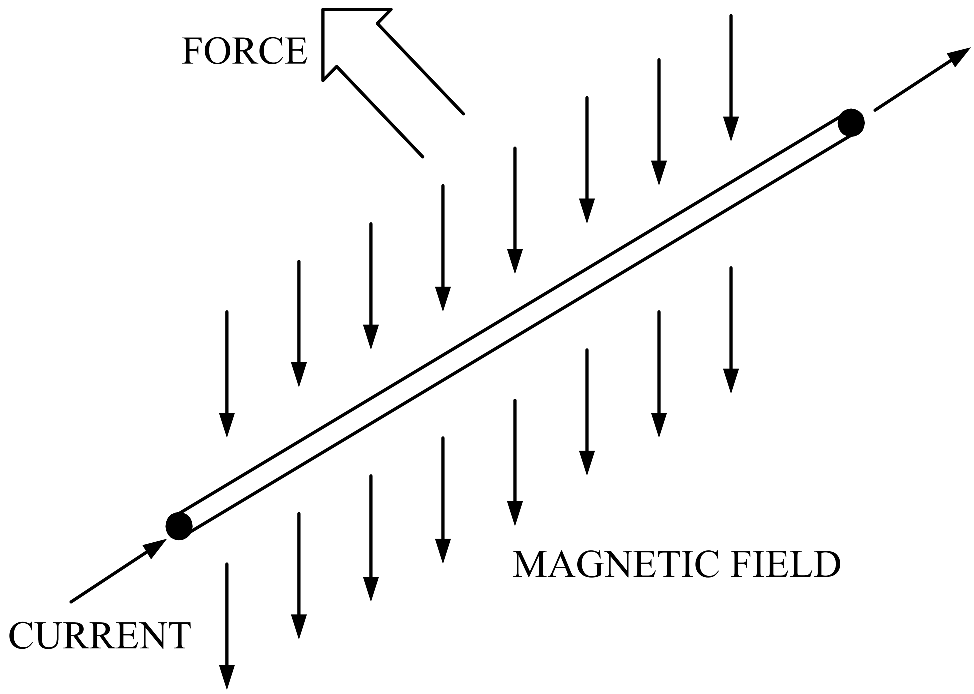
CHAPTER V
Motor Drives

- General principles motors
- Motor drive systems
- DC motor drives
- AC motor drives

Motor: Review of general principles



"Left Hand" Rule

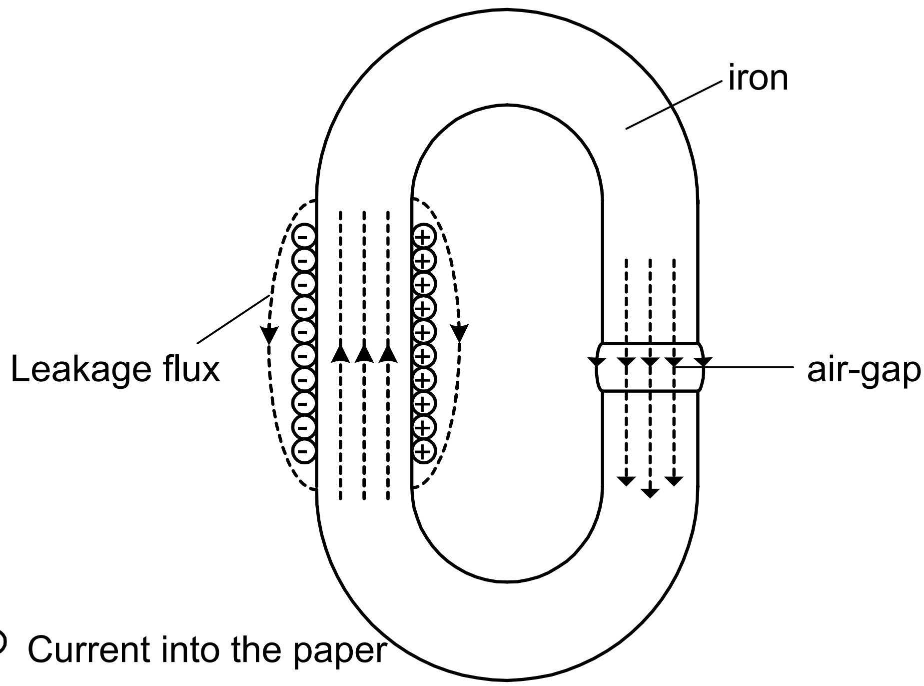
- Thumb $\Rightarrow$ Force (F)
- Pointing Finger $\Rightarrow$ Magnetic Field (Flux) (Φ)
- Middle Finger $\Rightarrow$ Current (I)

$$\text{Flux Density}: B = \frac{\phi}{A}$$

$$\text{Force}: F = B \cdot Il$$

A : Area; l : length of current carrying wire

Flux in C-core



⊕ Current into the paper

⊖ Current out of the the paper

NOTE: Use right hand "Screw Rule" to determine the direction of flux

Electric - magnetic analogy

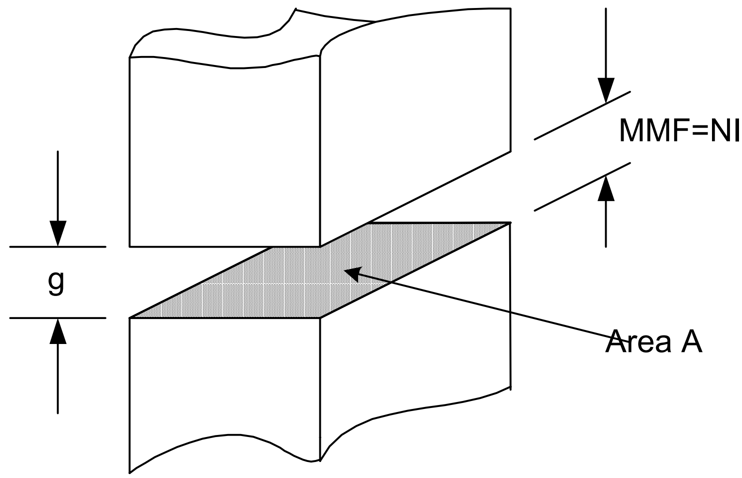
$$Current = \frac{EMF}{\text{Resistance}}$$

$$I = \frac{V}{R}$$

$$Flux = \frac{MMF}{\text{Reluctance}}$$

$$\phi = \frac{NI}{\Lambda}$$

Air-gap flux densities



Reluctance of air (in the air - gap),

$$\Lambda == \frac{g}{\mu_o A}$$

Then,

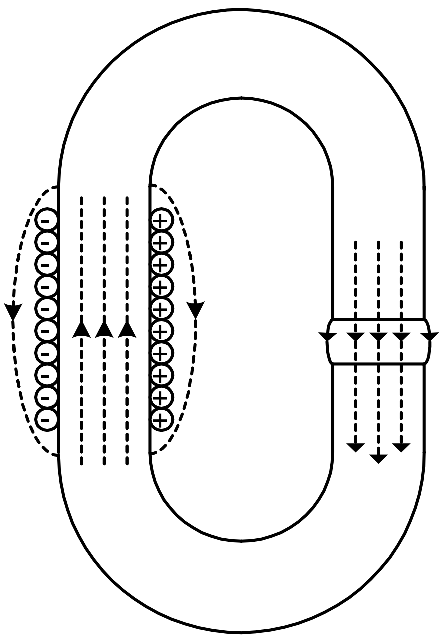
$$\phi = \frac{MMF}{\Lambda} = \frac{NIA\mu_o}{g}$$

