DC Motor Drive

- General Concept
- Speed Control
- SCR Drives
- Switched-mode DC Drives

DC Motor

- 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 DC drive is relatively simple and cheap (compared to induction motor drives). But DC motor itself is more expensive.

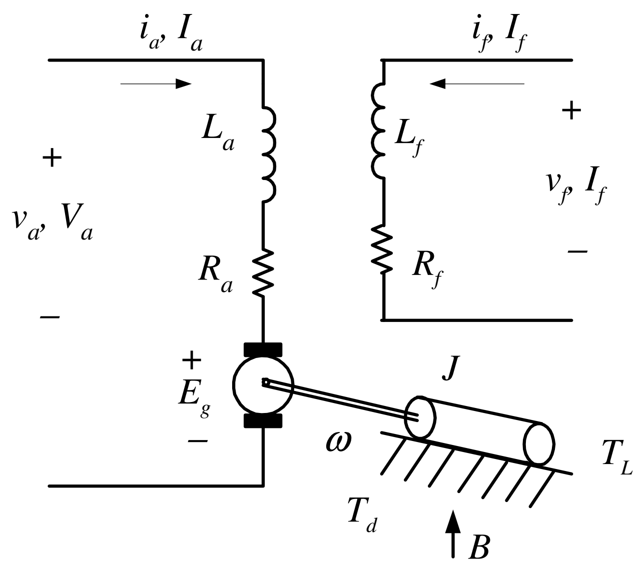
- Due to the numerous disadvantages of DC motor (esp. maintenance), it is getting less popular, particularly in high power applications.

- For low power applications the cost of DC motor plus drives is still economical.

- For servo application, DC drives is still popular because of good dynamic response and ease of control.

- Future Trend? Not so bright prospect for DC, esp. in high power drives.

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:

$$e_g = K_v \omega i_f$$

K_v is the motor voltage constant (in V/A - rad/s) 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.

(in V/A - rad/s)

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. :

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

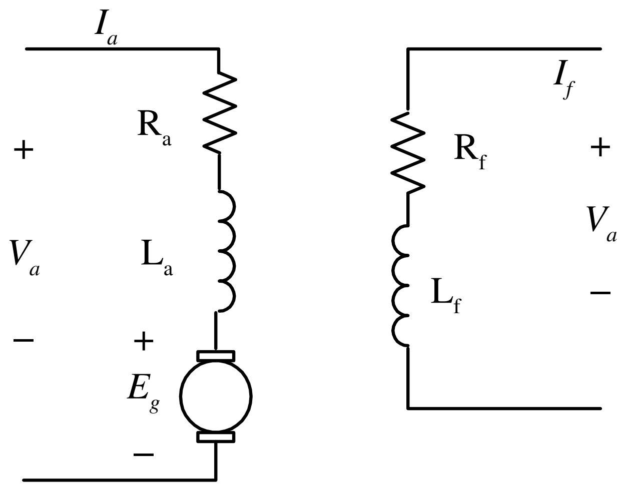
where

B : viscous friction constant, (N.m/rad/s)

T_L : load torque (N.m)

J : inertia of the motor (kg.m^2)

