemes for the inverters, namely, square wave switching and PWM switching.

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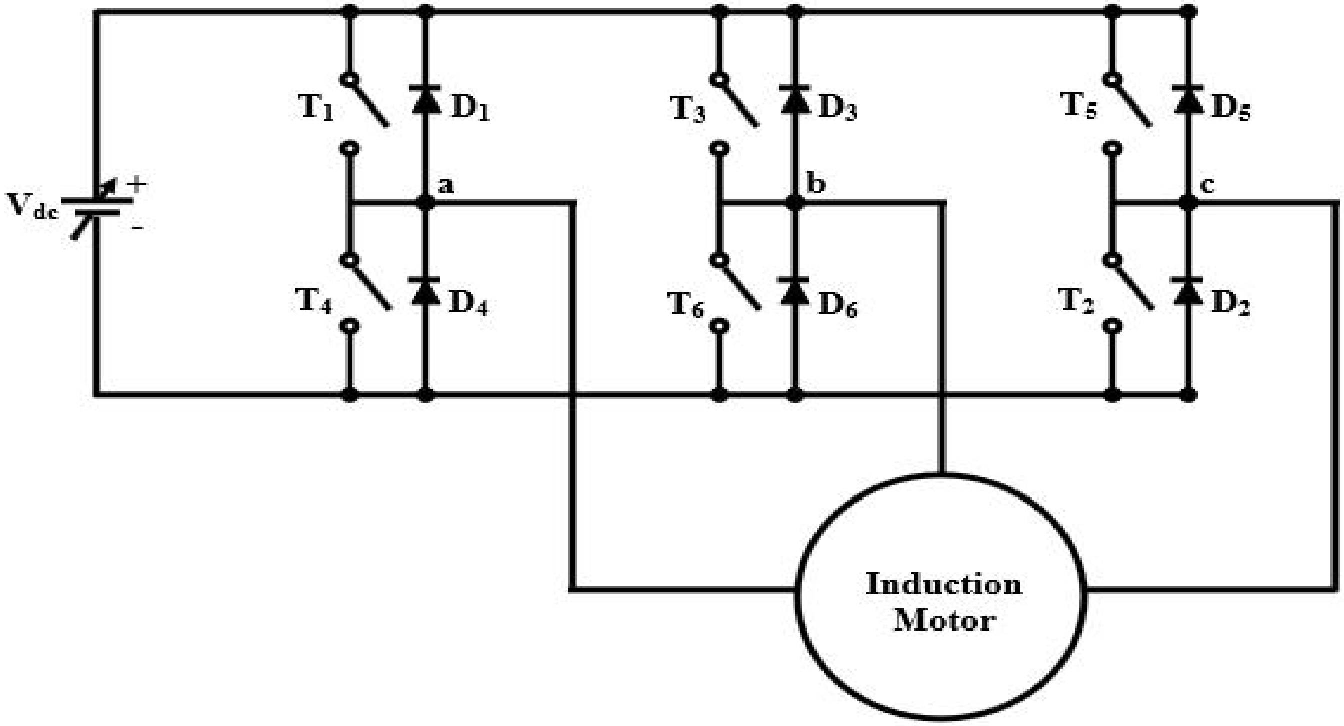

schematic of the generic inverter-fed induction motor drive

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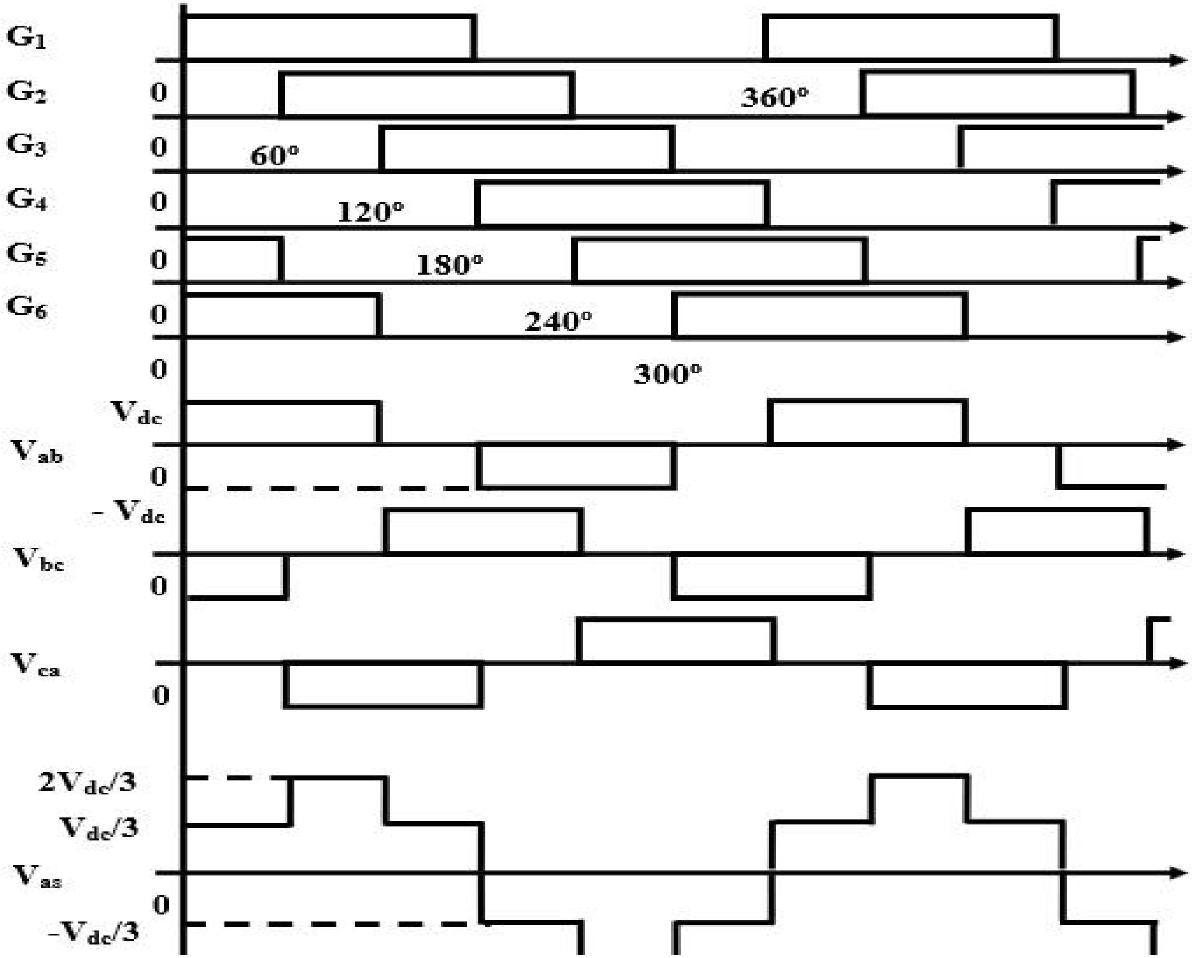


Inverter gate (base) signals and line-and phase-voltage waveforms

Comparison of voltage source inverter and current source inverter operations

- There are following difference between current source inverter and voltage source inverter.
- The input voltage in the voltage source inverter is constant whereas the input current may constant or variable. The input current in the current source inverter is constant.
- The input supply source may be short circuited due to misfiring of the switching semiconductor device in the VSI whereas there is not any difficult due misfiring of semiconductor switches to input supply current constant in the CSI.
- The maximum current passes through semiconductor device in the VSI depend upon circuit condition whereas the input current in the CSI is constant therefore the maximum current passes through semiconductor device are limited.

Contd..

- The commutation circuit of the SCR in the CSI is simple than that of VSI.
- There is no necessary of freewheeling diode in the CSI for reactive power or regenerative load whereas a freewheeling diode is used in the VSI for reactive power or regenerative load.
- The large inductor is connected at the input side in order to keep constant current at the input side of the CSI.
- There is necessary of controlled converter in order to input voltage control in the VSI similarly a converter is necessary to control input current in the CSI.

Comparison between VSI and CSI

VSI	CSI
VSI is fed from a DC voltage source having small or negligible impedance.	CSI is fed with adjustable current from a DC voltage source of high impedance.
Input voltage is maintained constant	The input current is constant but adjustable.
Output voltage does not dependent on the load	The amplitude of output current is independent of the load.
The waveform of the load current as well as its magnitude depends upon the nature of load impedance.	The magnitude of output voltage and its waveform depends upon the nature of the load impedance.
VSI requires feedback diodes	The CSI does not require any feedback diodes.
The commutation circuit is complicated	Commutation circuit is simple as it contains only capacitors.
Power BJT, Power MOSFET, IGBT, GTO with self commutation can be used in the circuit.	They cannot be used as these devices have to withstand reverse voltage.

Numerical problems on induction motor drives

1. A 440V, 60Hz, 6 pole three phase induction motor runs at a speed of 1140rpm when connected to a 440V line. Calculate the speed if voltage increases to 550V.

Solution:

$T_1 = S_1 V_1^2$

$T_2 = S_2 V_2^2$

$S_2 = S_1(V_1/V_2)^2$

$Ns = 120f/p = 120*60/8 = 1200rpm$

$S_1 = (1200 – 1140)/1200 = 0.05$

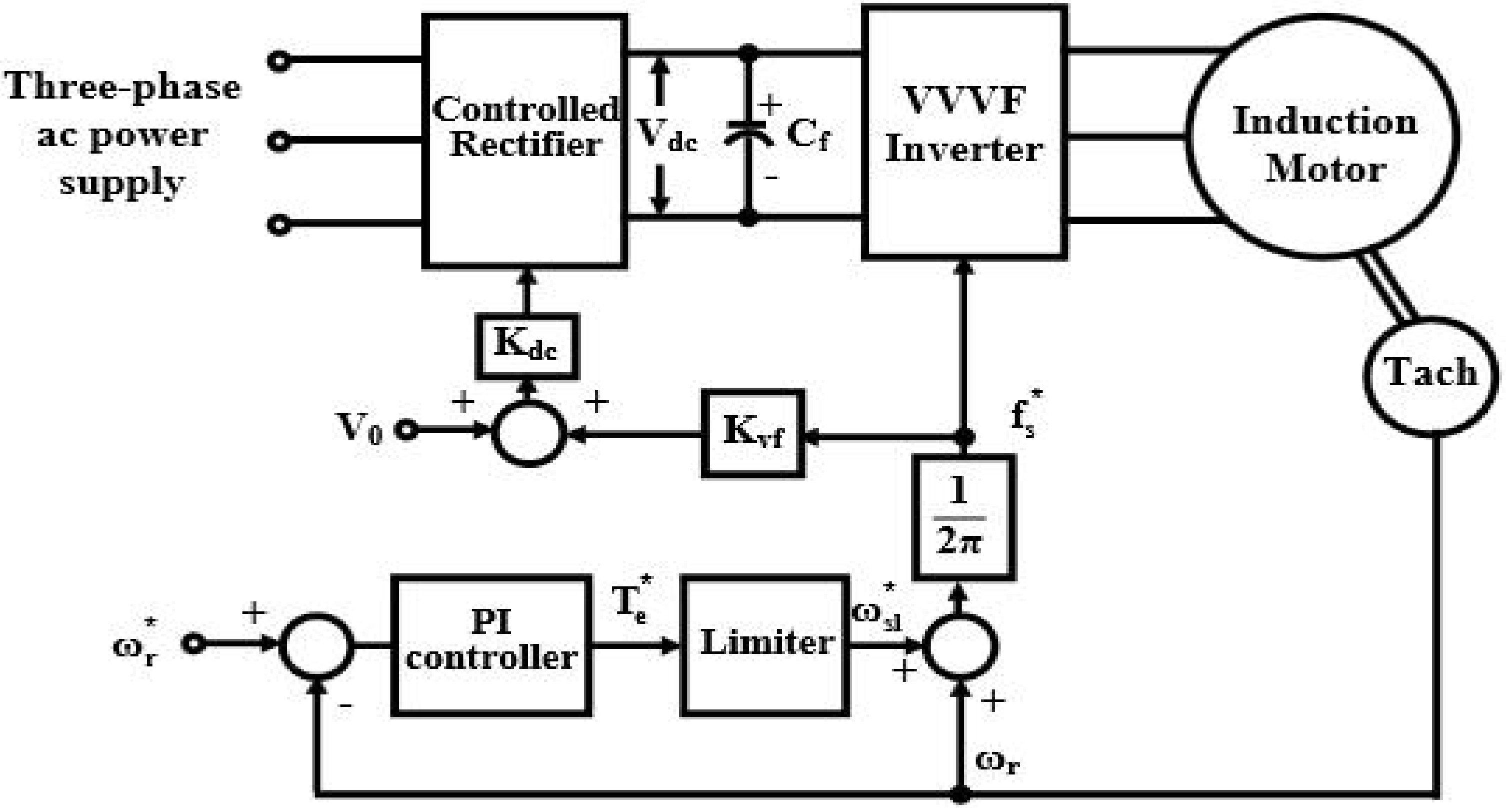
$S_2 = 0.05(440/550)^2 = 0.032$

$N_2 = N_s(1\text{-}S_2) = 1200(1\text{-}0.032) = 1161.6rpm$

Contd..

2. If three phase SCIM runs at a speed of (i) 1455rpm (ii) 1350rpm, determine the maximum current in terms of rated current at these speeds. The induction motor drives a fan and no load rotational losses are ignored.