$$B = \frac{\phi}{A} = \frac{NI\mu_o}{g}$$

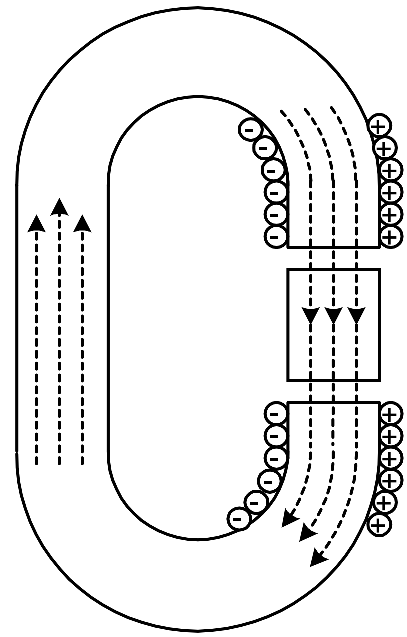
Note that air - gap flux density can be calculated by only knowing the MMF of the coil (NI) and the length of the gap.

The flux density is limited by the saturation of the iron (1.6 - 1.8T)

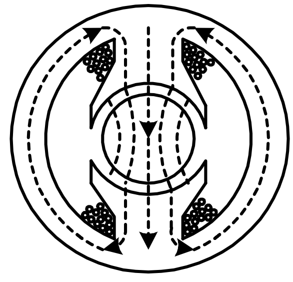
Evolution of motor geometry



C--Core

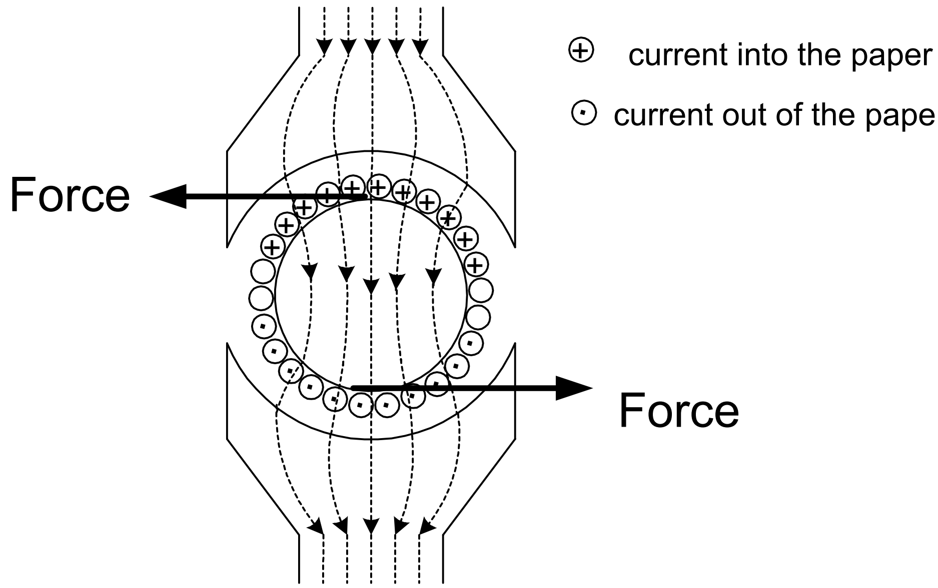


Split air-gap

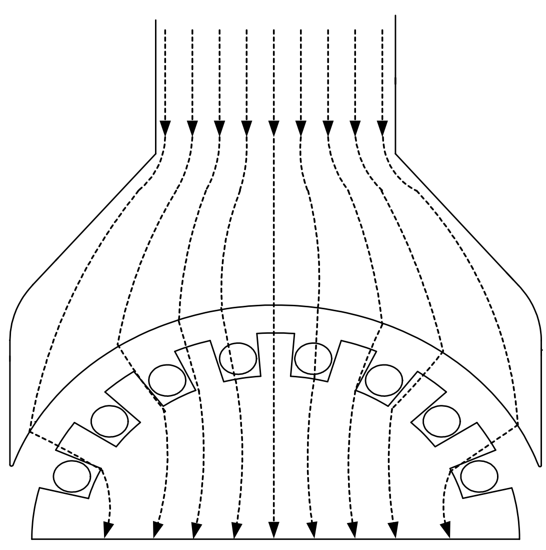


Simple motor
geometry

Torque Production



TORQUE PRODUCTION

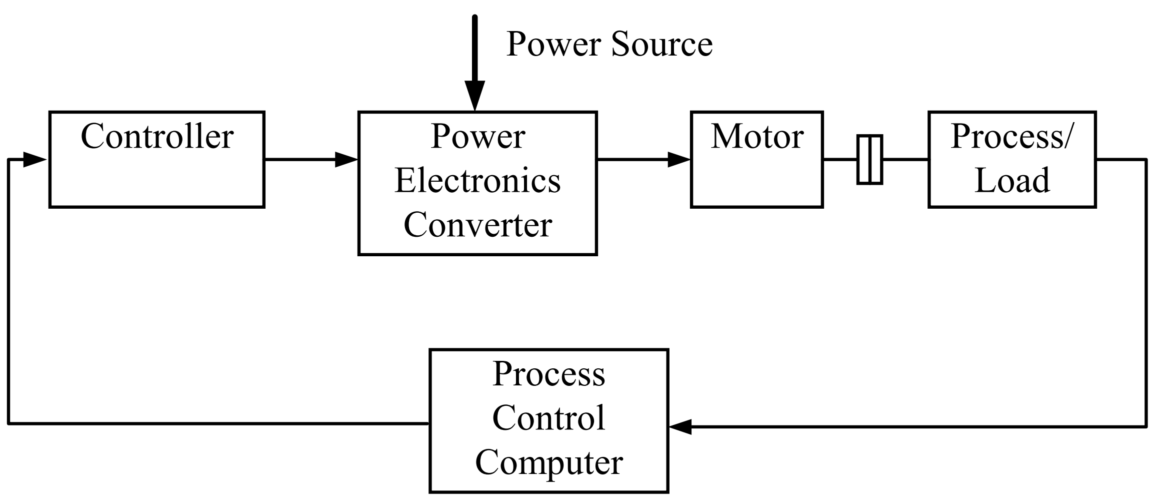


"SLOTTING"