Steady-state operation



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 1

- 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,

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

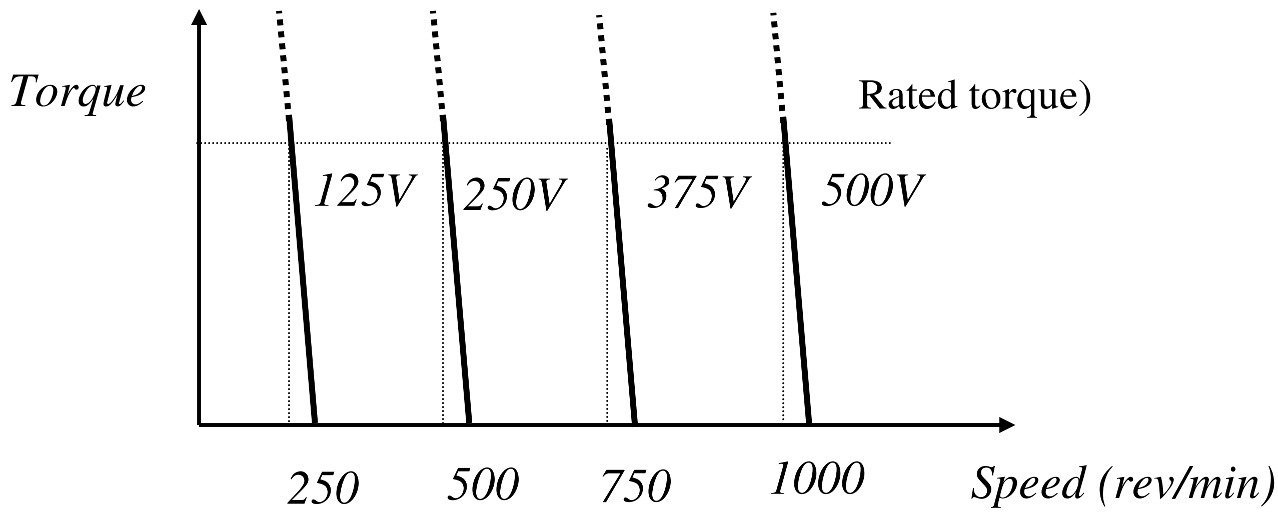
At no - load and voltage at 250V,

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

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

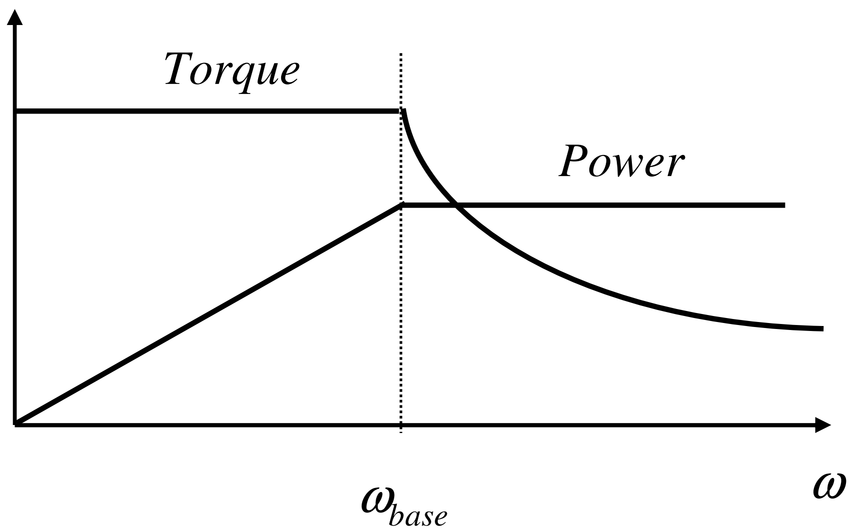
(Note : in reality, this equation strictly rad/sec)