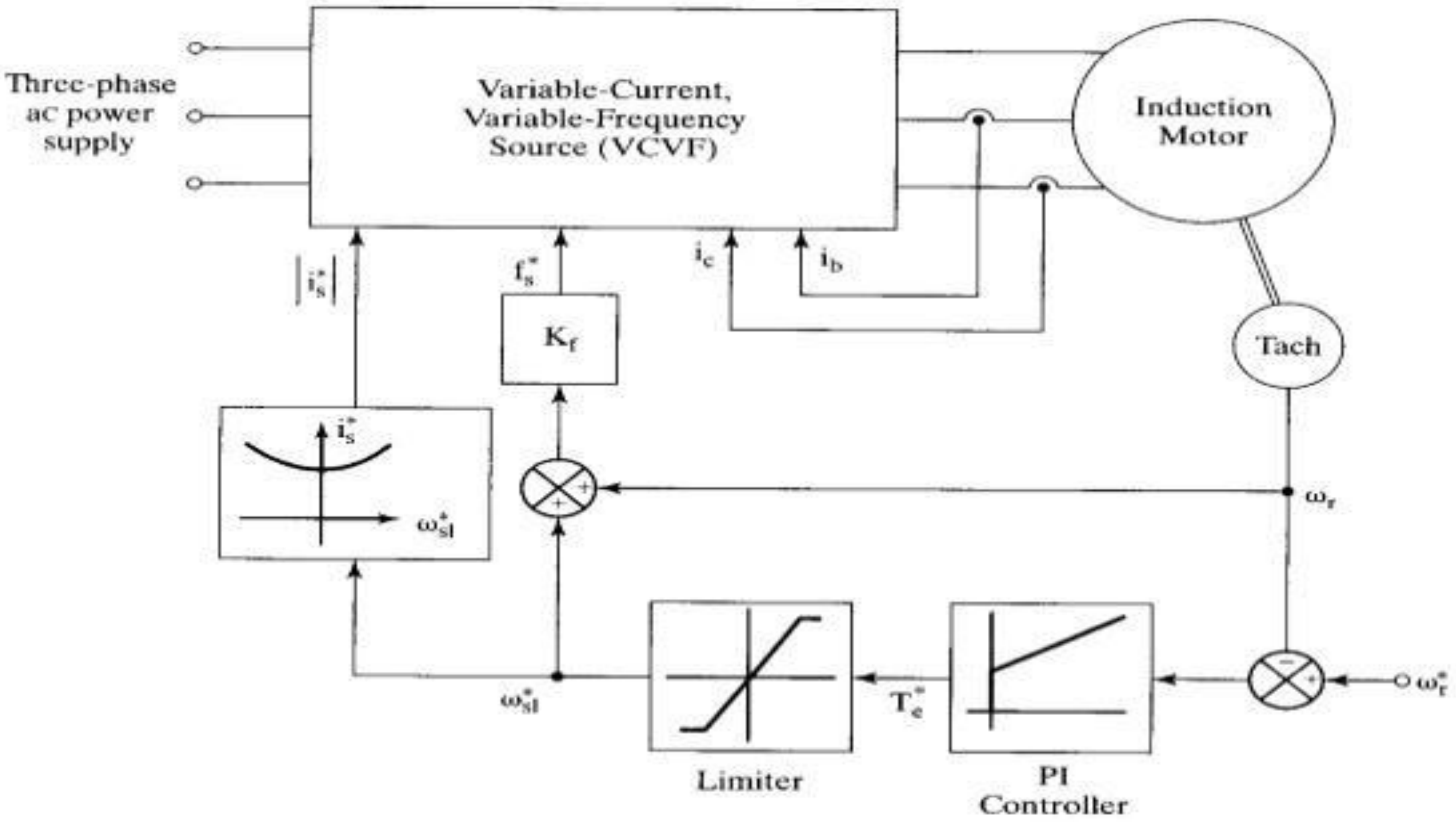
Closed loop operation of induction motor drives



Closed-loop induction motor drive with constant volts/Hz control strategy

Contd..

- An outer speed PI control loop in the induction motor drive, shown in Figure computes the frequency and voltage set points for the inverter and the converter respectively. The limiter ensures that the slip-speed command is within the maximum allowable slip speed of the induction motor. The slip- speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter, the stator frequency command is processed in an open-loop drive. Kdc is the constant of proportionality between the dc load voltage and the stator frequency.



Block diagram of closed loop speed control

Numerical problems on induction motor drives

1. A three phase, 400V, 50Hz, 4 pole, 1440rpm delta connected squirrel cage induction motor has a full load torque of 48.13Nm. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate motor torque at 1200 rpm

Solution:

$N_s = 120f/p = 120*50/4 = 1500\text{rpm}$

Rotor speed is 1440 rpm

$W_m = 1440*2/60 = 150.8$ rad/sec

$K= 0.00211$

Motor torque at 1200 rpm is

$W_m = 1200*2/60 = 125.66$ rad/sec

$T = 0.00211*125.66^2$

$T = 33.32\text{Nm}$

Contd..

2. At 50 Hz the synchronous speed and full load speed are 1500 rpm and 370 rpm respectively. Calculate the approximate value speed for a frequency of 30 Hz and 80% of full load torque for inverter fed induction motor drive.

UNIT IV

SPEED CONTROL OF INDUCTION MOTORS THROUGH ROTOR RESISTANCE AND VECTOR CONTROL

Introduction to rotor resistance control of induction motors

Rotor resistance control is one among the various methods for the speed control of induction motor. In this method of speed control, the rotor circuit resistance is varied by connecting a variable external resistance. This method is only applicable for slip ring or wound rotor induction motor (WRIM). As in squirrel cage induction motor (SCIM), rotor windings terminals are not available for external connection; its speed cannot be regulated by rotor resistance control. Therefore, this method is not applicable for squirrel cage induction motor.

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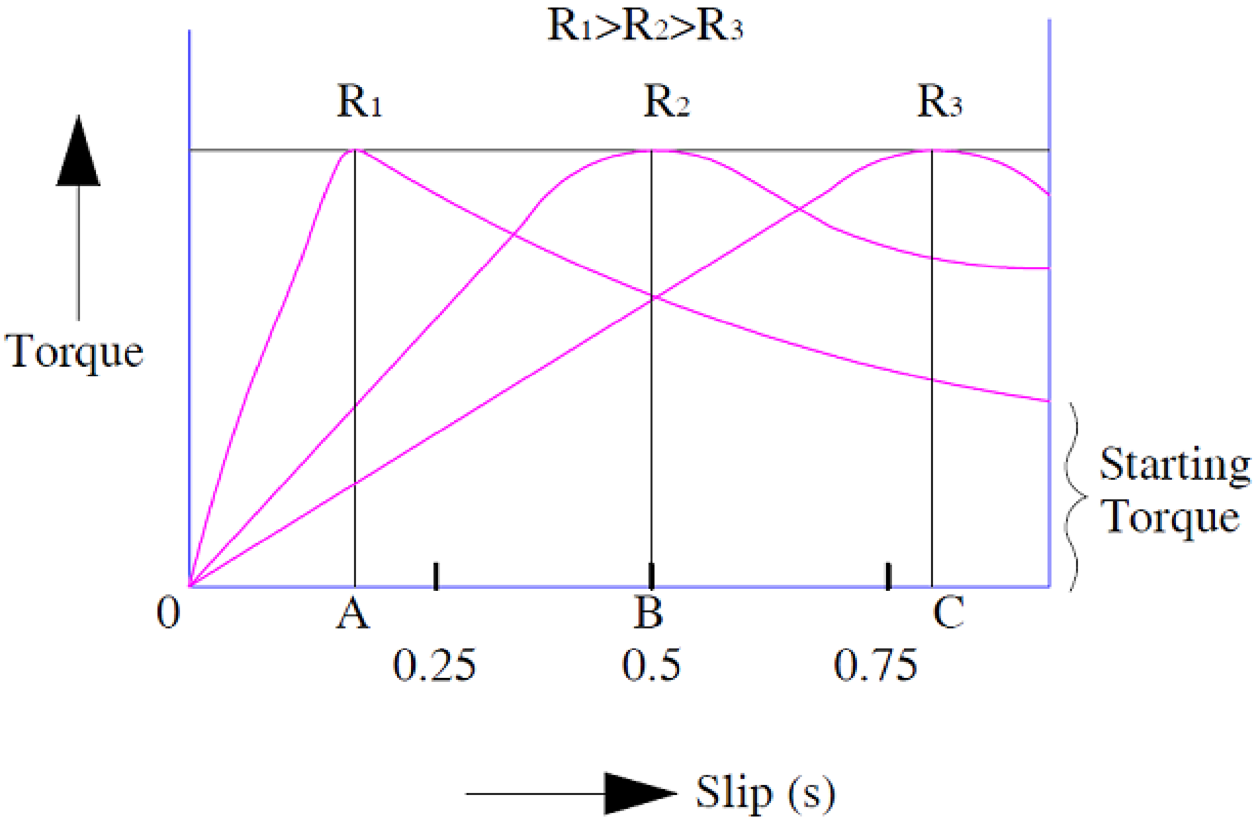

Torque speed characteristics of induction motor through rotor resistance

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- In the above figure, the maximum torque is same for rotor resistance R_1, R_2 and R_3 but the slip increase from point A to B & C. This means, increasing rotor resistance results in increase in slip. Increase in slip in turn means reduction in induction motor speed. Thus we can say that by rotor resistance control, we can achieve variable speed at a constant torque. This is the reason; this method is suitable for constant torque drive.
- It may also be noted from the above torque slip characteristics that, starting torque increases with increase in rotor resistance. Therefore this method is advantageous where we require high starting torque.

Contd..

- In spite of the above two advantages of rotor resistance control, this method have some disadvantage:
- This method cannot be employed for speed control of squirrel cage induction motor. This is because of non-availability of rotor winding terminals for external resistance connection.
- This method is not very efficient. Losses in external resistance and losses in carbon brushes at high slip operation cause wastage of energy.

Static rotor Resistance control of induction motors

- GTO chopper allows the effective rotor circuit resistances to be varied for the speed control of SRIM.
- Diode rectifier converts slip frequency input power to dc at its output terminals.

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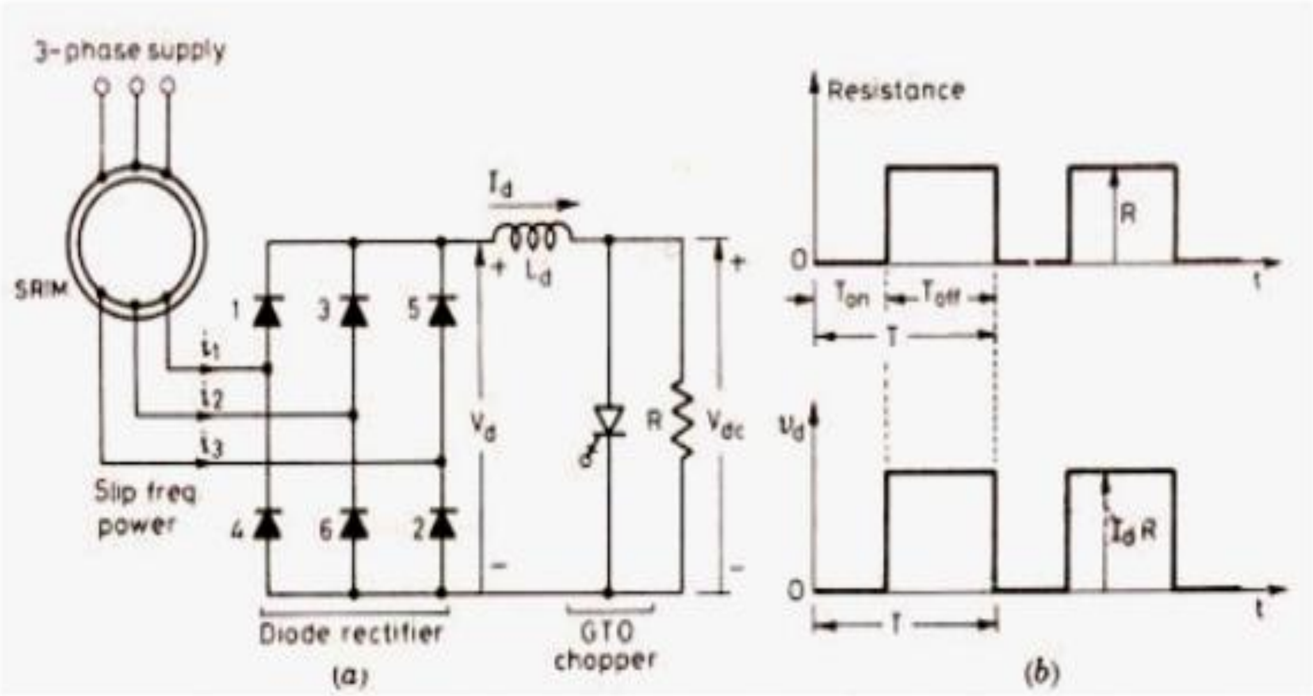


Static rotor Resistance control

Contd..

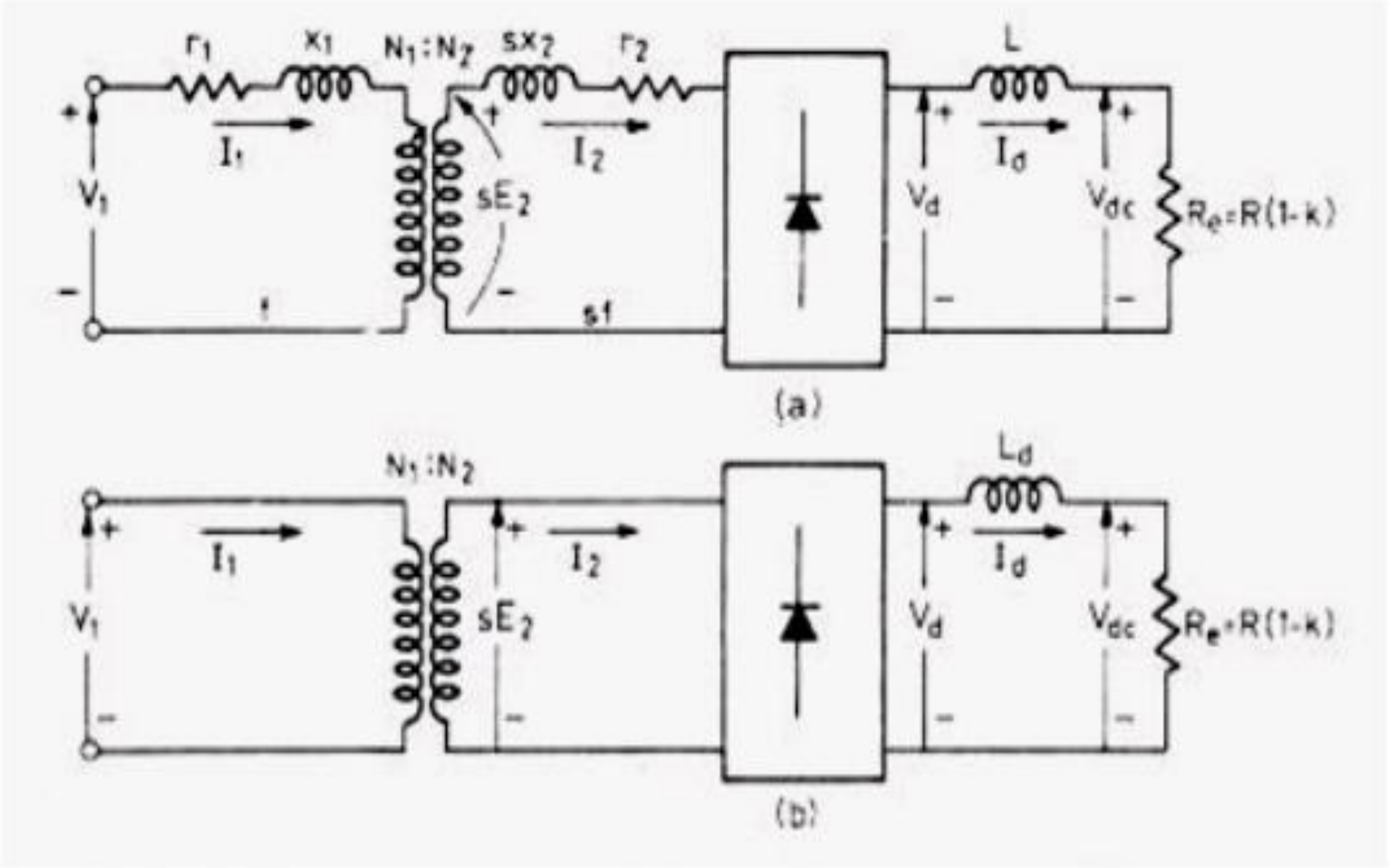
a) When chopper is on, Vdc=Vd=0Vdc=Vd=0 and resistance R gets short circuited.

b) When chopper is off, Vdc=VdVdc=Vd and resistance in the rotor circuit is R. This is shown in fig

c) From this figure, effective external resistance ReRe is

Re=R.ToffT=R(T−Ton)T=R(1−k)where k=TonT=duty cycle of chopper.