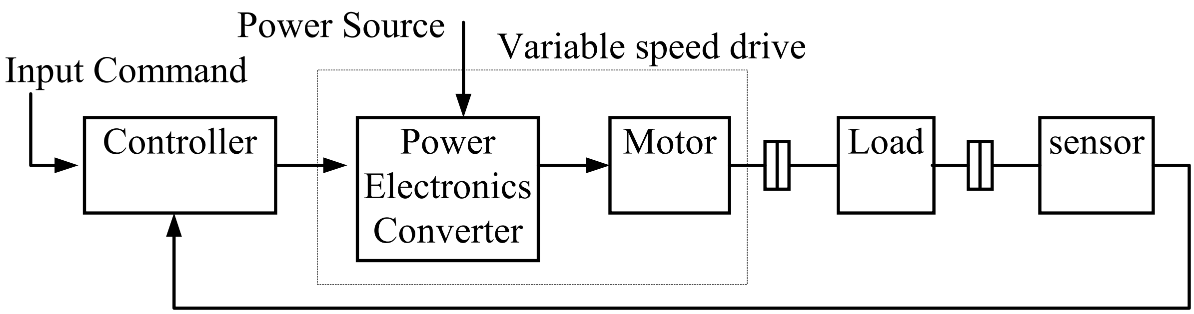
Electric Motor Drives

- DEFINITION: Electric drives for motor is used to draw electrical energy from the mains and supply the electrical energy to the motor at whatever voltage, current and frequency necessary to achieve the desired mechanical output.

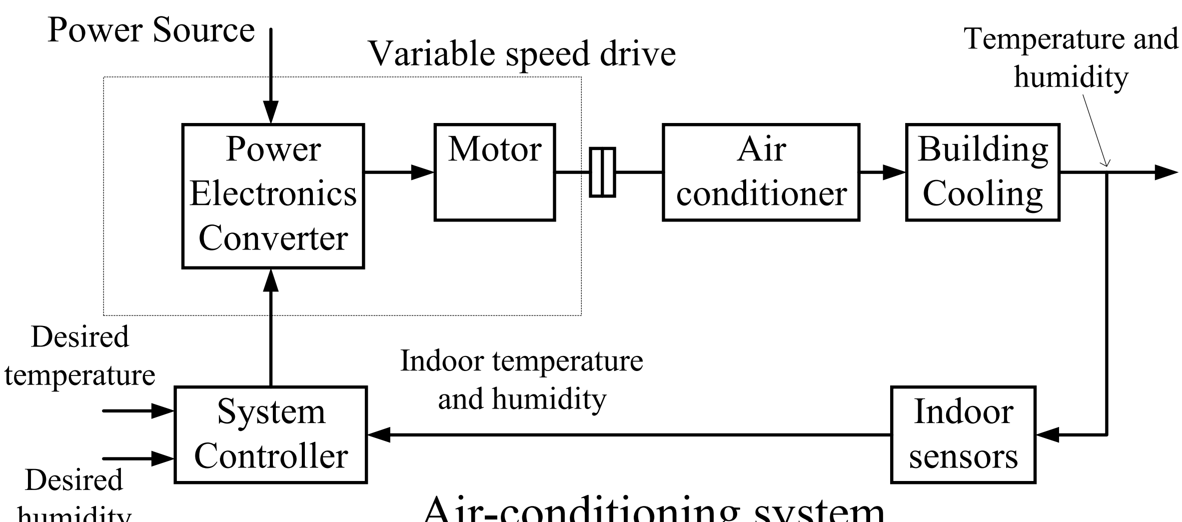
- General arrangement for variable speed drive.



Examples of drive systems



Servo system

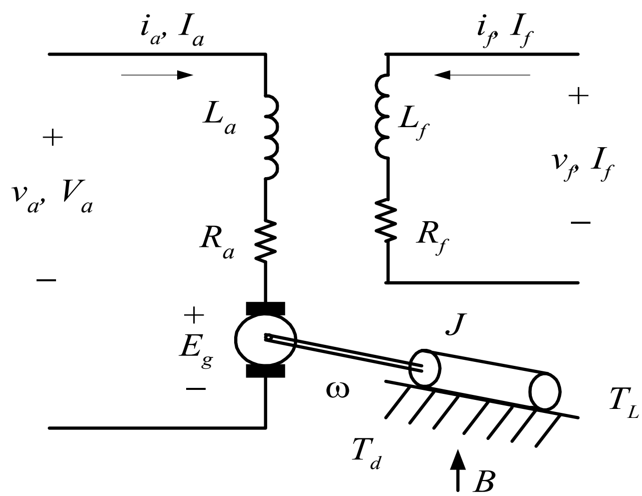


Air-conditioning system

DC Motor Drives

- Advantages of DC motor
  - Ease of control
  - Deliver high starting torque
  - Near-linear performance
- Disadvantages:
  - High maintenance
  - Large and expensive (compared to induction motor)
  - Not suitable for high-speed operation due to commutator and brushes
  - Not suitable in explosive or very clean environment
- DC motor drives:
  - The drive is relatively simple and cheap (compared to induction motor drives. But DC motor itself is more expensive
  - Due to the numerous disadvantages of DC motor, it is getting less popular

Separately Excited DC Motor



- The field windings is used to excite the field flux.
- Armature current is supplied to the rotor via brush and commutator for the mechanical work.
- Interaction of field flux and armature current in the rotor produces torque.

Operation

- When a separately excited motor is excited by a field current of i_f and an armature current of i_a flows in the circuit, the motor develops a back emf and a torque to balance the load torque at a particular speed.
- The i_f is independent of the i_a .Each windings are supplied separately. Any change in the armature current has no effect on the field current.
- The i_f is normally much less than the i_a.

Field and armature equations

Instantaneous field current :

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

where R_f and L_f are the field resistor and inductor, respectively

Instantaneous armature current :

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

where R_f and L_f are the armature resistor and inductor, respectively.

The motor back emf, which is also known as speed voltage, is expressed as :

$$e_g = K_v \omega i_f$$

where K_v is the motor voltage constant and ω is the motor speed in rad/sec.

Basic torque equation

The torque develped by the motor is :

$$T_d = K_t i_f i_a$$

where $(K_t = K_v)$ is the torque constant.