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

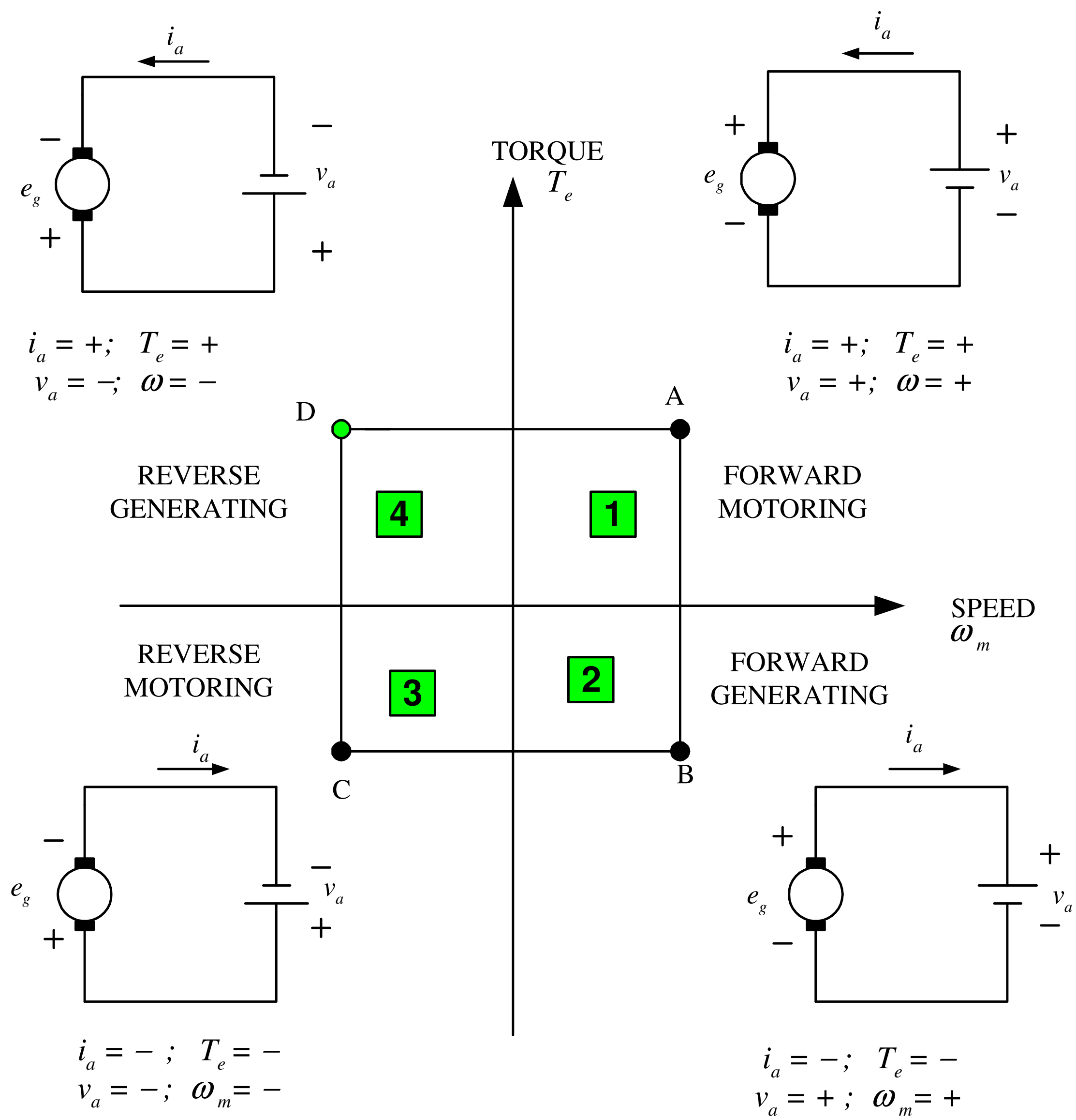


- **Base speed**: ω_{base}
  - the speed which correspond to the rated V_a, rated I_a and rated I_f.

- **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



Regenerative Braking (in Q2)

- Say the motor running at position A. Suddenly v_a is reduced (below e_g). The current ia will reverse direction.Operating point is shifted to B.

- Since i_a is negative, torque T_e is negative.

- Power is also negative, which implies power is "generated" back to the supply.

- In other words, during the deceleration phase, kinetic energy from the motor and load inertia is returned to the supply.

- This is known as regenerative braking-an efficient way to brake a motor. Widely employ in electric vehicle and electric trains. If we wish the motor to operate continuously at position B, the machine have to be driven by mechanical source.

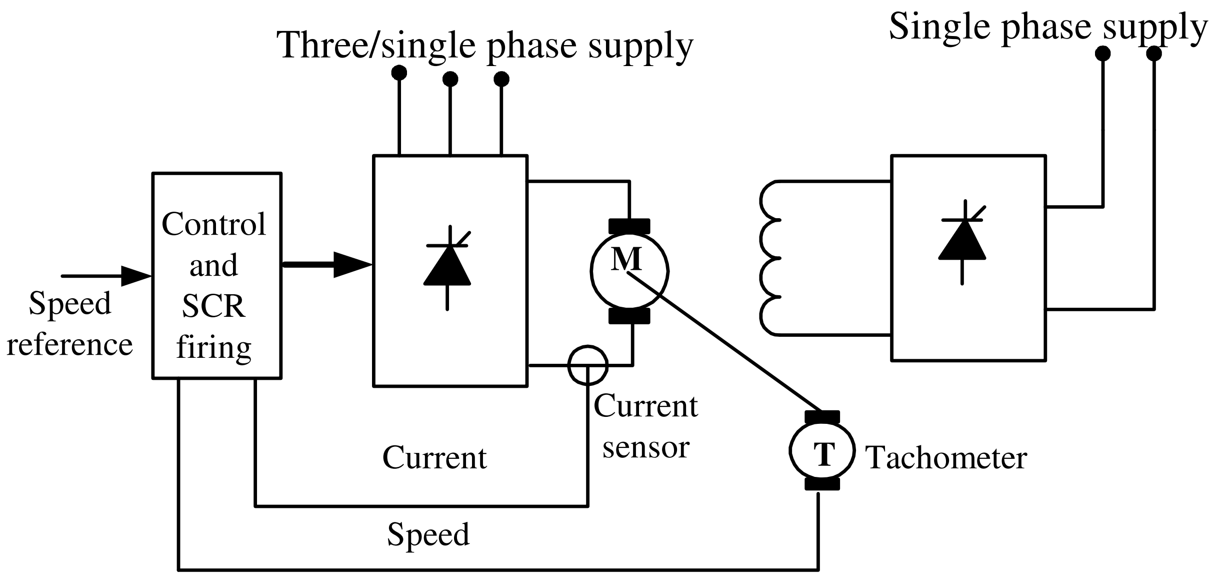
- The mechanical source is a "prime mover".
- We must force the prime mover it to run faster so that the generated e_g will be greater than v_a.

Drive types

- SCR “phase-angle controlled” drive
  - By changing the firing angle, variable DC output voltage can be obtained.
  - Single phase (low power) and three phase (high and very high power) supply can be used
  - The line current is unidirectional, but the output voltage can reverse polarity. Hence 2- quadrant operation is inherently possible.
  - 4-quadrant is also possible using “two sets” of controlled rectifiers.