Contd..



Static rotor Resistance control with chopper control

Slip power recovery schemes of induction motor

Whenever an slip ring induction motors is connected to load such as fans, there excess energy is generated due to virtue of it's momentum and starts to run beyond synchronous speed. Intern emf is induced in rotor and excess energy will be lost which is also called as slip power.

That power can be utilized back to grip that scheme is called slip power recovery system.

In cement industry such system still available with additional recovery transformer arrangements.

During speed control of an Induction motor (WRIM) using rotor resistance control, rotor power is wasted in the external rotor resistance. The same can be utilized to increase the efficiency of the drive. Basically there are two schemes for recovering the wasted power.

Contd..

Scherbius drive

- Here the variable frequency (sf) rotor power is converted to dc by a diode bridge rectifier and then an inverter converts it back to ac (50/60 Hz) and is fed back to the supply mains. Thus the slip power is fed back to the source instead of wasting it in the rotor resistance thereby increasing the efficiency of the drive .

Contd..

Kramer Drive

- Here the variable frequency (sf) rotor power is converted to dc by a diode bridge rectifier. The dc power is fed to a dc motor which is mechanically coupled to the induction motor. Thus the torque supplied to the load is the sum of the torque produced by induction and dc motor. In this scheme, the slip power is utilized mechanically.

Static Scherbius drive performance and speed torque characteristics

Static scherbius drive system:

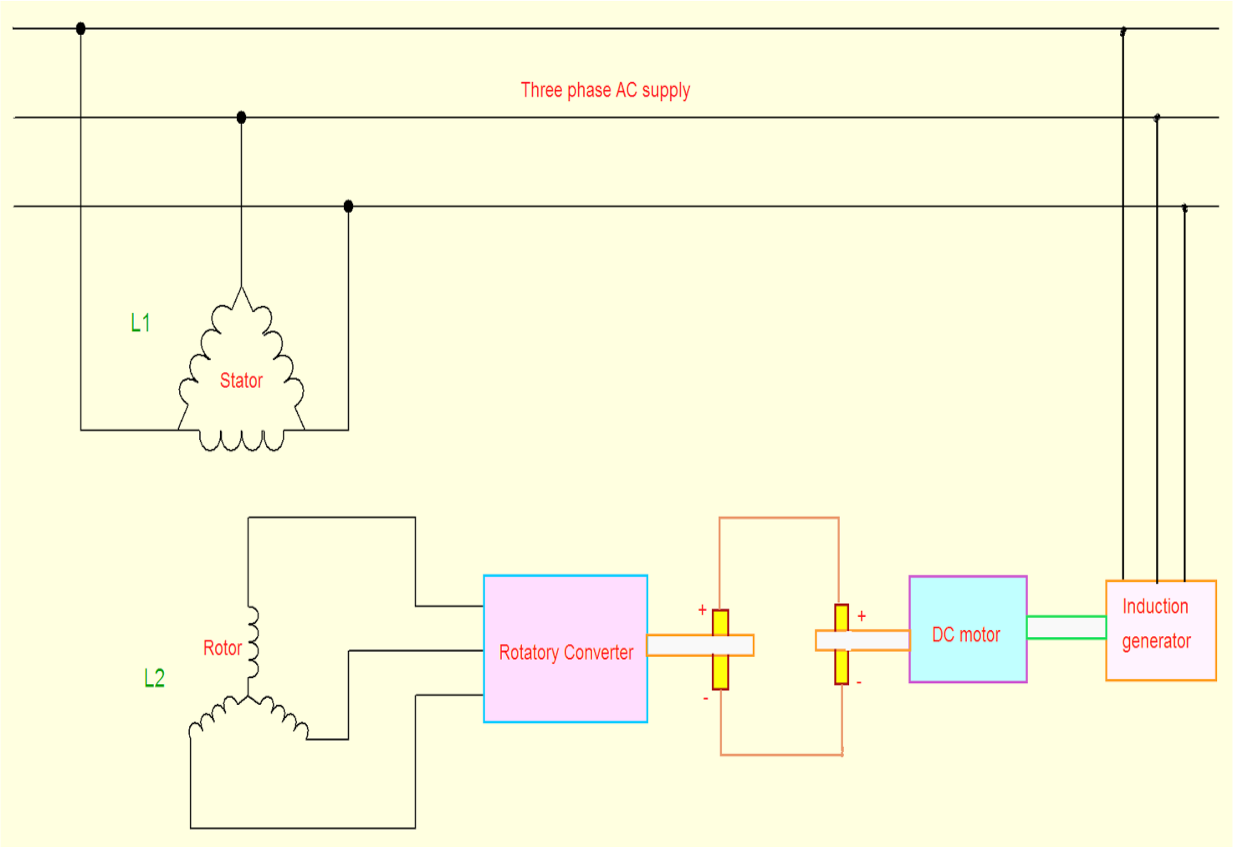
This system provides feedback path i.e. the wastage of slip power is again fed to AC mains supply. The static scherbius system is of two types

i) Conventional Scherbius system
ii) Static Scherbius system

i) Conventional scherbius system:

In this system the recovery scheme is done by feedback path. The output of three phase Induction motor is connected to the DC motor by coupling them the mechanical power input of DC motor is converted into electrical power and fed to Induction generator and again back to mains.

Contd..



Conventional scherbius system

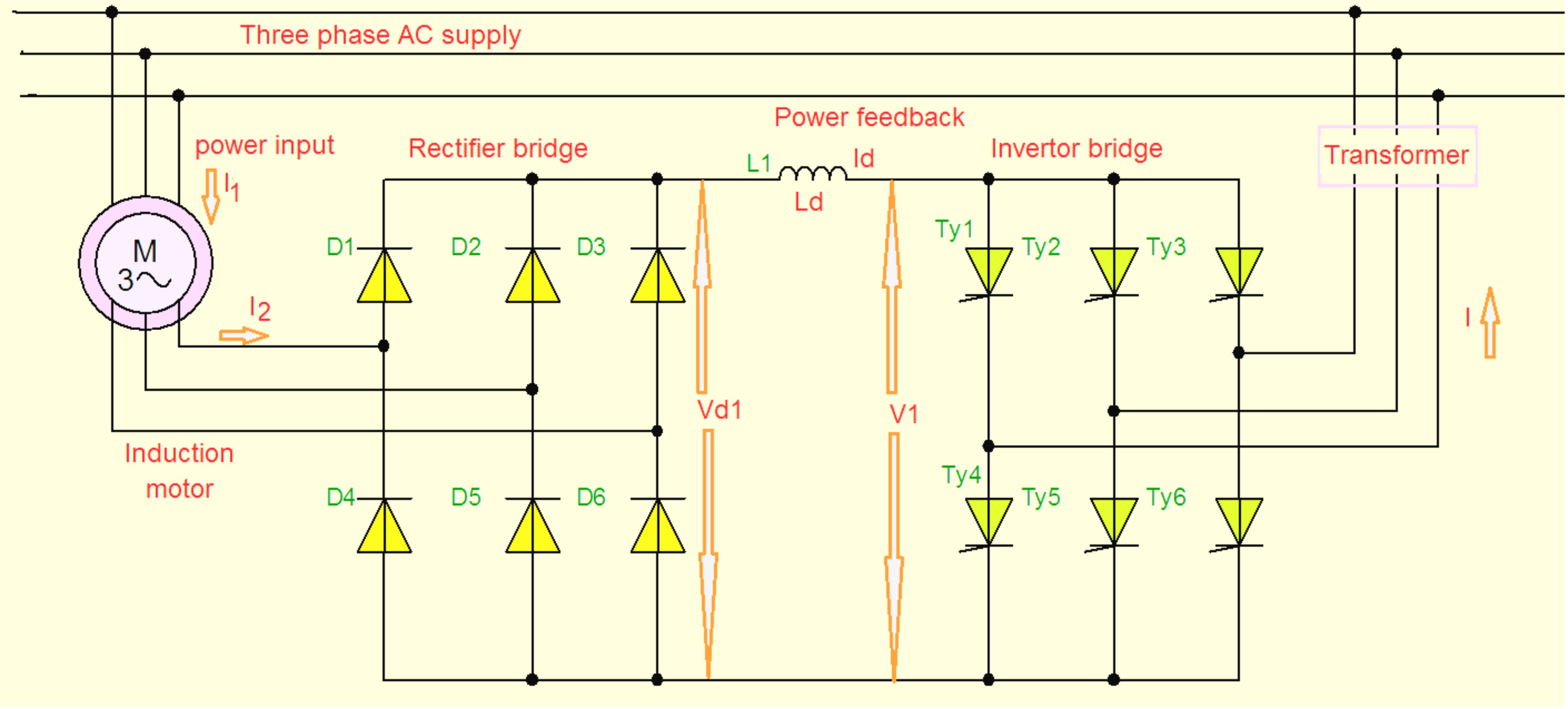
Contd..

ii) Static Scherbius drive system:

The phenomenon of this system is same as conventional type but the only difference is this system provides with diode bridge rectifier along with thyristor bridge inverter. This is also known as Sub-synchronous cascade drive.

When Induction motor is operating at slip frequency the rotor slip power is rectified by the diode rectifier. The output of rectifier is fed to inverter three phase bridge again the output is fed back to supply lines with the help of transformer.

Contd..



Static scherbius system

Static Kramer drive performance and speed torque characteristics

Static Kramer drive:

In this method the rotatory slip power is coverted into DC by a diode bridge. The DC power is fed to the DC motor which is mechanically coupled with the Induction motor. The speed control is done by varying the field current I_f.

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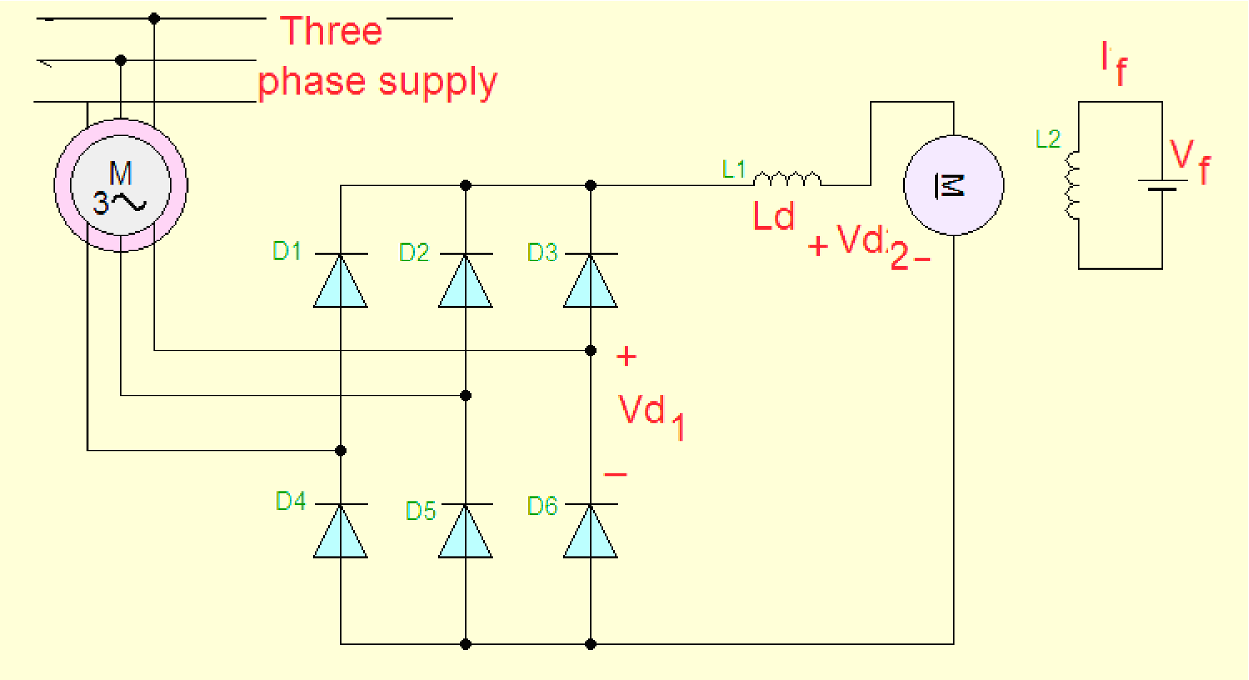


Static Kramer drive

Contd..