Sometimes it is written as :

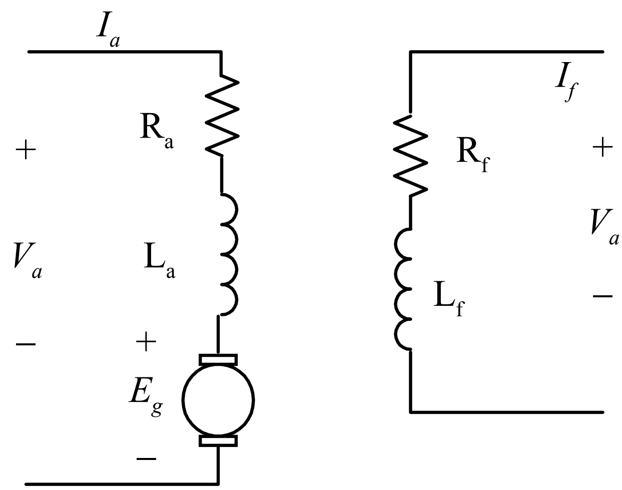
$$T_d = K_t \phi i_a$$

For normal operation, the developed torque must be equal to the load torque plus the friction and inertia, i.e. :

$$T_d = J\frac{d\omega}{dt} + B\omega + T_L$$

where
B : viscous friction constant, N.m/rad/s
T_L : load torque, N.m
J : inertia of the motor

Steady-state operations



Under steady - state operations, time derivatives is zero. Assuming the motor is not saturated. For field circuit,

$$V_f = I_f R_f$$

The back emf is given by :

$$E_g = K_v \omega I_f$$

The armature circuit

$$V_a = I_a R_a + E_g = I_a R_a + K_v \omega I_f$$

Steady-state torque and speed

The motor speed can be easily derived :

$$\omega = \frac{V_a - I_a R_a}{K_v I_f}$$

If R_a is a small value (which is usual), or when the motor is lightly loaded, i.e. I_a is small,

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

That is if the field current is kept constant, the motor speed depends only on the supply voltage.

The developed torque is :

$$T_d = K_t I_f I_a = B\omega + T_L$$

The required power is :

$$P_d = T_d \omega$$

Torque and speed control

- From the derivation, several important facts can be deduced for steady-state operation of DC motor.
- For a fixed field current, or flux (I_f) , the torque demand can be satisfied by varying the armature current (I_a).
- The motor speed can be varied by:
  - controlling V_a (voltage control)
  - controlling V_f(field control)
- These observations leads to the application of variable DC voltage to control the speed and torque of DC motor.

Example

- Consider a 500V, 10kW , 20A rated- DC motor with armature resistance of 1 ohm. When supplied at 500V, the UNLOADED motor runs at 1040 rev/min, drawing a current of 0.8A (ideally current is zero at no-load).
  - Estimate the full load speed at rated values
  - Estimate the no-load speed at 250V.

$$V_a = I_a R_a + E_g = I_a R_a + K_v \omega I_f$$

$$K_v I_f = \frac{V_a - I_a R_a}{\omega} = \frac{500 - 0.8(1)}{1040} = 0.48$$

At full load and rated value,

$$\omega_{fl} = \frac{V_a - I_a R_a}{K_v I_f} = \frac{500 - 20(1)}{0.48} = 1000 \text{ rev/min}$$

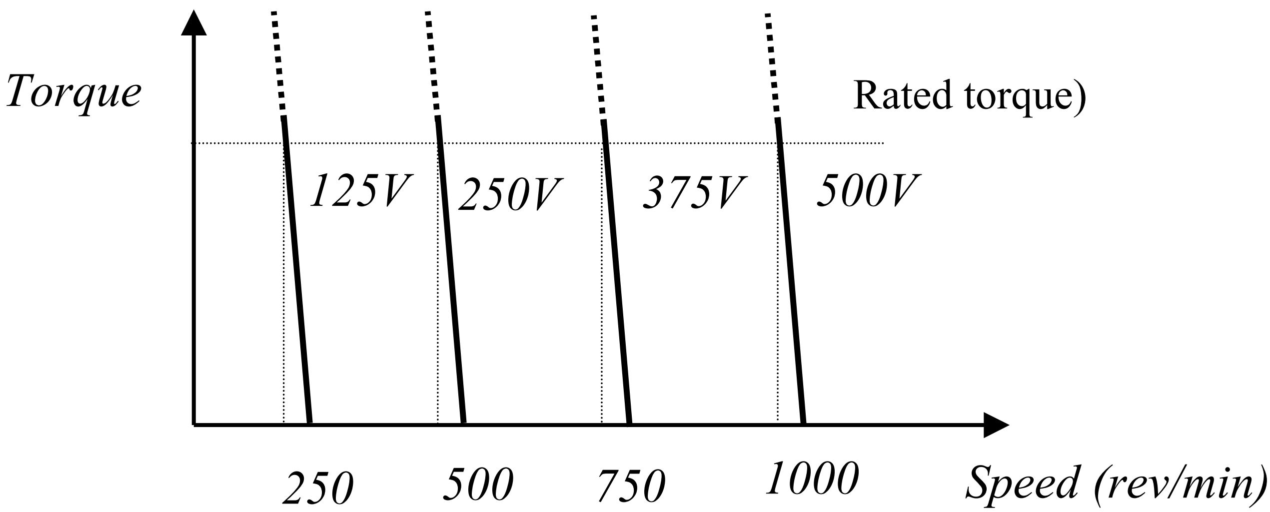
At no-load and voltage at 250V,

$$V_a = I_a R_a + K_v \omega I_f$$

$$\omega = \frac{V_a - I_a R_a}{K_v I_f} = \frac{250 - 0.8(1)}{0.48} = 519 \text{ rev/min}$$

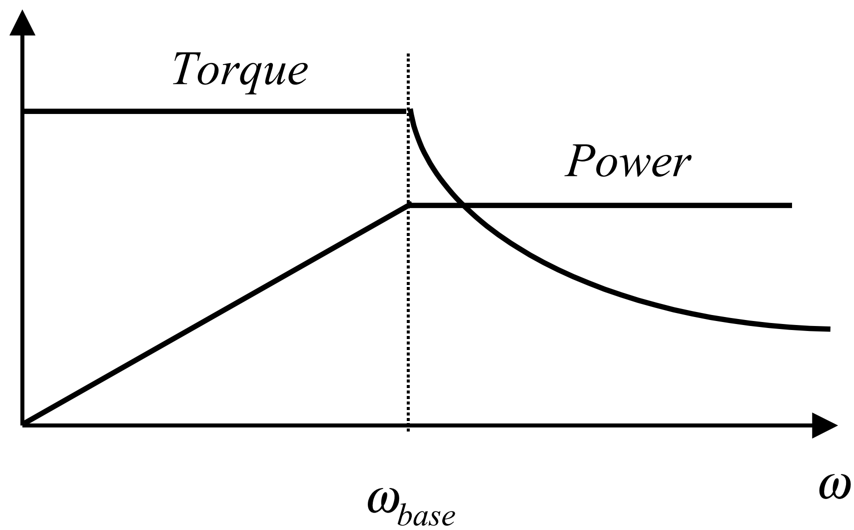
(Note : in reality, this equation strictly rad/sec)