- Switched-mode drive
  - Using switched mode DC-DC converter. Dc voltage is varied by duty cycle.
  - Mainly used for low to medium power range.
  - Single-quadrant converter (buck): 1- quadrant
  - Half bridge: 2-quadrant
  - Full bridge: 4-quadrant operation

Thyristor/SCR drives

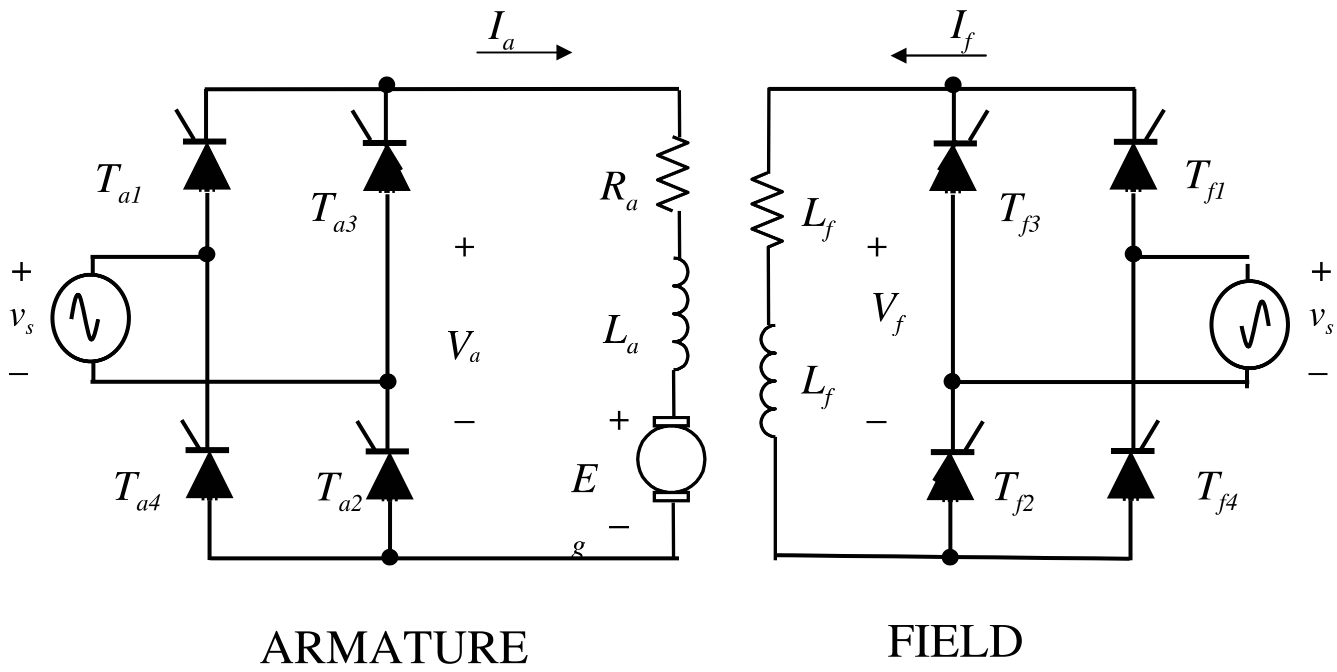


- Mains operated.
- Variable DC voltages are obtained from SCR firing angle control.
- Slow response.
- Normally field rectifier have much lower ratings than the armature rectifier. It is only used to establish the flux.

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:

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

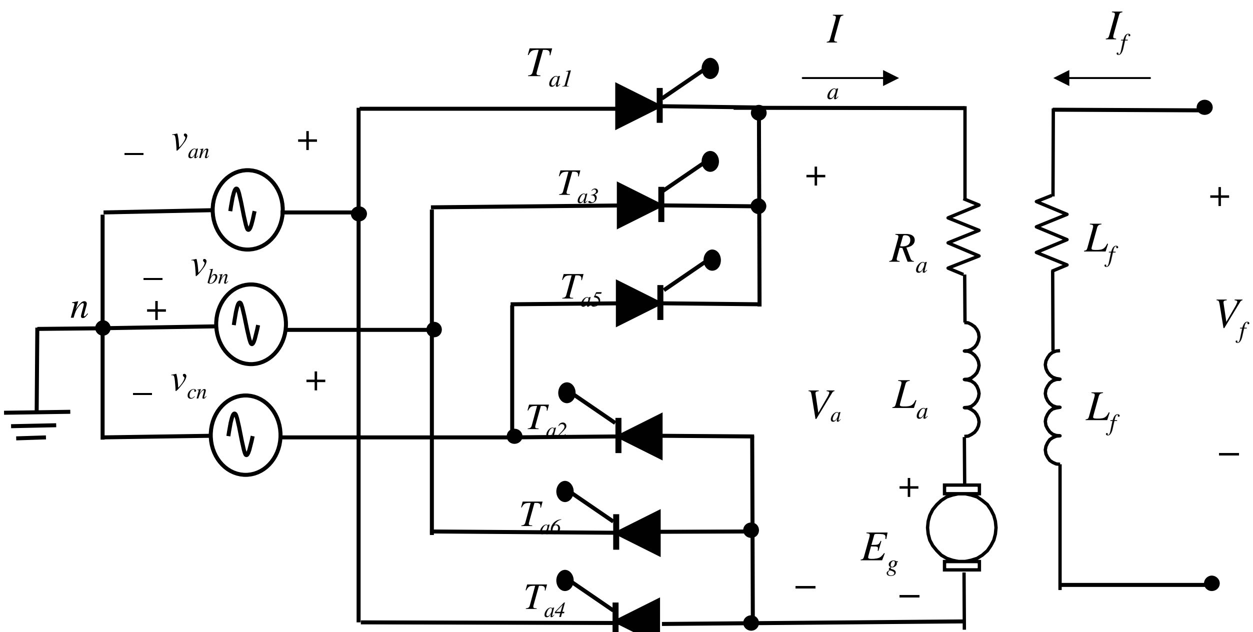
Armature (DC) current is:

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

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:

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

If single phase is used for field:

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

Example 2

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 3

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.