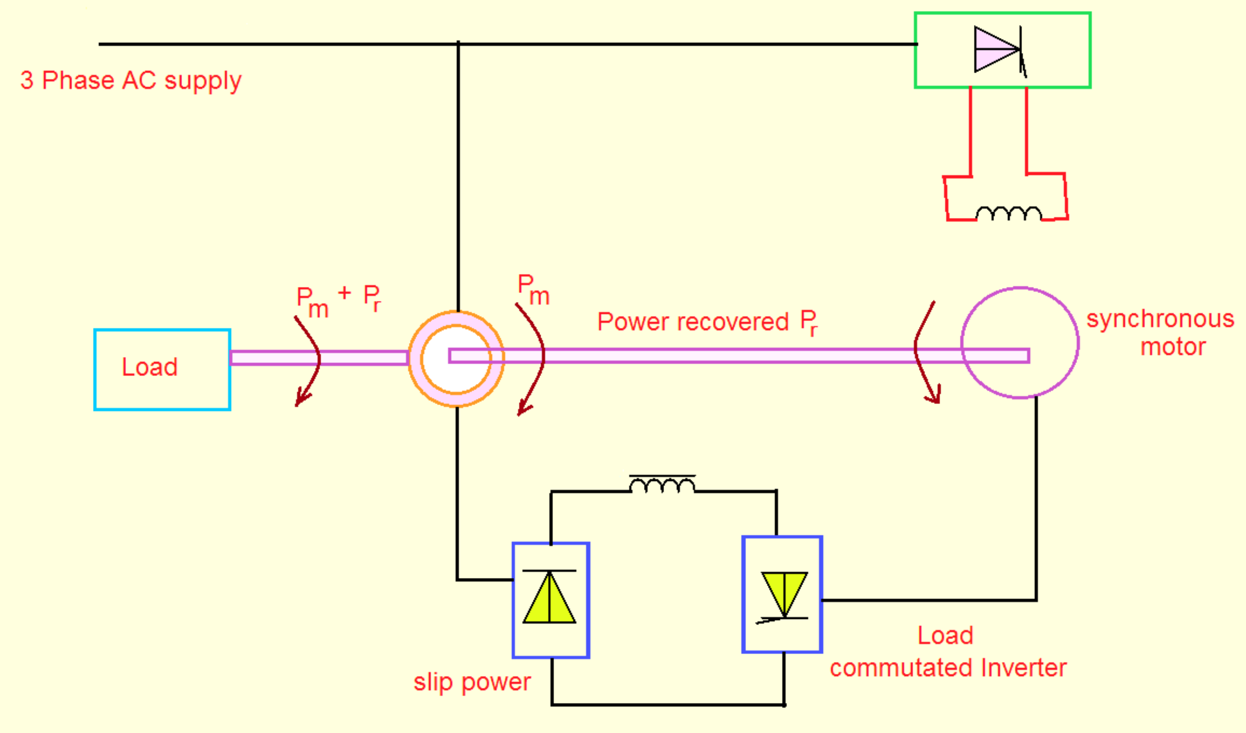
- From the characteristics you can easily observe the voltage and field current differences. The steady state operation is possible at $V_{d1} = V_{d2}$

  For large speed applications the diode bridge is replaced by using thyristor bridge, the speed can be controlled by varying the firing angle. Upto standstill condition the speed can be controlled.

- Modification:

- The static Kramer drive system is modified by placing commutator less DC motor instead of DC machine. The DC motor consists of synchronous motor fed by load commutated inverter, the speed is controlled by field current

Contd..



Modified Static Kramer drive

Static Kramer drive performance and speed torque characteristics

Static Kramer drive:

In this method the rotatory slip power is coverted into DC by a diode bridge. The DC power is fed to the DC motor which is mechanically coupled with the Induction motor. The speed control is done by varying the field current I_f.

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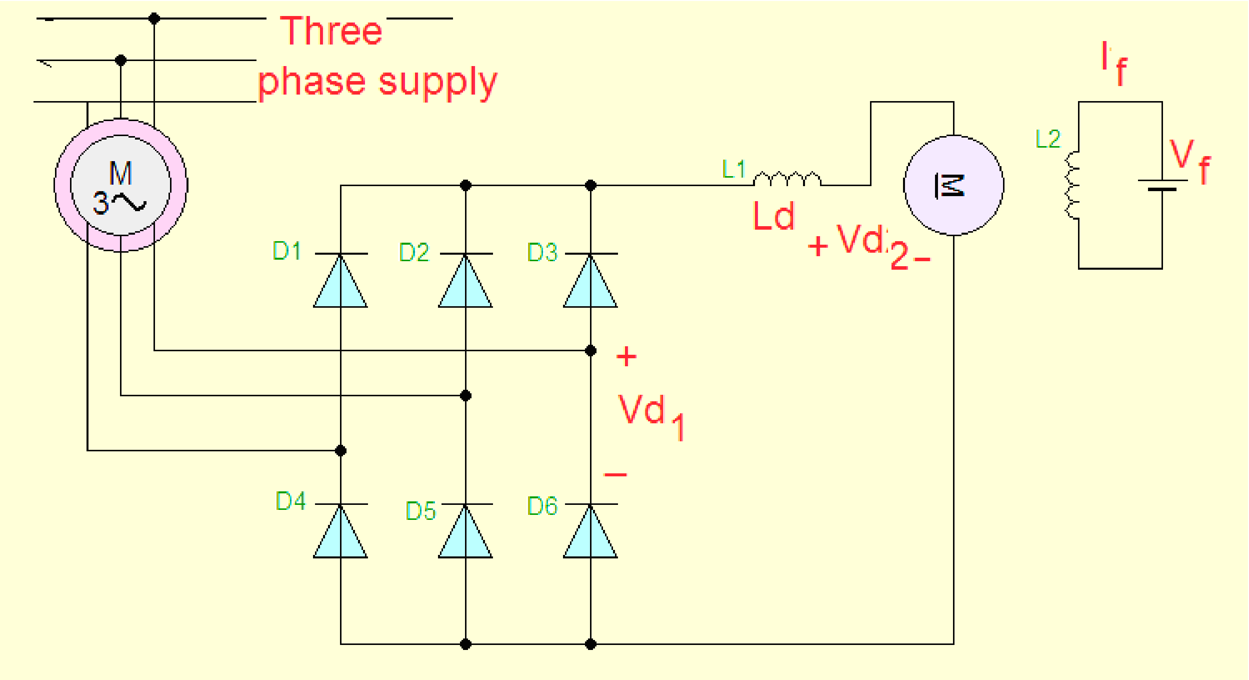

Static Kramer drive

Contd..

- From the characteristics you can easily observe the voltage and field current differences. The steady state operation is possible at $V_{d1} = V_{d2}$
- For large speed applications the diode bridge is replaced by using thyristor bridge, the speed can be controlled by varying the firing angle. Upto standstill condition the speed can be controlled.

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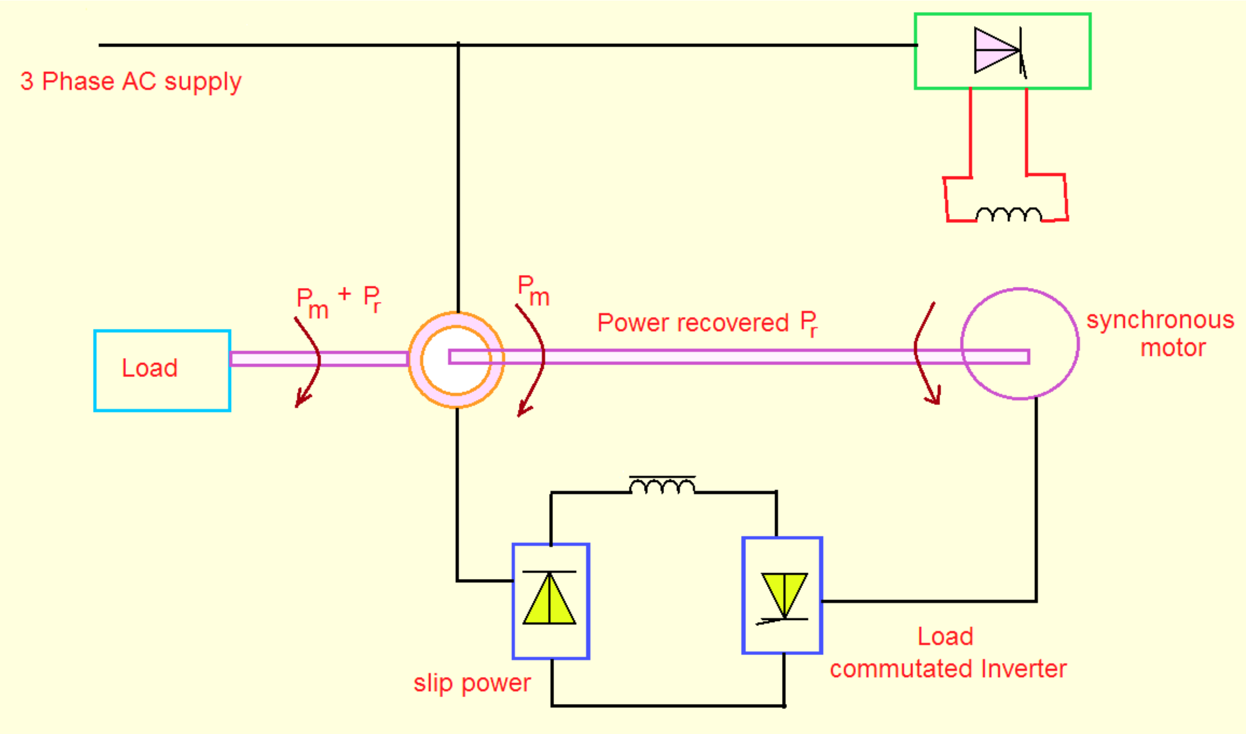


Modified Static Kramer drive

Numerical problems on rotor resistance control

1. The speed of a three phase slip ring induction motor is controlled by variation of rotor resistance. The full load torque of the motor is 50Nm at slip of 0.3. the motor drives load having a characteristics $T \alpha N^2$. The motor has 4 poles and operates on 50Hz, 400V supply. Determine the speed of the motor for 0.8 times the rated torque.

Solution:

Synchronous speed $N_s = 120f/p = 120*50/4 = 1500$rpm

Slip = 0.3

$N = N_s(1-s) = 1500(1-0.3) = 1050$rpm

$T_2 = T_1*0.8 = 50*0.8 = 40$Nm

$T \alpha N^2$

$T_1/T_2 = N_1^2/N_2^2$

$50/40 = 1050^2/ N_2^2$

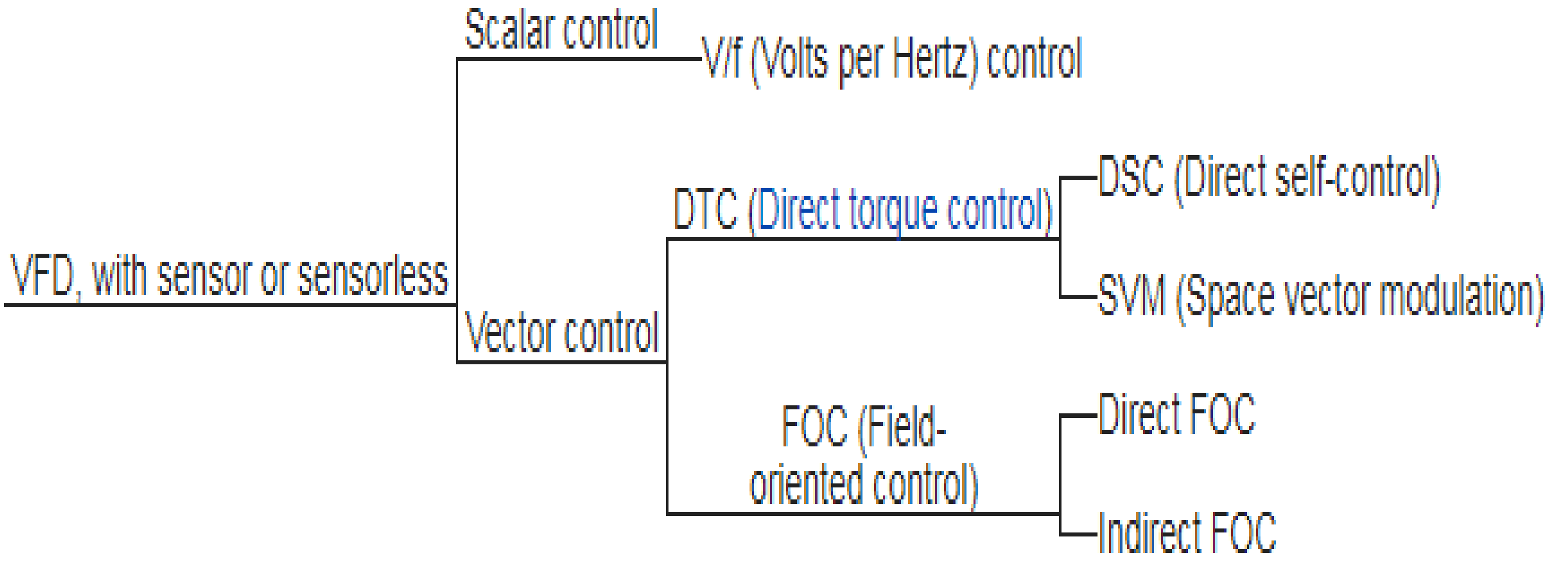
$N_2 = 939$ rpm

Contd..

2 A static krammer drive is used for the speed control of a 4 pole SRIM fed from415V, 50Hz supply. The inverter is directly connected to supply. If the motor is required to operate at 1200 rpm, find the firing advance angle of the inverter. Voltage across open circuited slip rings at standstill is 700V. Allow a voltage drop of 0.7V and 1.5V across each of the diodes and SCRs respectively.

Introduction to vector control of induction motor drives

Overview of key competing VFD control platforms:



VFD, with sensor or sensorless

- Scalar control
  - V/f (Volts per Hertz) control
- Vector control
  - DTC (Direct torque control)
    - DSC (Direct self-control)
    - SVM (Space vector modulation)
  - FOC (Field-oriented control)
    - Direct FOC
    - Indirect FOC

Contd..

Vector control, also called field-oriented control (FOC), is a variable-frequency drive (VFD) control method in which the stator currents of a three-phase AC electric motor are identified as two orthogonal components that can be visualized with a vector. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control.