Variable speed operation



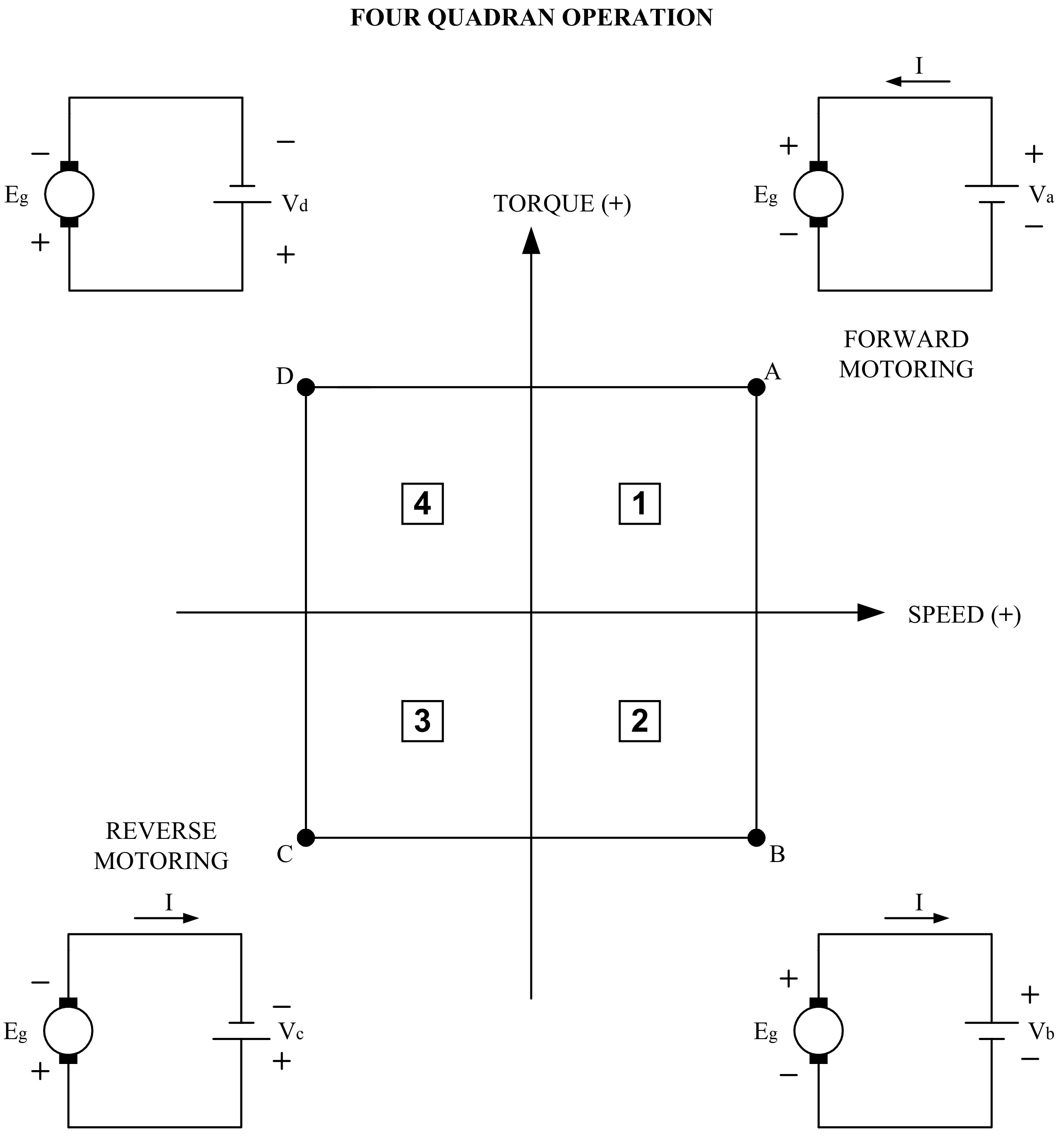
- Family of steady-state torque speed curves for a range of armature voltage can be drawn as above.
- The speed of DC motor can simply be set by applying the correct voltage.
- Note that speed variation from no-load to full load (rated) can be quite small. It depends on the armature resistance.

Base Speed and Field-weakening



- Base speed: ω_{base}
  - the speed which correspond to the rated V_a, rated I_a and rated I_f.
- Constant Torque region ($\omega > \omega_{base}$,)
  - I_a and I_f are maintained constant to met torque demand. V_a is varied to control the speed. Power increases with speed
- Constant Power region ($\omega > \omega_{base}$,)
  - V_a is maintained at the rated value and i_f is reduced to increase speed . However, the power developed by the motor (= torque x speed) remains constant. Known as field weakening.

Four quadrant operation



Quadrant 1: Forward Motoring

- running at forward direction
- operating point at A
- applied voltage is greater than back emf
- positive current flows into the armature
- the power drawn from the supply (Va.Ia) is positive

Quadrant 2: Forward Braking

- If with the motor running at position A, the supply voltage is suddenly reduced to Vb (which is below the back emf value), the current will reverse direction.Operating point is shifted to B.
- Since current is negative, power is negative.
- Power is supplied from machine to the supply. Behave like a generator.
- The combined effect of load torque and negative machine torque will cause the speed to fall.
- Back emf again falls below the applied voltage, Vb.
- The current becomes positive again. Motor settles back to Quadrant 1 but at lower speed corresponding to the lower supply voltage.

Regenerative Braking

- During the deceleration phase, kinetic energy fromthe motor and load inertia is returned to the supply.
- This is an example of regenerative braking. It occurs naturally every time we reduce the voltage to reduce the speed.
- If we wish the motor to operate continuously at position B, the machine have to be driven by mechanical source.
- The mechanical source is a “prime mover”.
- We must force the prime mover it to run faster so that the generated emf will be greater than Va.

Quadrant 3 and 4

- Quadrant 3:Reverse motoring.
  - Operating point C.
  - Speed and torque is negative
  - In practice, only need to change the polarity of the armature supply

- Quadrant 4:Reverse braking.
  - Operating point D
  - Same explanation as quadrant-2, but with negative speed.
  - Note that torque is positive

DC Drive types

- For low cost, low power applications (up to about 10kW) a single phase rectifiers can be used.Low-power, economical drives can also be constructed using single phase half-wave rectifier with free-wheeling diodes.

- For higher power drives (up to MW range), three-phase supply with three-phase rectifier is normally employed.

- For low to medium power DC supplied drives (such as battery), a chopper (DC-DC converter) is used.