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 3 (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 $\alpha_a = 45^{\circ}$,

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

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

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

(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.

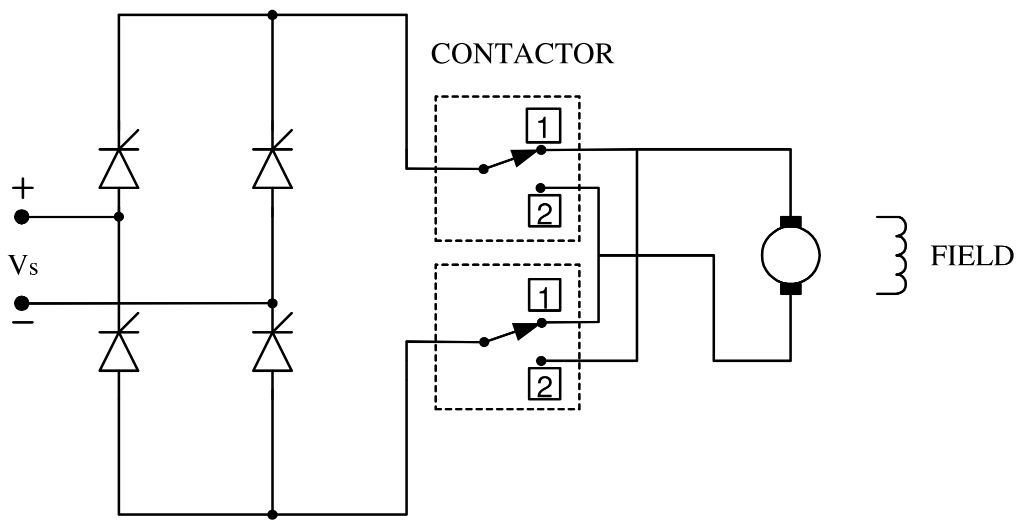
- But the rectifier is unidirectional, because the SCR are unidirectional devices.

- However, if the rectifier is fully controlled, it can be operated to become negative DC voltage, by making firing angle greater than 90 degrees,

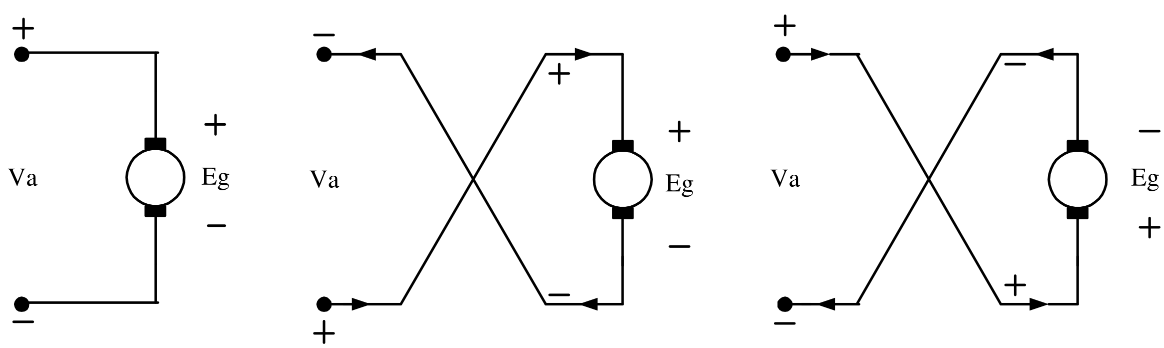
- Reversal can be achieved by:
  - **armature reversal** using contactors (2-quadrant)
  - **field reversal** using contactors (2-quadrant)
  - **double converter** (full 4-quadrants)

Reversal using armature or field contactors

DRIVE REVERSING USING ARMATURE OR FIELD CONTACTORS



CONTACTOR AT THE ARMATURE SIDE (SINGLE PHASE SYSTEM)

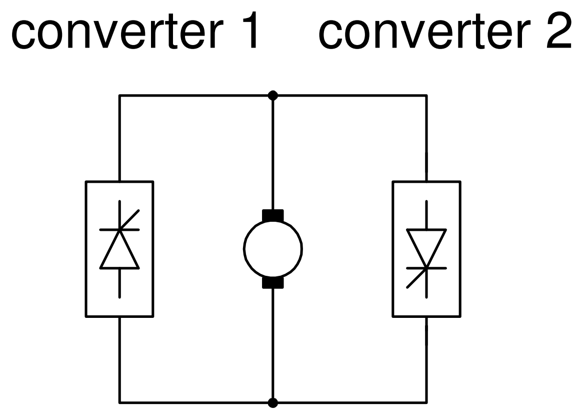


CONTACTOR AT POSITION 1 (MOTORING)