Principles of vector control

- The control of AC machine is basically classified into scalar and vector control. The scalar controls are easy to implement though the dynamics are sluggish. The objective of FOC is to achieve a similar type of controller with an inner torque control loop which makes the motor respond very fast to the torque demands from the outer speed control loop. In FOC, the principle of decoupled torque and flux control are applied and it relies on the instantaneous control of stator current space vectors.

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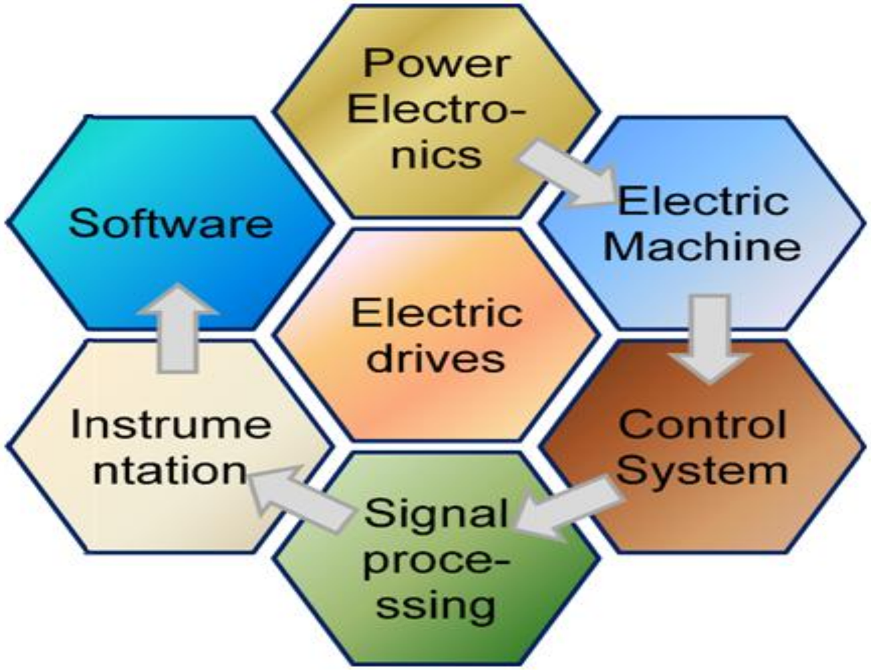

Electric drive system

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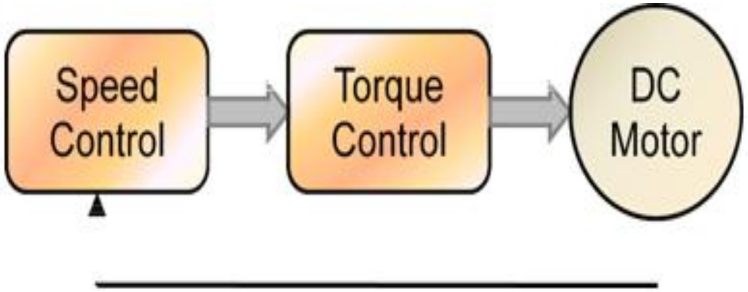
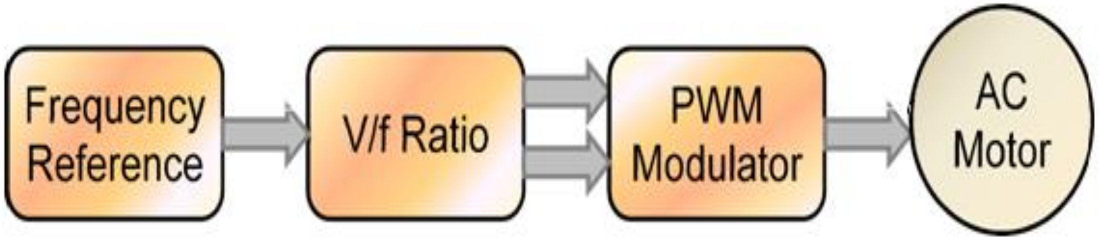


a) DC drive



b) AC drive – scalar control

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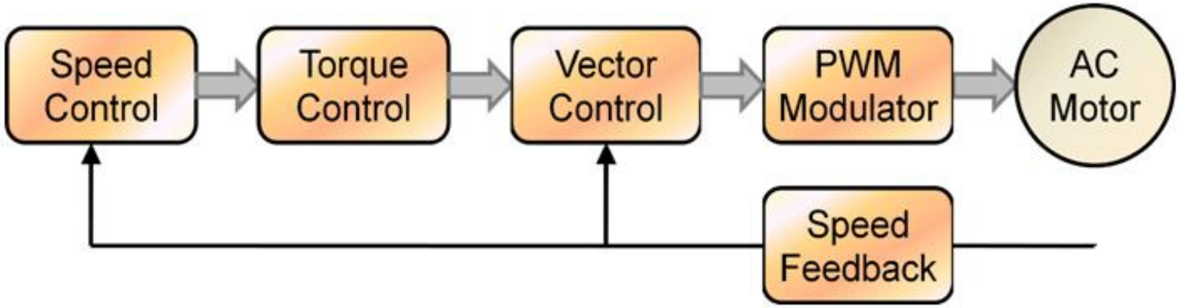
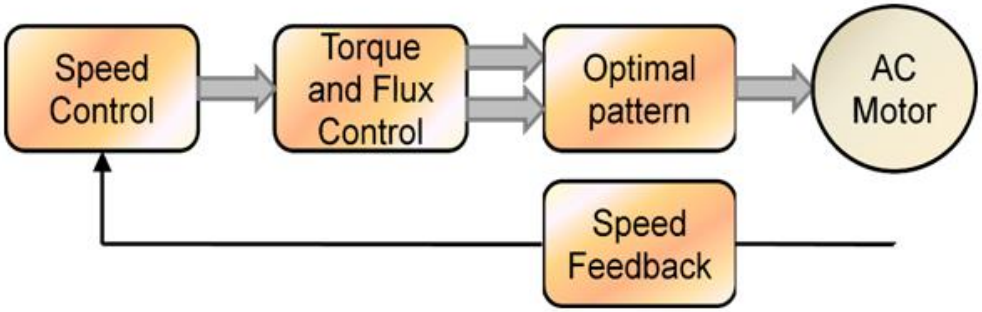


c) AC drive – Field Oriented Control



d) AC drive – Direct Torque Control

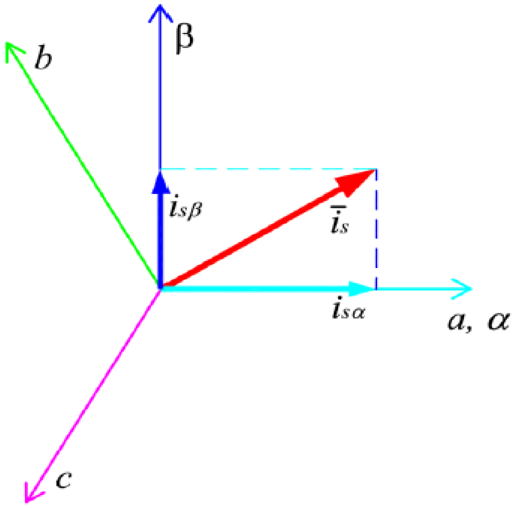
Vector control methods of induction motor

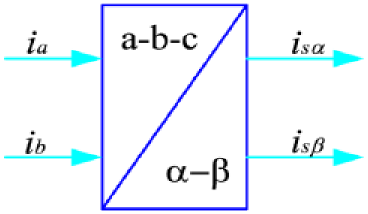
Clarke Transformation

- This transformation block is responsible for translating three axes to two axes system reference to the stator. Two of the three phase currents are measured because the sum of the three phase currents equal to zero. Basically the transformation shift from a three axis, two- dimensional coordinate system attached to the stator of the motor to a two axis system referred to the stator. The measured current represents the vector component of the current in a three axis coordinate system which are spatially separated by 120.

Contd..

$$i_{s\alpha} = \mathrm{Re}\left(\frac{2}{3}\left(i_a(t) + i_b(t)e^{j2\pi/3} + i_c(t)e^{-j2\pi/3}\right)\right)$$





Clarke transformation

Contd..

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$\vec{i}_s = i_{sd} + j i_{sq}$$

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}$$

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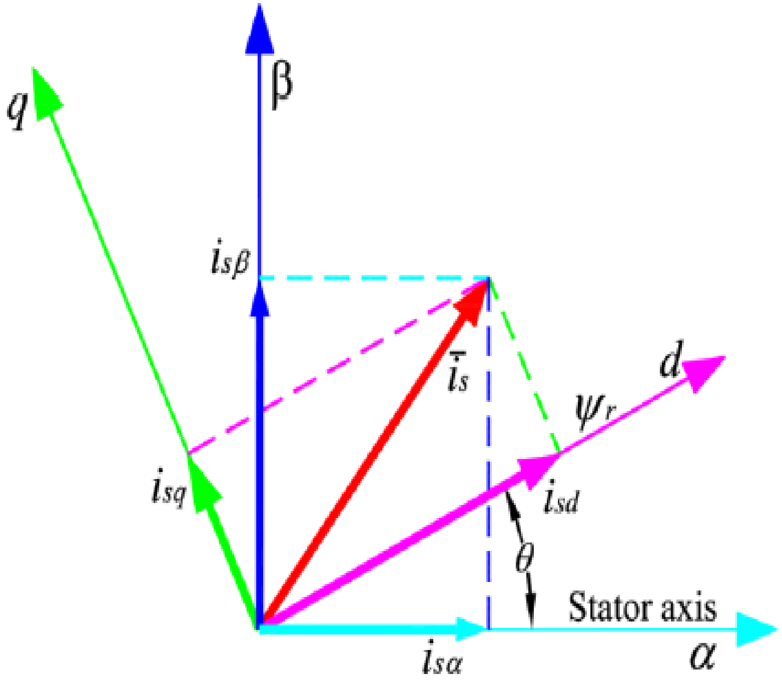

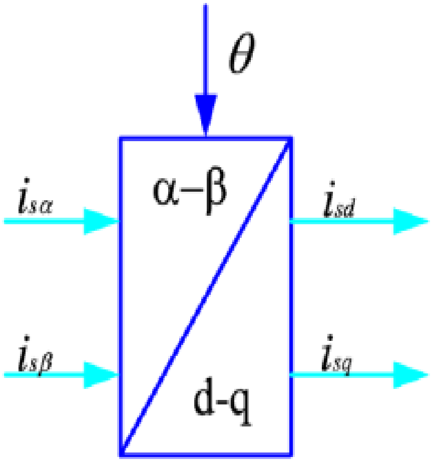

Park transformation

Direct methods of vector control

Direct Field Oriented Control

- In DFOC, an estimator or observer calculates the rotor flux angle. Inputs to the estimator or observer are stator voltages and currents. In DFOC, rotor flux vector orientation can be measured by the use of a flux sensor mounted in the air gap like Hall-effect sensor, search coil and other measurement techniques introduces limitations due to machine structural and thermal requirements or it can be measured using the voltage equations.

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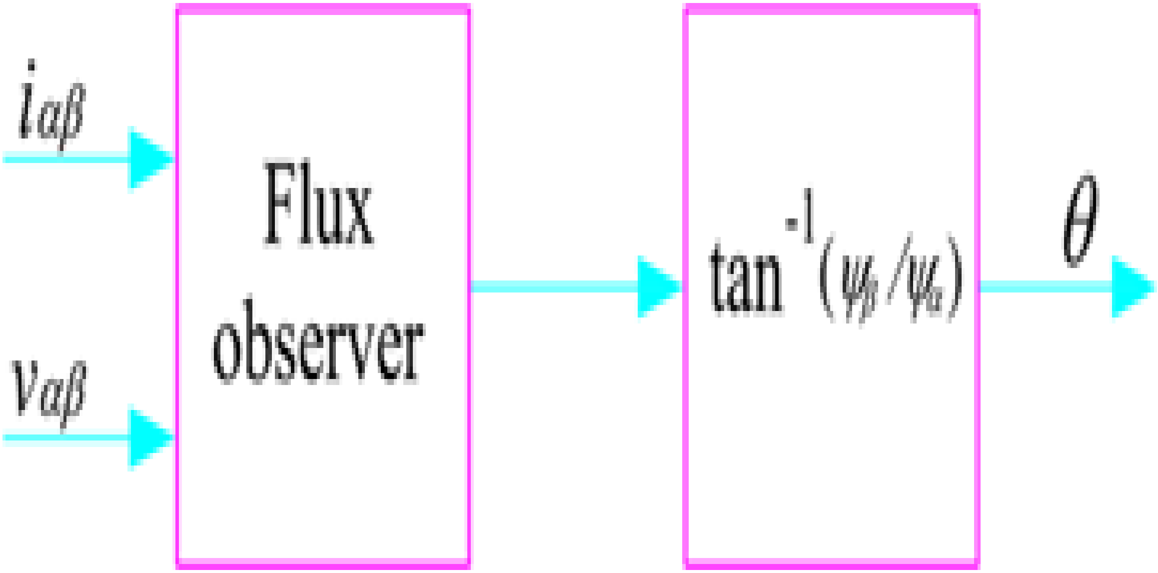

$i_{\alpha\beta}$
$v_{\alpha\beta}$
Flux observer
$\tan^{-1}(\psi_\beta/\psi_\alpha)$
θ