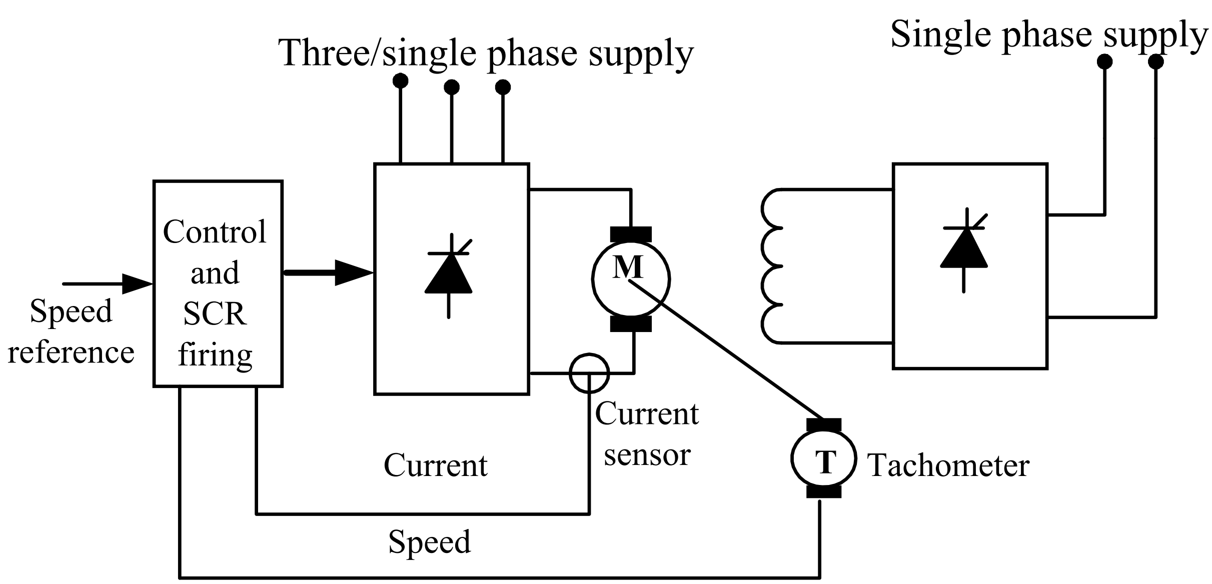
- Is is also common to find in some applications (especially locomotives), choppers are used in conjunction with uncontrolled bridge rectifiers. They are normally rated at medium power (100s of kW)

Drive types

- Using Switched-mode:
  - Full bridge dc-dc converter: 4 quadrant operation
  - Half bridge: 2 quadrant
  - Simple single-quadrant converter (buck): 1 quadrant

- Using line-frequency Controlled Rectifier:
  - Normally in high power drives
  - Using SCR and changing firing angle
  - The line current is unidirectional, but the output voltage can reverse polarity. Hence two quadrant operation is possible.

Thyristor/SCR drives



- Mains operated. Variable DC voltages are obtained from SCR (controlled) rectifiers.

- Normally field rectifier have much lower ratings than the armature rectifier. It is only used to establish the flux.

Continuous/Discontinuous current

- The key reason for successful DC drive operation is due to the large armature inductance L_a.

- Large L_a allows for almost constant armature current (with small ripple) due to "current filtering effect of L". (Refer to notes on Rectifier).

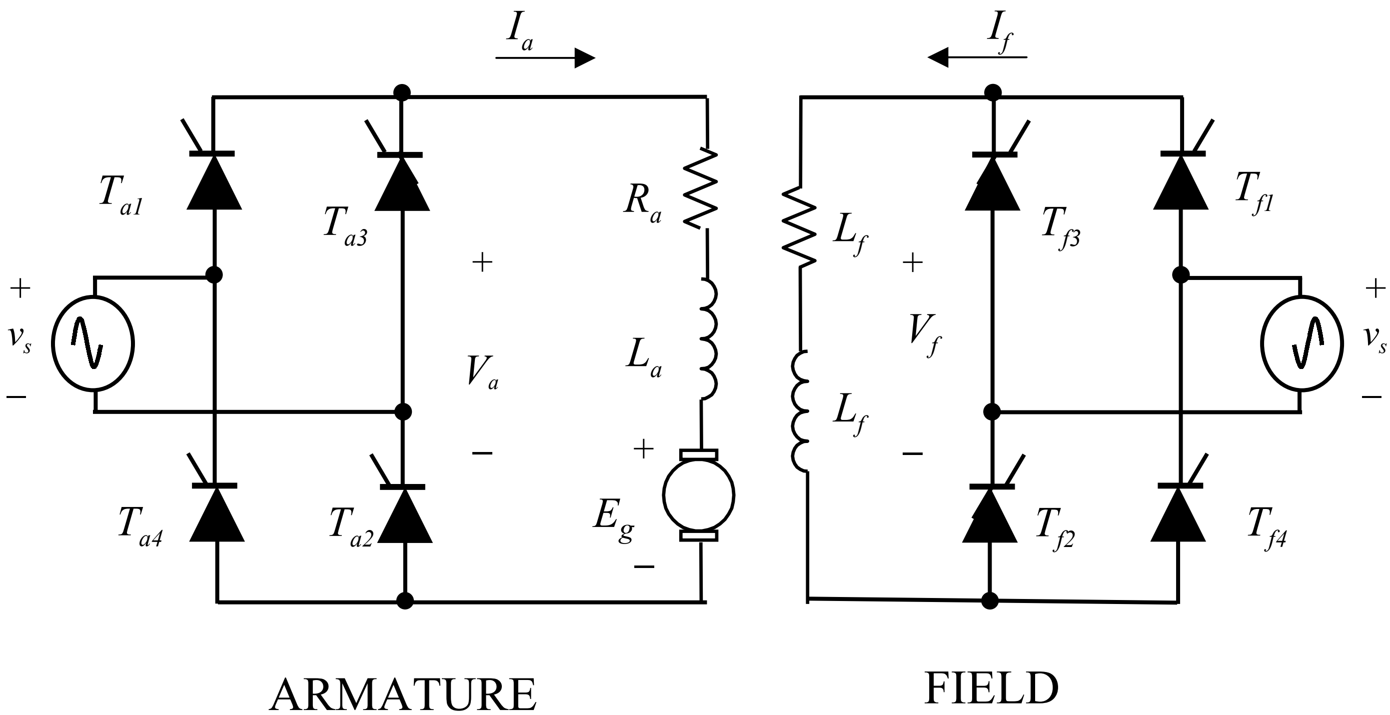
- Average value of the ripple current is zero. No significant effect on the torque.

- If L_a is not large enough, or when the motor is lightly loaded, or if supply is single phase (half-wave), discontinuous current may occur.

- Effect of discontinuous current: Output voltage of rectifier rises; motor speed goes higher. In open-loop operation the speed is poorly regulated.

- Worthwhile to add extra inductance in series with the armature inductance.