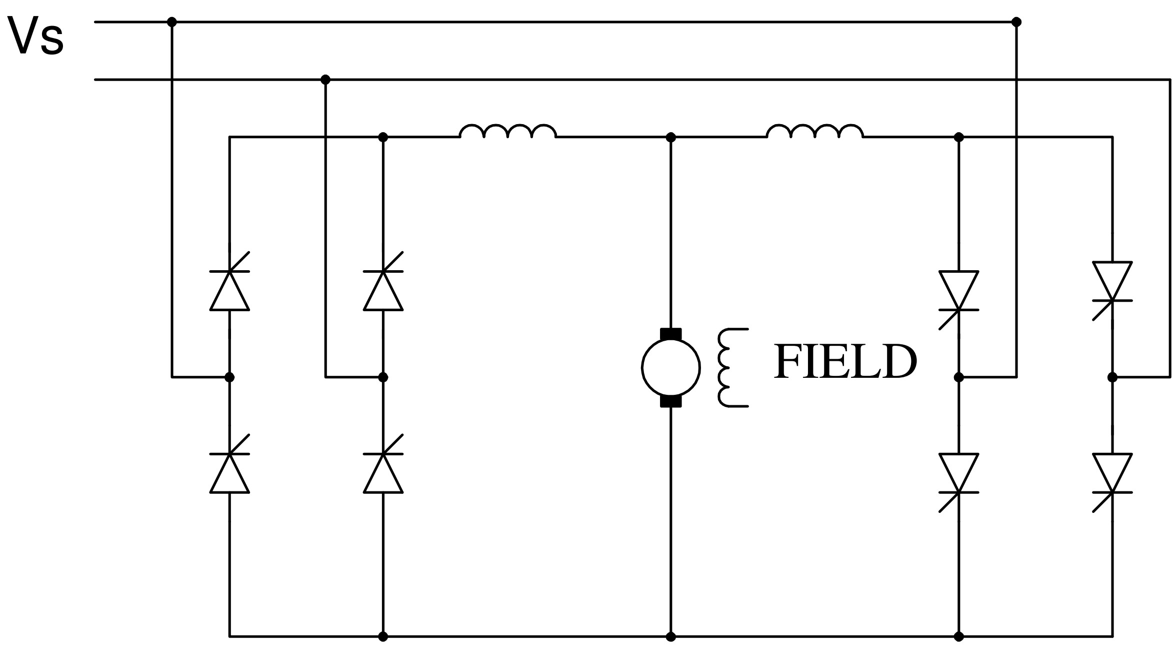
CONTACTOR AT POSITION 2 (BRAKING/ GENERATION)

CONTACTOR AT POSITION 2 (RESERVE)

Reversing using double converters



Principle of reversal



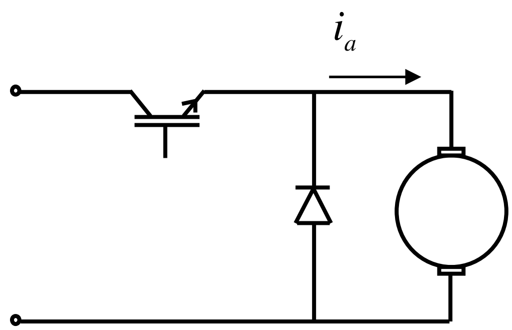
Practical circuit

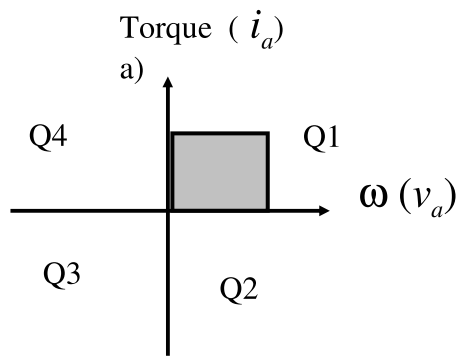
Switched–mode DC drives

- Supply is DC (maybe from rectified-filtered AC, or some other DC sources).
- DC-DC converters (coppers) are used.
- suitable for applications requiring position control or fast response, for example in servo applications, robotics, etc.
- Normally operate at high frequency
  - the average output voltage response is significantly faster
  - the armature current ripple is relatively less than the controlled rectifier
- In terms of quadrant of operations, 3 possible configurations are possible:
  - single quadrant,
  - two–quadrant
  - and four–quadrant

Single-quadrant drive

- Unidirectional speed. Braking not required.