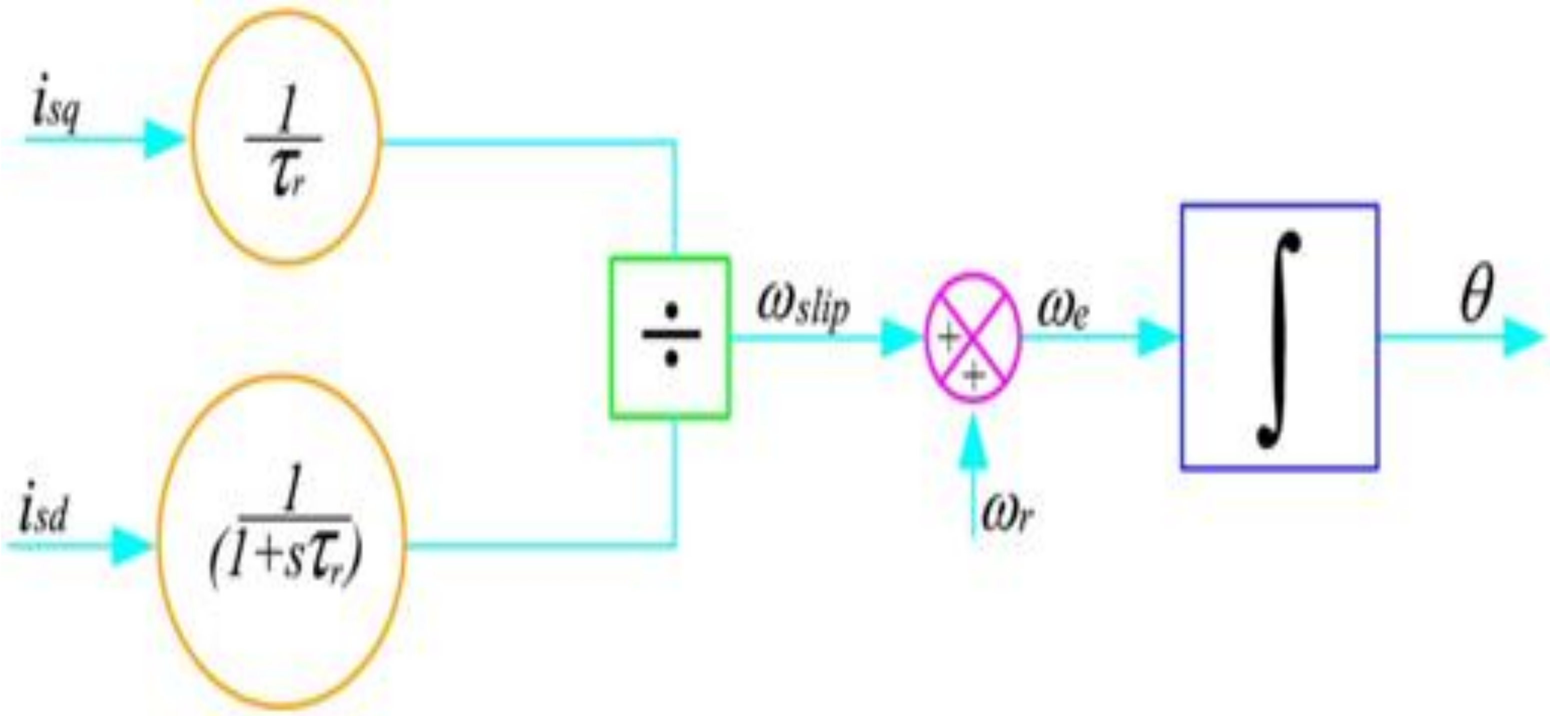
Contd..

- Field Oriented Control or Vector Control (VC) techniques are being used extensively for the control of induction motor. This technique allows a squirrel cage induction motor to be driven with high dynamic performance comparable to that of a DC motor. In FOC, the squirrel cage induction motor is the plant which is an element within a feedback loop and hence its transient behavior has to be taken into consideration. This cannot be analyzed from the per phase equivalent circuit of the machine, which is valid only in the steady state condition.

Indirect methods of vector control

The field orientation concept implies the current components supplied to the machine should be oriented in such a manner as to isolate the stator current magnetizing flux component of the machine from the torque producing component. This can be obtained by the instantaneous speed of the rotor flux linkage vector and the *d* axis of the *d*-*q* coordinates are exactly locked in rotor flux vector orientation. In IFOC, the rotor flux angle is obtained from the reference currents

Contd..


i_{sq}
$\frac{1}{\tau_r}$
i_{sd}
$\frac{1}{(1+s\tau_r)}$
÷
ω_{slip}
+
+
ω_r
ω_e
$\int$
θ

Contd..

Properties of the FOC methods are,

- It is based on the analogy to the control of separately excited DC motor,
- Coordinate transformations are required,
- PWM algorithm is needed,
- Current controllers are necessary,
- Sensitive to rotor time constant,
- Rotor flux estimator is essential in DFOC and
- Mechanical speed is required in IFOC.

Numerical problems on vector control of induction motor

1. A 440V, 50Hz, 6 pole star connected wound rotor motor has the following parameters. Rs=0.5 ohm, R’r=0.4 ohm, Xs=Xr’=1.2 ohm, Xm=50 ohm, stator to rotor turns ratio is 3.5. Motor is controlled by static rotor resistance control. External resistance is chosen such that the breakdown torque is produced at standstill for a duty ratio of zero. Calculate the value of external resistance. How duty ratio should be varied with speed so that the motor accelerates at maximum torque.

Contd..

Solution

$$S = (Re + Rr')/\sqrt{(Rs^2 + (Xs + Xr^{\wedge\prime})^2)}$$

$$= (Re + 0.4)/\sqrt{(0.5^2 + (2.4)^2)}$$

$R_e = 2.45\ S - 0.4$

$R_e = 0.5R(1-\alpha)1/a^2$

$R_e = 6.125(1-\alpha)R$

$6.125(1-\alpha)R = 2.45\ S - 0.4$

At standstill $s=1$

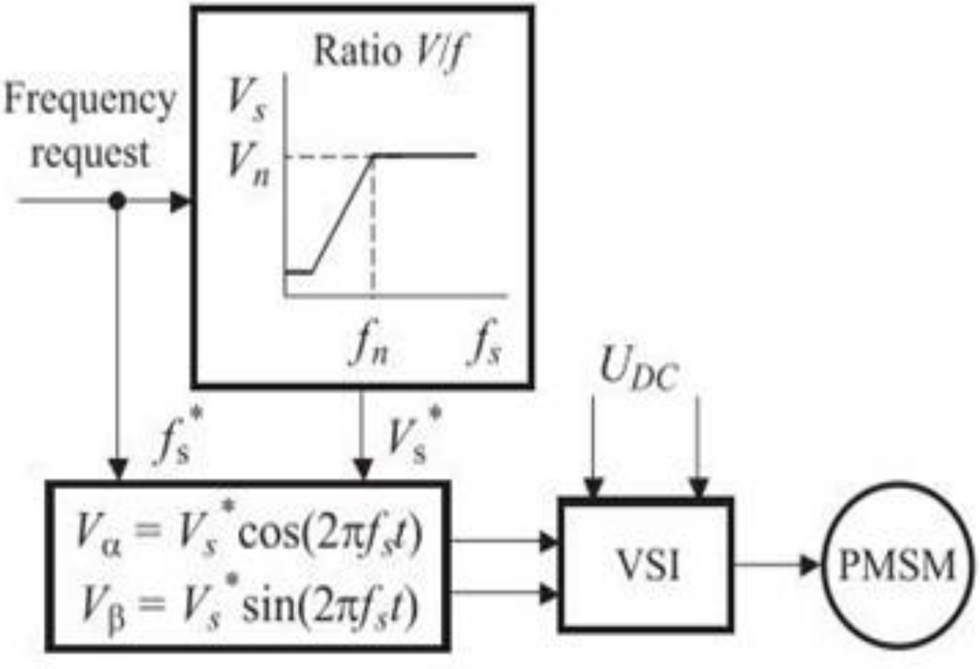
$R = 0.3347$

Contd..

2. A 440V, 50Hz, 6 pole, 970rpm star connected 3-ph wound rotor motor has the following parameters referred to stator. Rs=0.1 ohm, R’r=0.08 ohm, Xs=0.3 ohm, Xr’=0.4 ohm, stator to rotor turns ratio is 2. Motor speed is controlled by static scherbius drive. Drive is designed for a speed range of 25% below the synchronous speed. Max. value of firing angle 165 deg, calculate (i) transformer turns ratio, (ii) torque for a speed of 780rpm and α=140 deg.

UNIT V
SPEED CONTROL OF SYNCHRONOUS MOTORS

Separate control of synchronous motors



Separate control of synchronous motors

Contd..

- Constant volt per hertz control in an open loop is used more often in the squirrel cage IM applications. Using this technique for synchronous motors with permanent magnets offers a big advantage of sensor less control. Information about the angular speed can be estimated indirectly from the frequency of the supply voltage. The angular speed calculated from the supply voltage frequency according to can be considered as the value of the rotor angular speed if the external load torque is nothing her than the break down torque.

Contd..

The mechanical synchronous angular speed ω_s is proportional to the frequency f_s of the supply voltage

$$\omega_s = \frac{2\pi f_s}{p},$$

Where p is the number of pole pairs.

The RMS value of the induced voltage of AC motors is given as

$$E_f = \sqrt{2}\pi f_s N_s k_w \phi .$$

By neglecting the stator resistive voltage drop and as sum- in steady state conditions, the stator voltage is identical to the induced one and the expression of magnetic flux can be written as

$$\phi = \frac{V_{sph}}{\sqrt{2}\pi f_s N_s k_w} = c\frac{V_{sph}}{f_s} .$$

Contd..

$$T_e = -\frac{m}{\omega_s}\left[\frac{V_{sph}E_f}{Z_d}\sin(\vartheta_L - \alpha) - \frac{E_f^2 R_s}{Z_d}\right]$$

$$T_m = \frac{3p}{2\pi f_s}\frac{V_{sph}E_{PM}}{2\pi f_s L_d} = \frac{3p}{2\pi f_s}\frac{V_{sph}2\pi f_s \Psi_{PM}}{2\pi f_s L_d}.$$

Separate control of synchronous motors

- Control of SM motors is performed using field oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor

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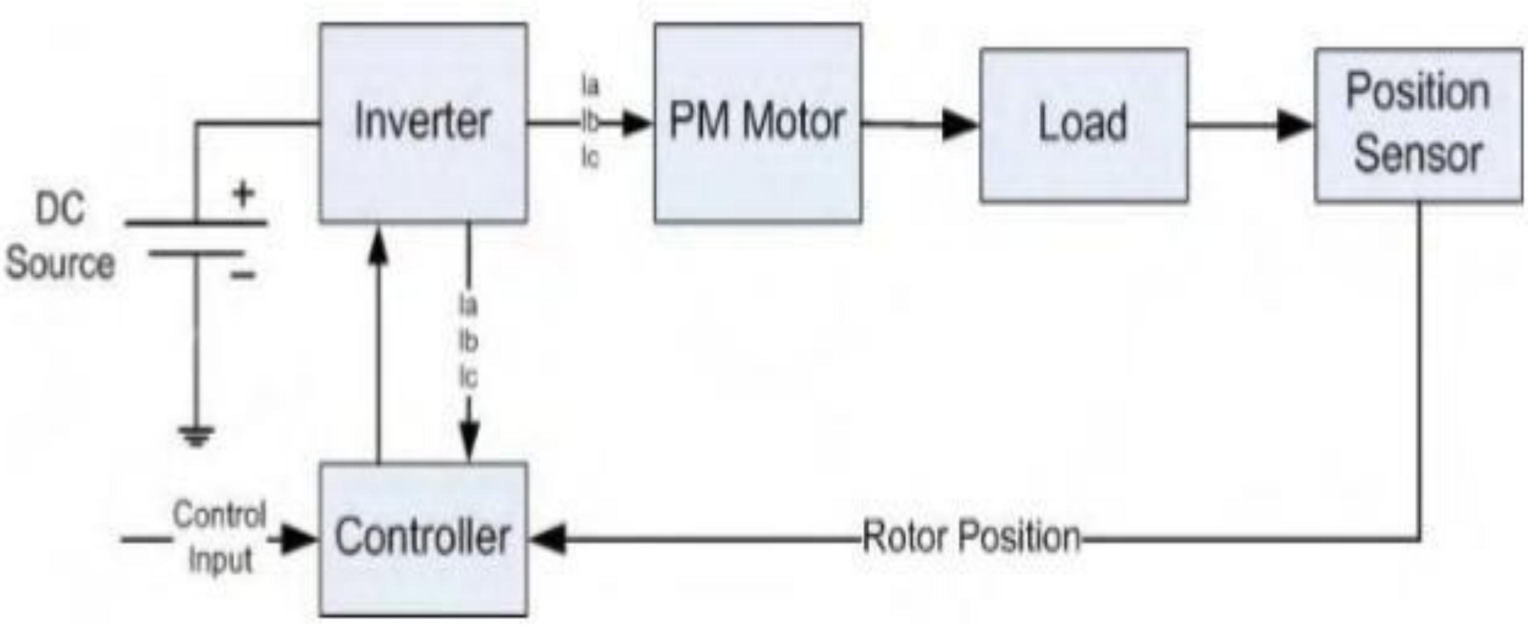

Self control of synchronous motors

Contd..

- Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective.
- In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder.
- Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor.