Basic single-phase drive



For continuous current, armature voltage is :

$$V_a = \frac{2V_m}{\pi}\cos\alpha_a$$

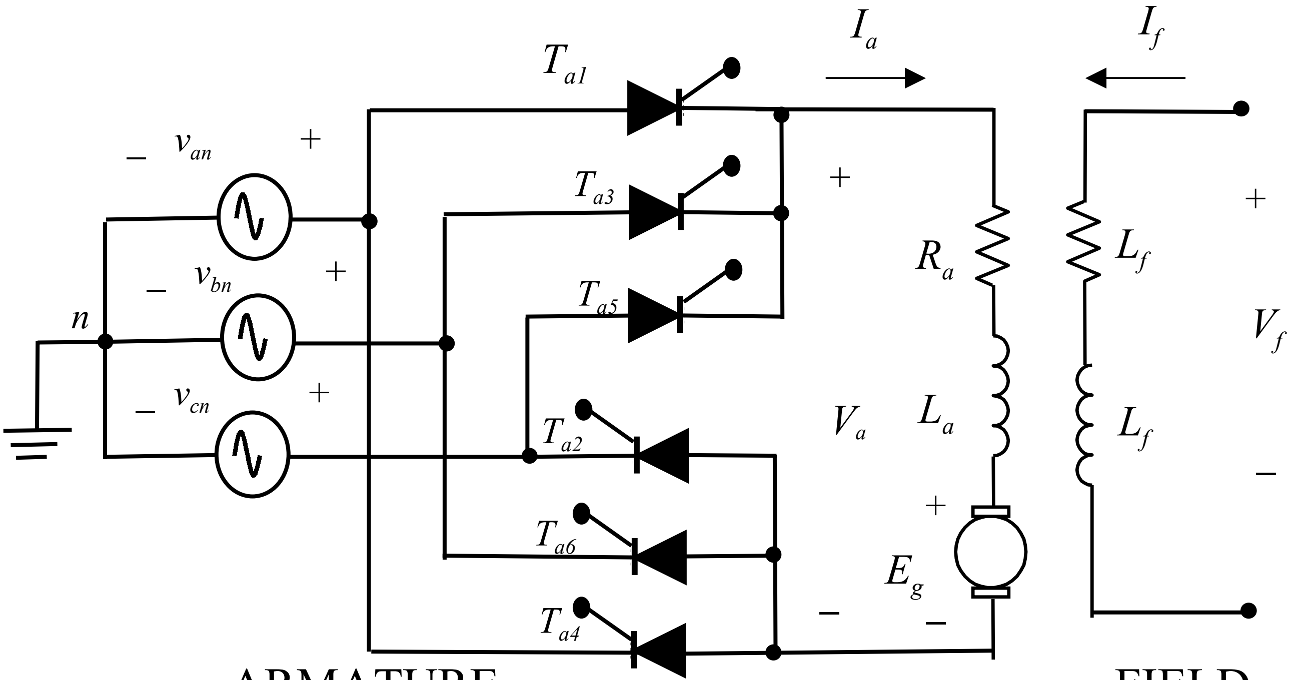
Armature (DC) current is :

$$I_a = \frac{V_a - E_g}{R_a}; \; E_g \text{ is the back emf}$$

Field voltage :

$$V_f = \frac{2V_m}{\pi}\cos\alpha_f$$

Basic three-phase drive



Armature voltage:

$$V_a = \frac{3V_{m,L-L}}{\pi}\cos\alpha_a$$

Armature (DC) current is:

$$I_a = \frac{V_a - V_E}{R_a};\ V_E \text{ is the back emf}$$

If single phase is used for field:

$$V_f = \frac{2V_m}{\pi}\cos\alpha_f$$

Example

A saperately excited DC motor has a constsnt torque load of 60 Nm. The motor is driven by s full - wave converter connected to a 240V ac supply. The field constant of the motor $KI_f = 2.5$ and the armature resistance is 2 ohm. Calculate the triggering angle for the motor to opearte at 200 rpm. Assume the current is continuous.

For continuous current,

$$V_a = \frac{2V_m}{\pi}\cos\alpha_a$$

And

$$V_a = I_a R_a + V_E$$

Where V_E is the back emf, i.e

$$V_E = KI_f\omega = 2.5\omega$$

and

$$T = KI_f I_a$$

$$\Rightarrow \frac{2V_m}{\pi}\cos\alpha_a = \left[\left(\frac{T}{KI_f}\right)R_a + KI_f\omega\right]$$

$$\alpha_a = \cos^{-1}\left\{\frac{\pi}{2V_m}\left[\left(\frac{T}{KI_f}\right)R_a + KI_f\omega\right]\right\}$$

$$= \cos^{-1}\left\{\frac{\pi}{2\sqrt{2}\times 240V}\left[\left(\frac{60}{2.5}\right)2 + 2.5\left(2\times\pi\times\frac{200}{60}\right)\right]\right\}$$

$$= 62.32^o$$

Example

A rectifier-DC motor drive is supplied by a three-phase, full controlled SCR bridge 240Vrms/50Hz per-phase. The field is supplied by a single-phase 240V rms/50Hz, with uncontrolled diode bridge rectifier. The field current is set as maximum as possible.

The separately excited DC motor characteristics is given as follows:

Armature resistance: R_a = 0.3 ohm

Field resistance: R_f =175 ohm

Motor constant: K_V =1.5 V/A-rad/s

Assume the inductance of the armature and field circuit is large enough to ensure continuous and ripple-free currents. If the delay angle of the armature converter (α_a) is 45 degrees and the required armature current is 30A,

- a) Calculate the developed torque, T_d.
- b) Speed of the motor, ω (rad/s)
- c) If the polarity of the field current is reversed, the motor back emf will reverse. For the same armature current of 30A, determine the required delay angle of the armature converter.

$$\text{Since the fiels current is maximum}, \alpha = 0.$$

$$(a)\ V_f = \frac{2V_m}{\pi}\cos\alpha_f = \frac{2\sqrt{2}\times 240}{\pi}\cos 0 = 216V$$

$$\Rightarrow I_f = \frac{V_f}{R_f} = \frac{216V}{175} = 1.235A$$

$$T_d = K_v I_f I_a = 1.5\times 1.235\times 30 = 55.58Nm$$

Example (cont)

(b) Motor speed

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

$$E_g = V_a - I_a R_a$$

The armature is supplied by three-phase with $\alpha_a = 45^{o}$,

$$V_a = \frac{3V_{m,L-L}}{\pi}\cos\alpha_a = \frac{3\times\sqrt{3}\times\sqrt{2}\times 240}{\pi}\cos 45^{o} = 396.3V$$

$$E_g = V_a - I_a R_a = 396.3 - 30\times 0.3 = 387.3V$$

$$\Rightarrow \omega = \frac{387.3V}{1.5\times 1.235} = 209.06 \text{ rad/sec}$$

(c) Now the polarity of field is reversed, then

$$E_g = -387.3V$$

and

$$V_a = E_g + I_a R_a = -387.3 + 30\times 0.3 = -378.3V$$

Also,

$$V_a = \frac{3V_{m,L-L}}{\pi}\cos\alpha_a$$

$$\alpha_a = \cos^{-1}\left(\frac{\pi\times V_a}{3V_{m,L-L}}\right) = \cos^{-1}\left(\frac{\pi\times(-378.5)}{3\sqrt{3}\times\sqrt{2}\times 240}\right)$$