For $0 < t < T$,

The armature voltage at steady state :

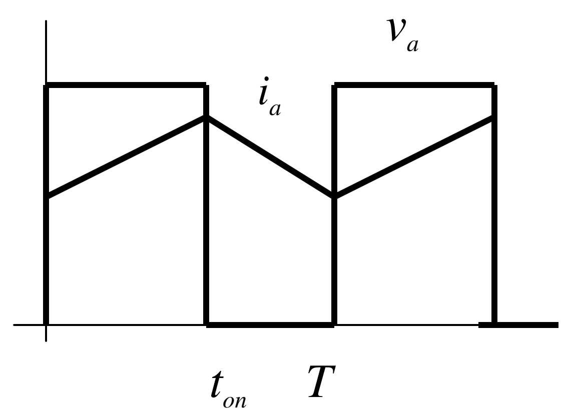
$$V_a = \frac{1}{T}\int_0^{t_{on}} V dt = \frac{t_{on}}{T} = DV$$

Armature (DC) current is :

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

and speed can be approximated as :

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

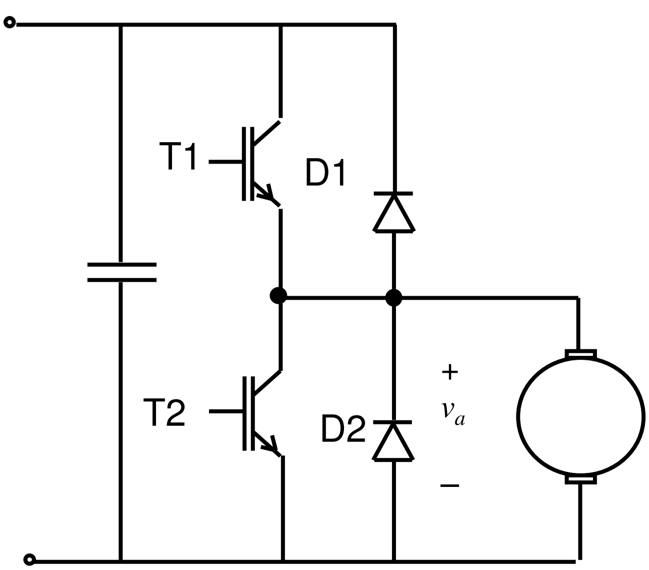


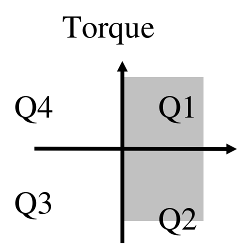
2 Quadrant DC drives

- 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.

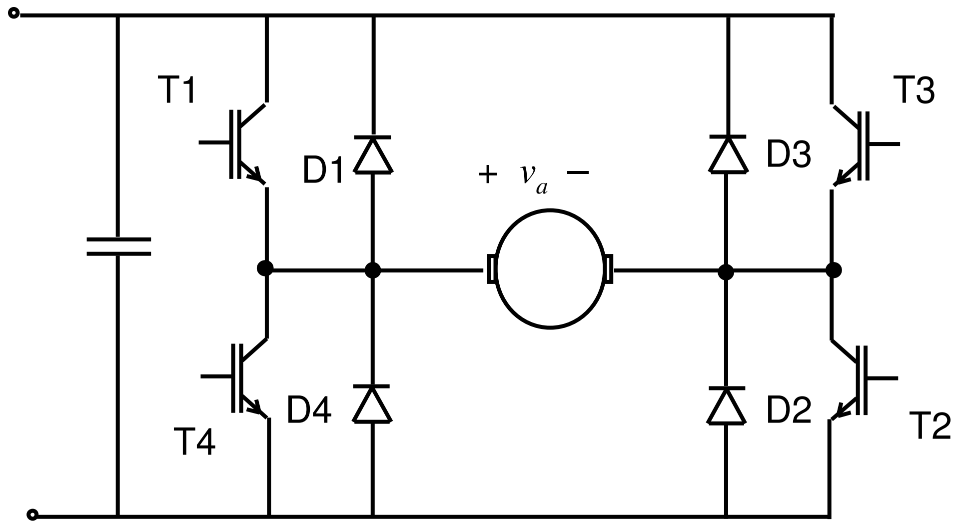
ω

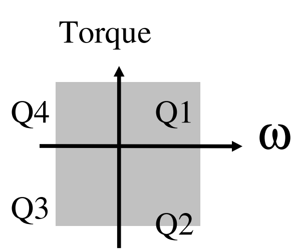




4 Quadrant DC drives

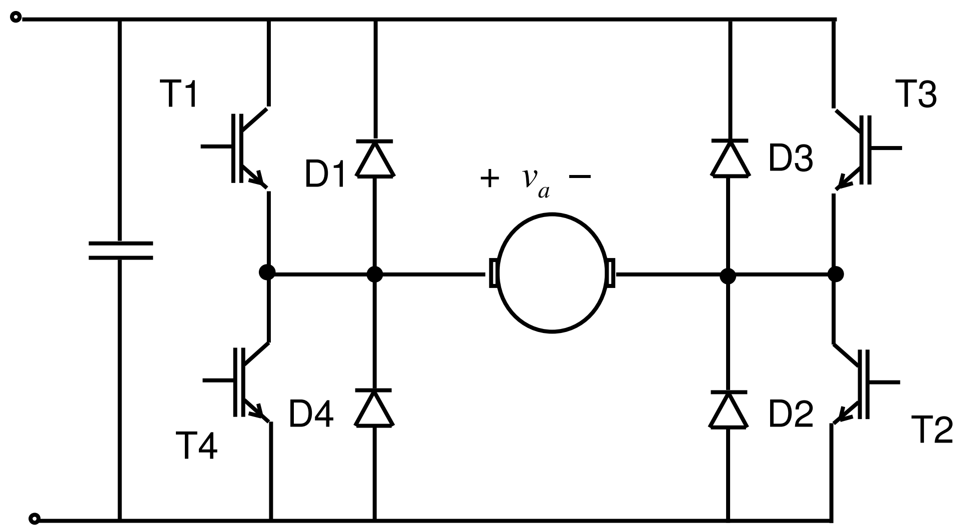
- A full-bridge DC-DC converter is used.