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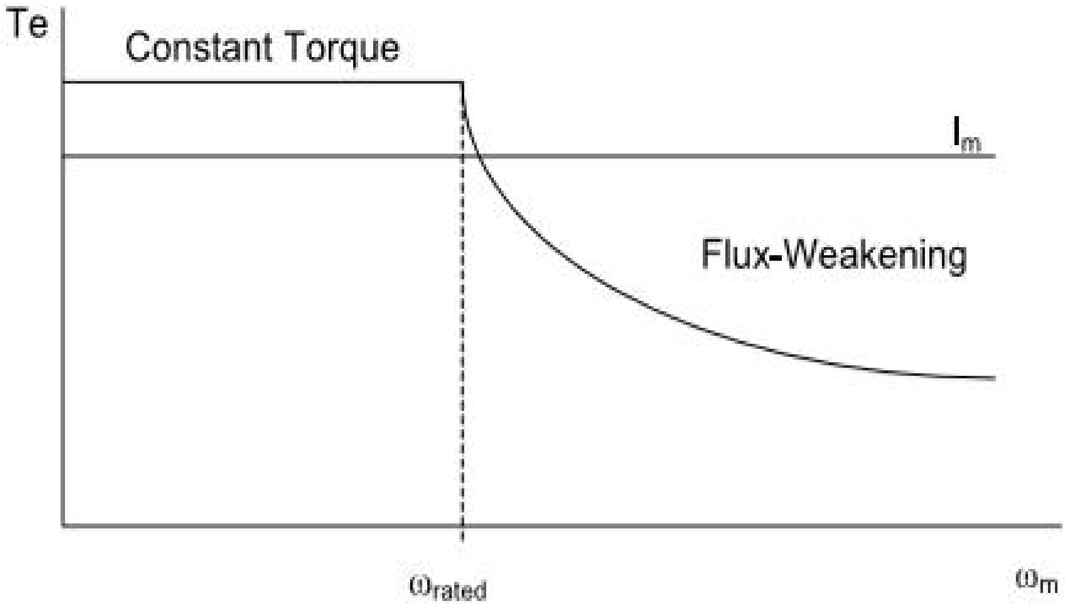
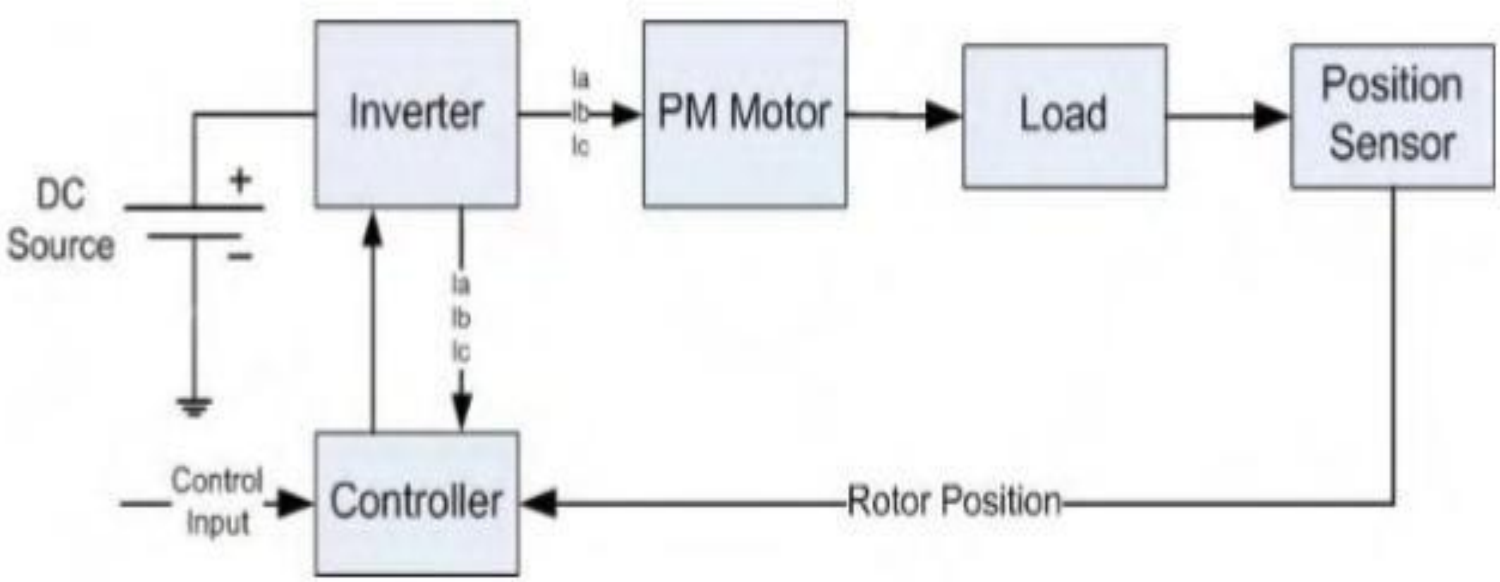


Speed torque characteristics of synchronous motors

Operation of self controlled synchronous motors by voltage source inverter

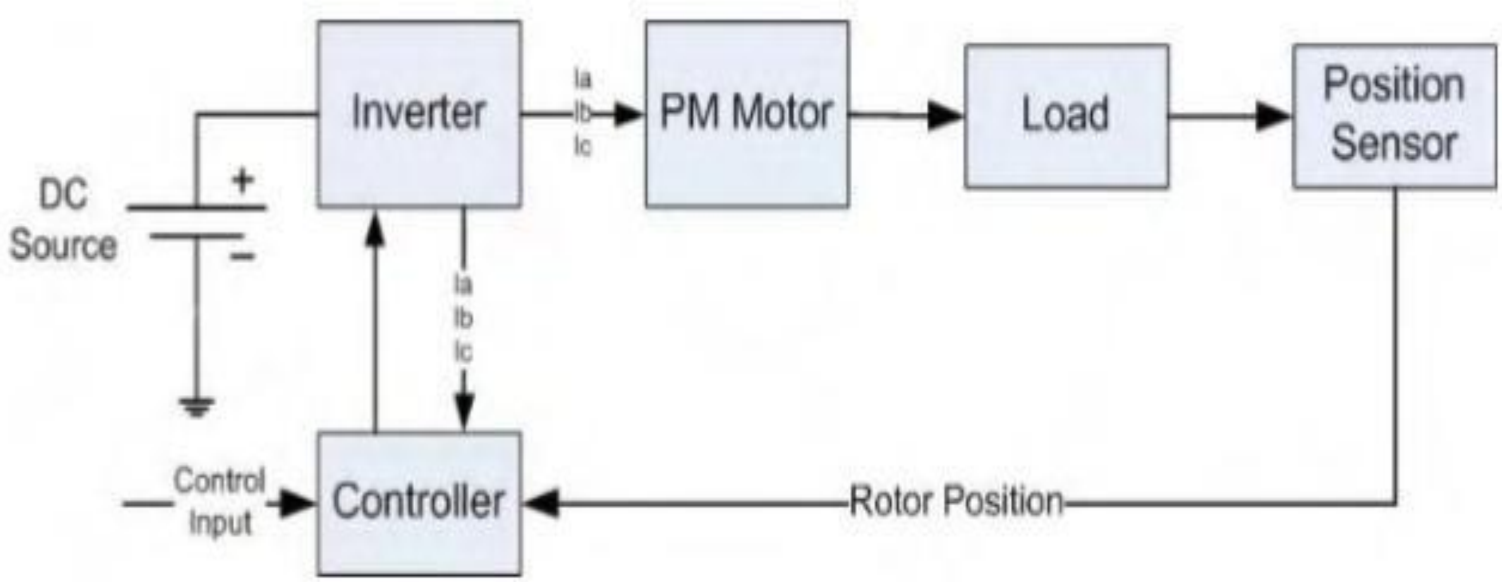


Self control of synchronous motors

Contd..

- Flux-weakening:
- Flux weakening is the process of reducing the flux in the d axis direction of the motor which results in an increased speed range.
- The motor drive is operated with rated flux linkages up to a speed where the ratio between the induced emf and stator frequency (V/f) is maintained constant. After the base frequency, the V/f ratio is reduced due to the limit of the inverter dc voltage source which is fixed. The weakening of the field flux is required for operation above the base frequency.
- This reduces the V/f ratio. This operation results in a reduction of the torque proportional to a change in the frequency and the motor operates in the constant power region.

Operation of self controlled synchronous motors by voltage source inverter



Self control of synchronous motors

Contd..

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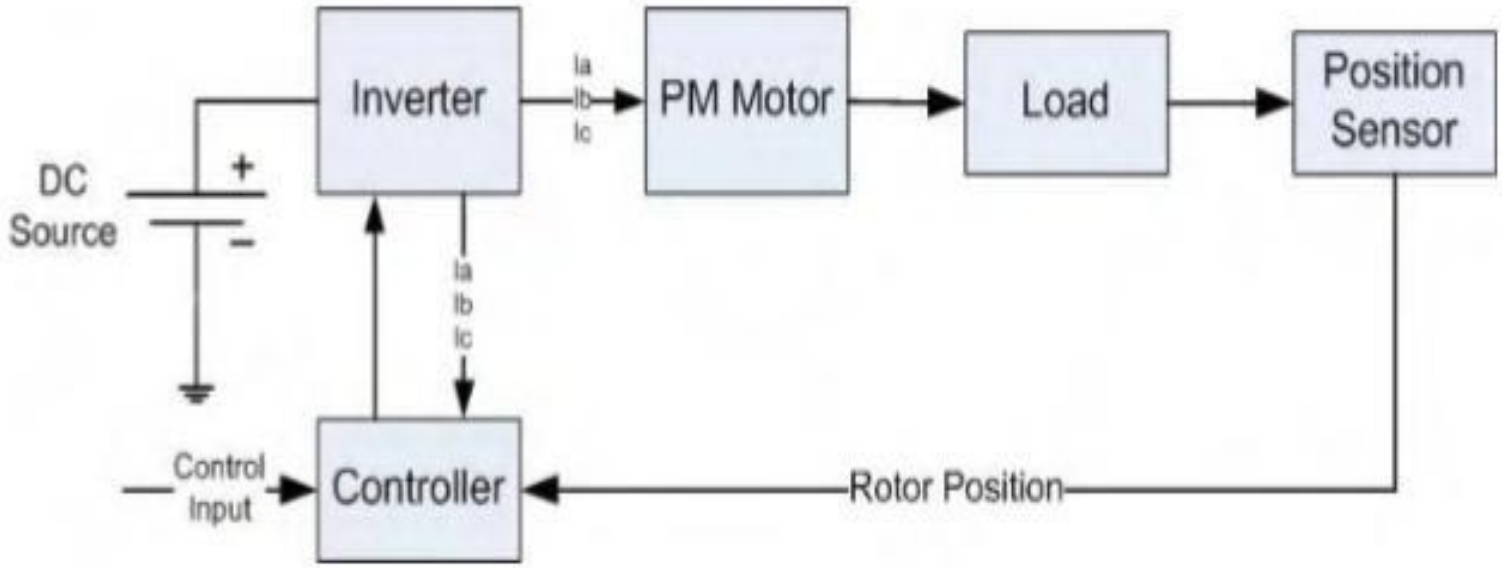
Contd..

$$\alpha = Tan^{-1}\left(\frac{i_q}{i_d}\right)$$

The current I_m is related to i_d and i_q by:

$$I_m = \sqrt{i_d^2 + i_q^2}$$

Operation of self controlled synchronous motors by voltage source inverter



Self control of synchronous motors

Contd..

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Load commutated CSI fed synchronous motor, operation and waveforms

ASCI mode of operation for a single-phase Current Source Inverter (CSI) was presented. Two commutating capacitors, along with four diodes, are used in the above circuit for commutation from one pair of thyristors to the second pair. Earlier, also in VSI, if the load is capacitive, it was shown that forced commutation may not be needed. The operation of a single-phase CSI with capacitive load (Fig. 5.10) is discussed here. It may be noted that the capacitor, C is assumed to be in parallel with resistive load (R). The capacitor, C is used for storing the charge, or voltage, to be used to force-commutate the conducting thyristor pair as will be shown.

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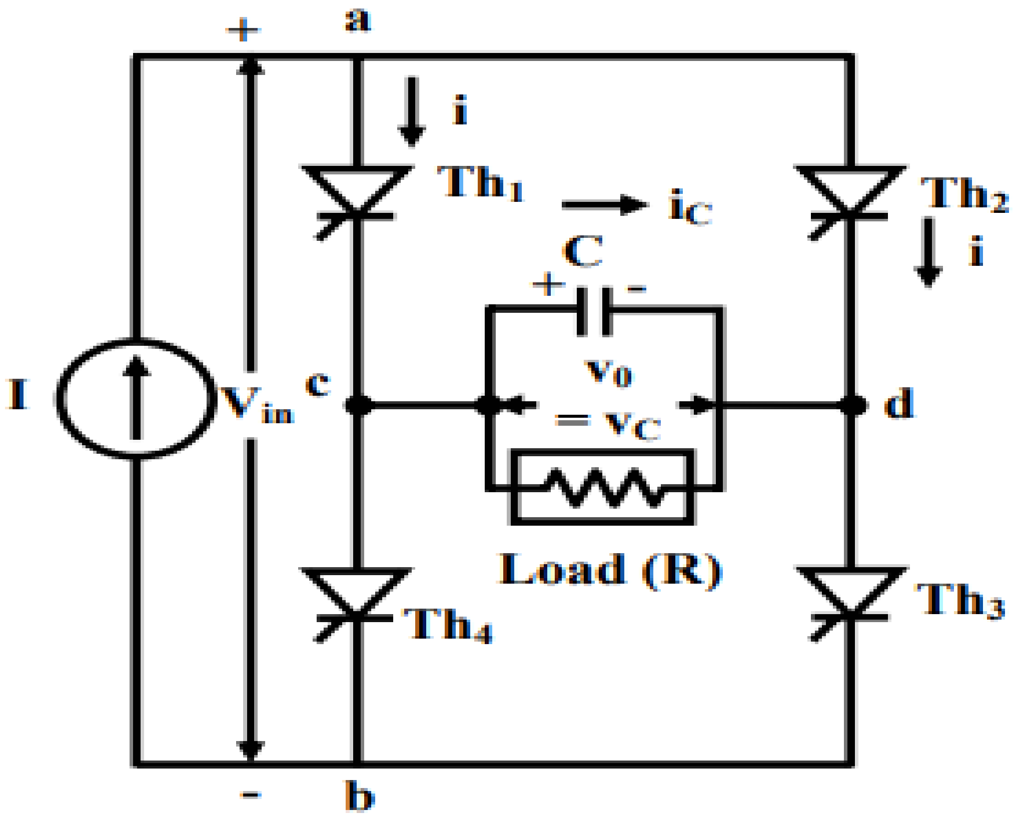

Load commutated Current source inverter fed synchronous motor

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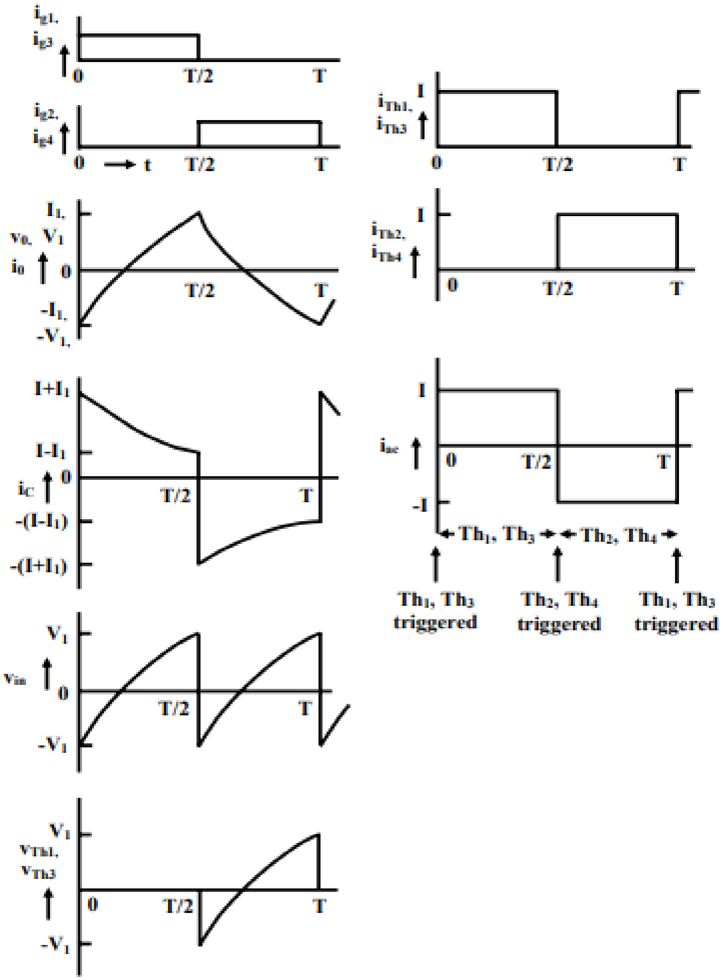

voltage and current waveforms

Applications and advantages of synchronous motor drives

- Synchronous motors find applications in all industrial applications where constant speed is necessary.
- Improving the power factor as Synchronous condensers
- Electrical power plants almost always use synchronous generators because it is important to keep the frequency constant at which the generator is connected.
- Low power applications include positioning machines, where high precision is required, and robot actuators.
- Mains synchronous motors are used for electric clocks.