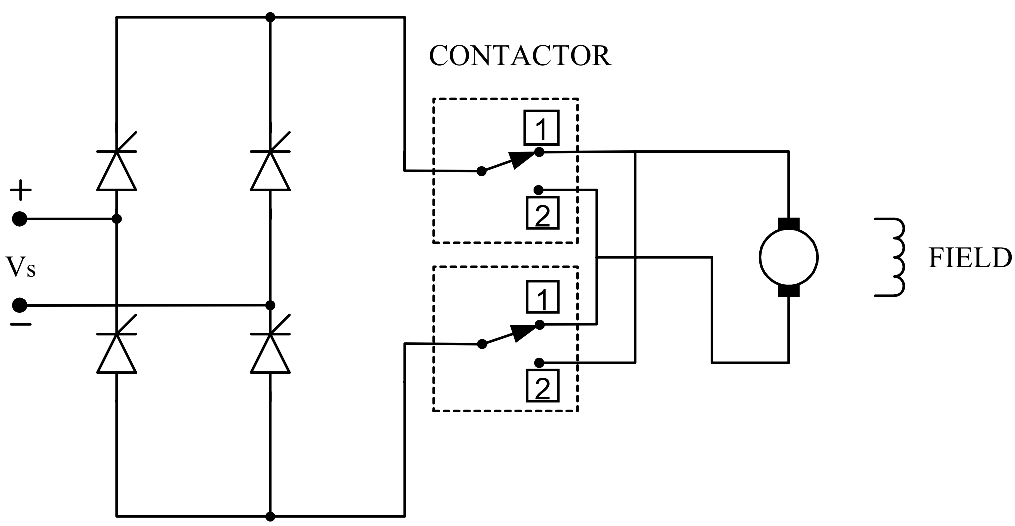
$$= 132.4^{o}$$

Reversal

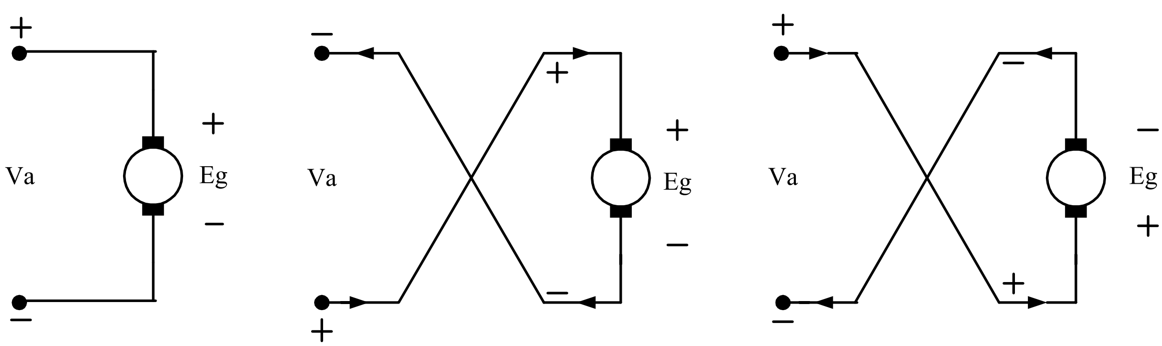
- DC motor in inherently bi-directional. Hence no-problem to reverse the direction. It can be a motor or generator.
- But the rectifier is unidirectional, because the thyristors are unidirectional devices.
- However, if the rectifier is fully controlled, it can be operated to become negative DC voltage, by making firing angle greater than 90 degrees,
- Reversal can be achieved by:
  - armature reversal using contactors (2 quadrant)
  - field reversal using contactors (2 quadrant)
  - double converter (full 4 quadrants)

Drive reversing using armature or field contactors

DRIVE REVERSING USING ARMATURE OR FIELD CONTACTORS



CONTACTOR AT THE ARMATURE SIDE (SINGLE PHASE SYSTEM)

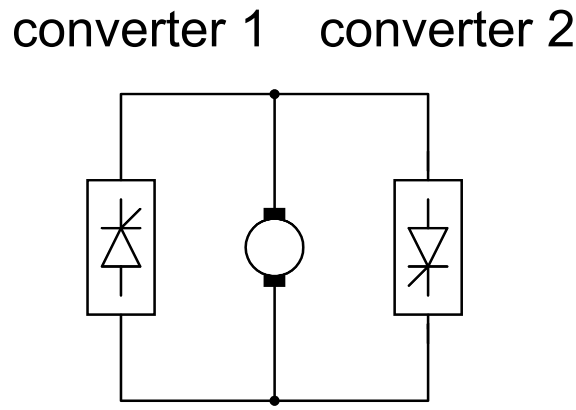


CONTACTOR AT POSITION 1 (MOTORING)

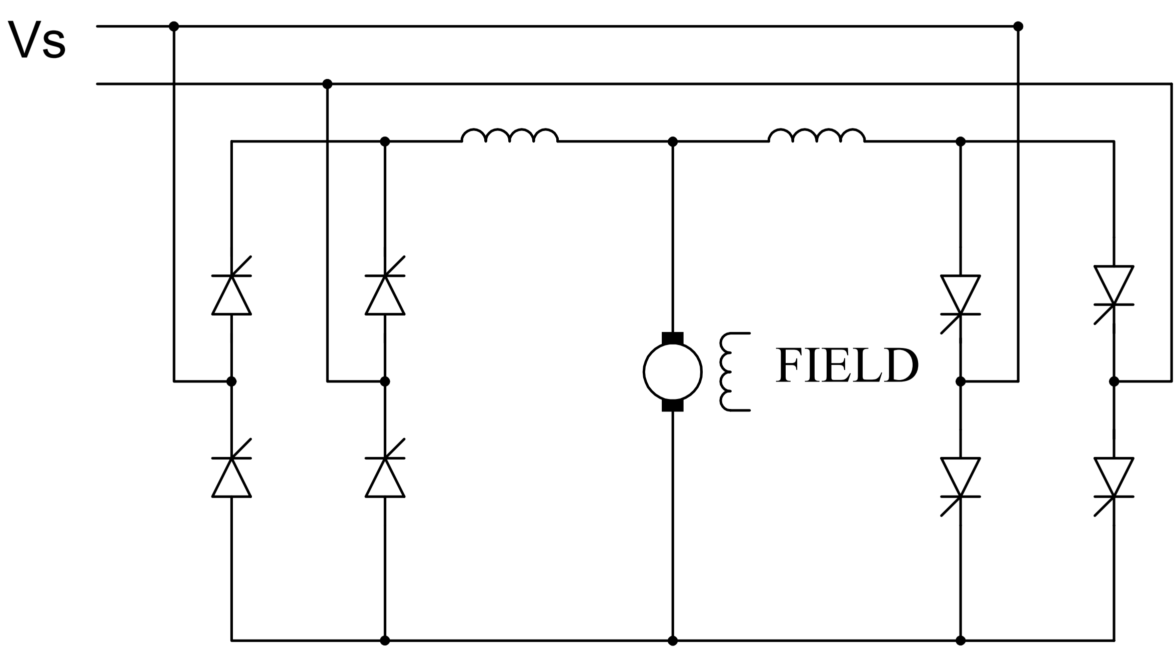
CONTACTOR AT POSITION 2 (BRAKING/ GENERATION)

CONTACTOR AT POSITION 2 (RESERVE)

Drive reversing using double converters



Principle of reversal



Practical circuit