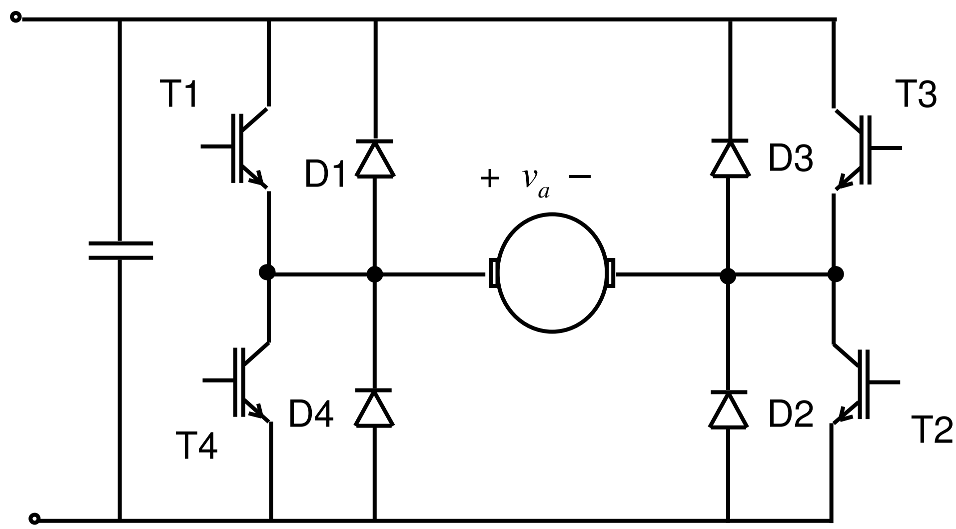
4-quadrant: Forward motoring

- T1 and T2 operate; T3 and T4 off.
- T1 and T2 turn on together: the supply voltage appear across the motor terminal. Armature current rises.
- T1 and T2 turn off: the armature current decay through D3 and D4



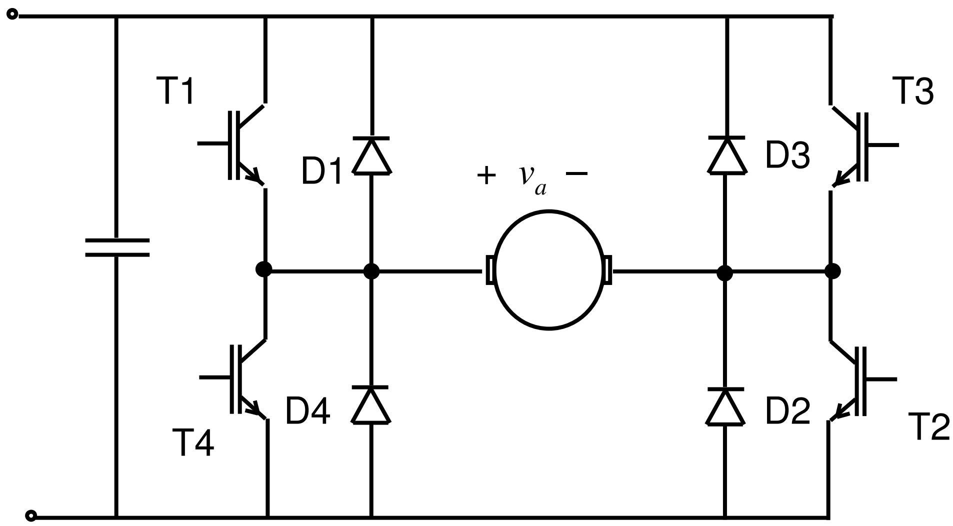
Regeneration

- T1, T2 and T3 turned off.
- When T4 is turned on, the armature current rises through T4 and D2.
- When T4 is turned off, the motor, acting as a generator, returns energy to the supply through D1 and D2.



Reverse motoring

- T3 and T3 operate; T1 and T2 off.
- When T3 and T4 are on together, the armature current rises and flows in reverse direction.
- Hence the motor rotates in reverse direction.
- When T3 and T4 turn off, the armature current decays through D1 and D2.



Reverse generation

- T1, T3 and T4 are off.
- When T1 is on, the armature current rises through T2 and D4.
- When Q2 is turned off, the armature current falls and the motor returns energy to the supply through D3 and D4.