Contd..

- A Synchronous motor could also improve the power factor of the plant while operated at rated load.
- Synchronous motors operate at constant speeds regardless of voltage and dependent only on the frequency of the power supply.
- That means that they are quite useful for driving machinery that operates at a steady speed for long periods of time (conveyor belts, paper-making machines, ball mills, and the like).
- One use that you may not think of for synchronous motors is in the turntables of record players. (Which you may not have seen outside of displays of “historical artifacts”.)

Numerical problems on synchronous motor drives

1. A three phase 400V, 50Hz, 6 pole, star connected wound rotor synchronous motor has Zs = 0+j2Ω. Load torque is proportional to speed squared, is 340Nm at rated synchronous speed. The speed of the motor is lowered by keeping V/f constant and maintaining unity power factor by field control of the motor. For the motor operation at 600 rpm calculate Supply voltage and Armature current

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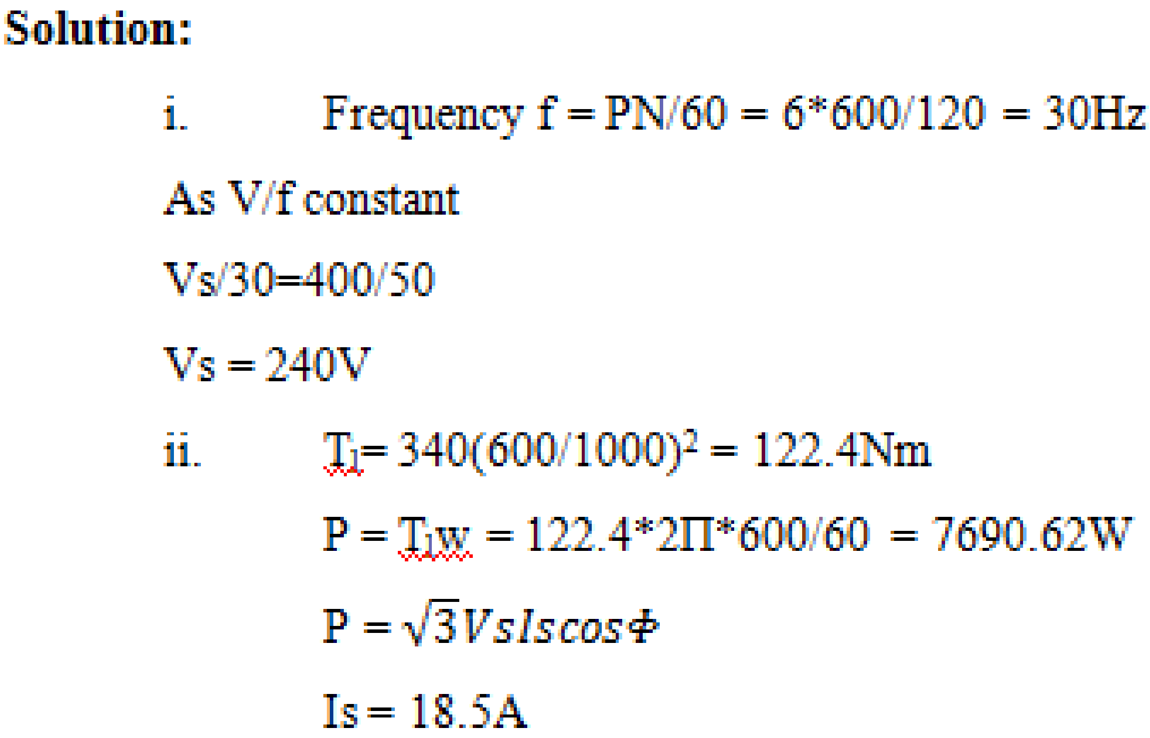

Solution:

i. Frequency $f = PN/60 = 6*600/120 = 30Hz$

As V/f constant

$Vs/30=400/50$

$Vs = 240V$

ii. $T_1 = 340(600/1000)^2 = 122.4Nm$

$P = T_1w = 122.4*2\Pi*600/60 = 7690.62W$

$P = \sqrt{3}VsIscos\Phi$

$Is = 18.5A$

Contd..

2. A synchronous motor is controlled by a load commutated inverter, which in turn is fed from a line commutated converter. Source voltage is 6.6kV, 50Hz. Load commutated inverter operates at a constant firing angle α1 of 130°. and when rectifying αγ = 0° dc link inductor resistance Rd = 0.2 Ω. Drive operates in self control mode with a constant (V/f) ratio. Motor has the details; 8MV, 3 phase 6600V, 6pole, 50Hz unity power factor, star connected, Xs = 2.6 Ω, Rs = o. Determine source side converter firing angles for the Motor operation at the rated and 500rpm. What will be the power developed by motor

Closed loop control operation of synchronous motor drives with block diagram

Close loop control employs outer speed control loop and inner current control loop with a limiter the terminal voltage sensor generates reference pulses whose frequency is same as thatϖ of the induced voltages in the rotor. These reference signals are shifted suitably by phase delay circuit to produce a constantϖ commutation lead angle. Based on the speed error, the value of βlc is set to provide either motoring or braking operation. Motoring operation is required to increase the speed and braking is required to reduce the speed. Actual speed of the rotor is sensed either from terminal voltage sensor or by using a separate tachometer.

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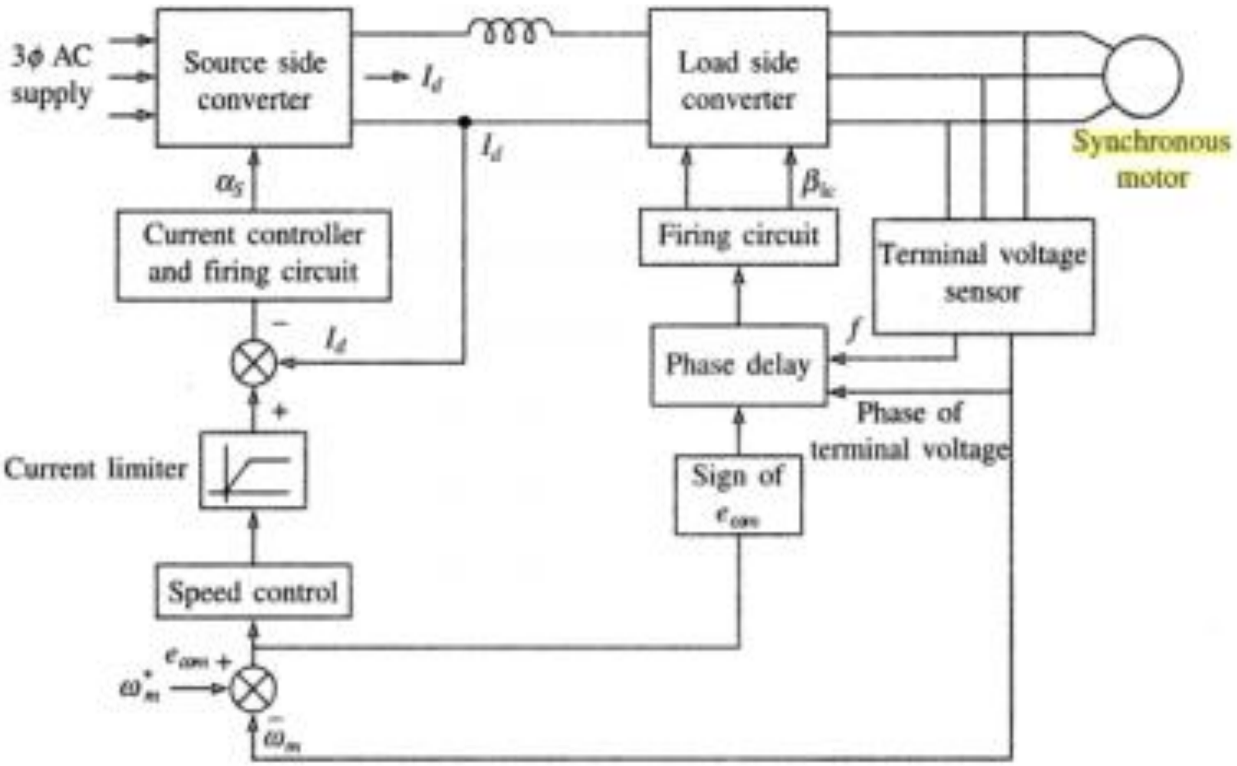

Closed loop control operation of synchronous motor drives

Contd..

Increasing the speed

- If the speed is to be increased, then it is given as reference speed ωm*. Actual speed and reference speed are compared at the comparator and it produces a positive speed error.
- Now the firing circuit produces βlc corresponding to motoring operation. The speed controller and current controller set the dc link current reference at the maximum allowable value. Now the machines starts accelerating and when rotor speed reaches the reference speed, the current limiter de-saturates and the acceleration stops. Hence the drive runs at constant speed at which motor torque is equal to load torque

Contd..

Decreasing the speed

- If the speed is to be decreased, then it is set as reference speed ωm*.
- Actual speed and reference speed are compared at the comparator and it produces a negative speed error. Now the firing circuit produces βlc corresponding to braking operation. The speed controller and current controller get saturated and set the dc link reference current at the maximum allowable value.
- Now the machines starts decelerating (braking operation) and when rotor speed reaches the reference speed, the current limiter de-saturates and the deceleration stops. Hence the drive runs at constant speed at which motor torque is equal to load torque.

Variable frequency control of synchronous motor with cycloconverter

DC link converter is a two stage conversion device which provides a variable voltage, variable frequency supply. Variable voltage, variable frequency sup-ply can be obtained from a cycloconverter which is single stage conversion equipment. The power circuit of a Three Phase Synchronous Motor Fed From Cycloconverter is shown in Fig. 5.13. This has several differences compared to a dc link converter

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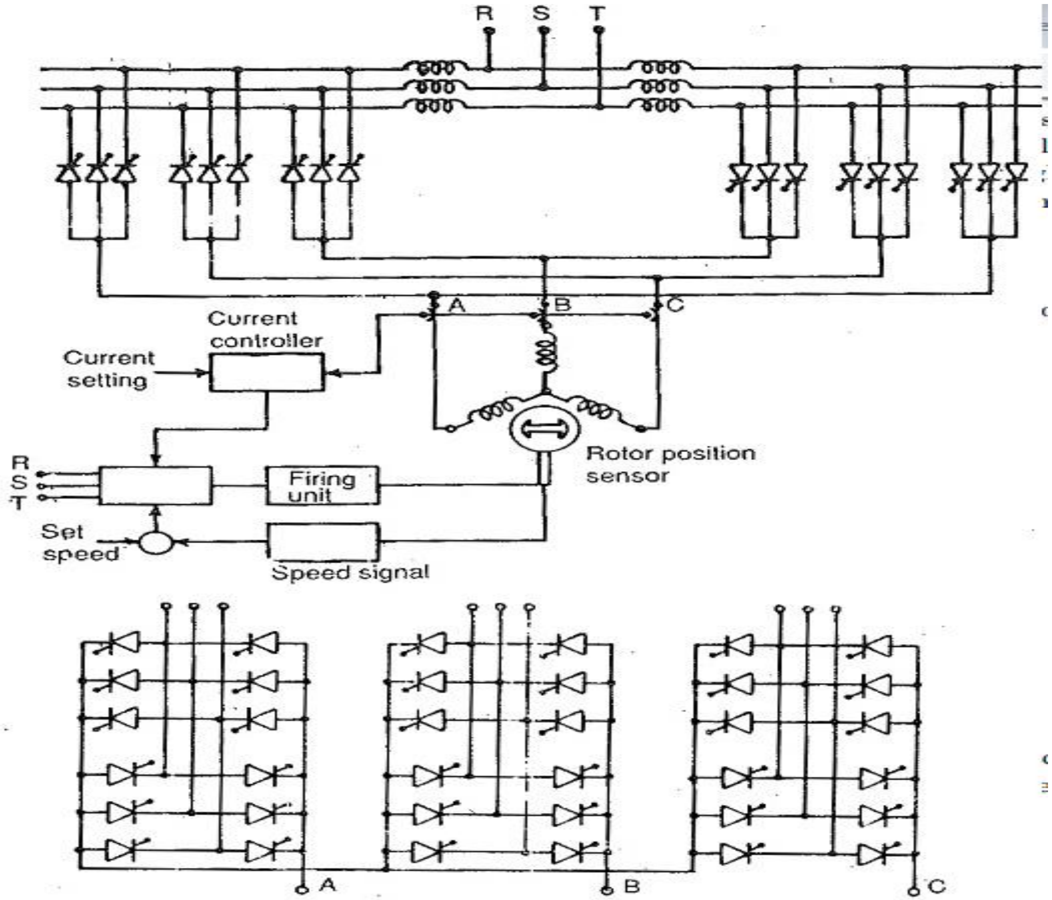

Variable frequency control of synchronous motor with cycloconverter

Contd..

- A cycloconverter can also be commutated using the load voltages if the load is capable of providing the necessary reactive power for the inverter. An overexcited synchronous motor can provide the necessary reactive power.
- Hence a cycloconverter feeding such a motor can be load commutated. The range of speed control is from medium to base speed. At very low speeds load commutation is not possible.
- The speed range can be extended to zero if line commutation is used at low speeds. Four quadrant operations are simple.