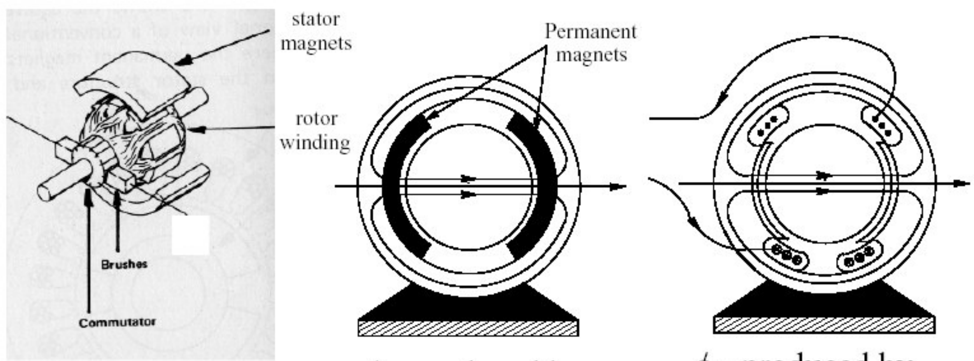
DC DRIVES

Principle of operation and construction – a review

DC machine consists of

stator – stationary – where the field flux is produced
rotor – rotating – where the armature winding is placed.

Field flux is obtained either from permanent magnet or from field winding excitation. Field flux interacts with current carrying conductors in armature to produce torque. Commutator in armature circuit will ensure that the torque production is always maximum, regardless of rotor position.



ϕ_f produced by permanent magnets

ϕ_f produced by stator winding current

Modeling of DC motor

The torque is produced as a result of interaction of field flux with current in armature conductors and is given by

$$T_e = k_t \Phi i_a \quad (1)$$

where k_t is a constant depending on motor windings and geometry
Φ is the flux per pole due to the field winding

For the motor with wound field, the flux can be varied to control the speed, but for permanent magnet motor, the flux is fixed and thus can be written as:

$$T_e = K_t i_a$$

where K_t depends on the permanent magnet material
The direction of the torque produced depends on the direction of the armature current
When the armature rotates, the flux linking the armature winding will vary with time and therefore according to Faraday's law, an emf will be induced across the winding. This generated emf, known as the back emf, depends on speed of rotation as well as on the flux produced by the field and is given by:

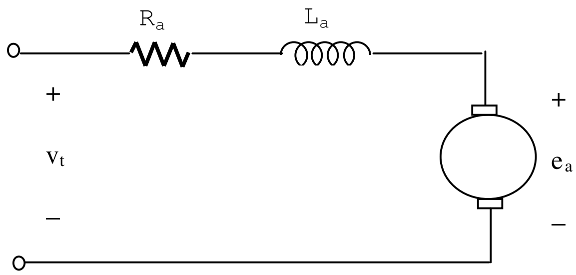
$$e_a = k_t \Phi \omega \quad (2)$$

Similarly, for permanent magnet, this can be written as:

$$e_a = K_t \omega$$

The polarity of the back emf depends on the direction of the motor rotation

For separately excited DC motor, the armature circuit is shown:



R_a – lumped armature winding resistance
L_a – self inductance of the armature winding
e_a – as defined before, is the back emf of the motor

Using KVL,

$$v_t = i_a R_a + L_a \frac{di_a}{dt} + e_a \tag{3}$$

In steady state condition,

$$V_t = I_a R_a + E_a \tag{4}$$

In terms of torque and speed the steady state equation can be written as:

$$V_t = \frac{T}{k_t \Phi} R_a + k_t \Phi \omega \tag{5}$$

which gives:

$$\omega = \frac{V_t}{k_t \Phi} - \frac{T}{(k_t \Phi)^2} R_a \tag{6}$$

Thus three methods can be used to control the speed: V_t, Φ and R_a

Speed control using armature resistance by adding external resistor R_{ext} is seldom used, especially for large motor due to the losses associated with $I_a^2 R_{ext}$. V_t is normally control for speed up to rated speed. Beyond rated speed, for separately excited DC motor, the speed control is achieved by flux control, Φ. When speed control by flux control is used, the maximum torque capability of the motor is reduced since for a given maximum armature current, the flux is less than the rated value and thus the maximum torque produced is less than the maxumum torque. Also it should be noted that , with permanent magnet excitation, speed control using flux weakening is not possible – thus maximum speed of permanent magnet motor is limited.

When designing controllers for DC motor drives used in servo or high performance applications, a small signal model of the motor is required. A separately excited DC motor with fixed field excitation, or a permanent magnet DC motor, is described by equations (3), (1) and (2). If a small perturbation around a DC operating point is introduced, these equations can be written as (7)-(9). The '~' indicates a small perturbation, which is add to the DC components of v_t, i_a, e_a, T_e, T_L and ω :

$$V_t + \tilde{v}_t = (I_a + \tilde{i}_a)R_a + L_a \frac{d(I_a + \tilde{i}_a)}{dt} + (E_a + \tilde{e}_a) \quad (7)$$

$$T_e + \tilde{T}_e = k_E (I_a + i_a) \quad (8)$$

$$E_e + \tilde{e}_e = k_E (\omega + \tilde{\omega}) \quad (9)$$

Equation describing the dynamic of the mechanical system is given by:

$$T_e = T_l + J \frac{d\omega_m}{dt} \quad (10)$$

where $T_l = T_L + B\omega$

T_l is the load torque composed of working torque of the load, T_L and torque due to friction, $B\omega$. The frictional torque depends on the rotational speed, while T_L depends on the nature of the load being driven. Similarly, if a small perturbation is introduced in T_e and T_L and ω, equation (10) can be written as:

$$T_e + \tilde{T}_e = T_L + \tilde{T}_L + B(\omega + \tilde{\omega}) + J \frac{d(\omega + \tilde{\omega})}{dt} \quad (11)$$

Separating the DC and small perturbation or AC components in (7)–(9) and (11), the steady state and small signal equations describing the DC motor can be obtained:

AC components	DC components
$\tilde{v}_t = \tilde{i}_a R_a + L_a \frac{d\tilde{i}_a}{dt} + \tilde{e}_a$	$V_t = I_a R_a + E_a$
$\tilde{T}_e = k_E (\tilde{i}_a)$	$T_e = k_E I_a$
$\tilde{e}_e = k_E (\tilde{\omega})$	$E_e = k_E \omega$
$\tilde{T}_e = \tilde{T}_L + B\tilde{\omega} + J \frac{d(\tilde{\omega})}{dt}$	$T_e = T_L + B(\omega)$

The transfer functionof the DC motor is obtained by taking the Laplace transform of the small signal equations.

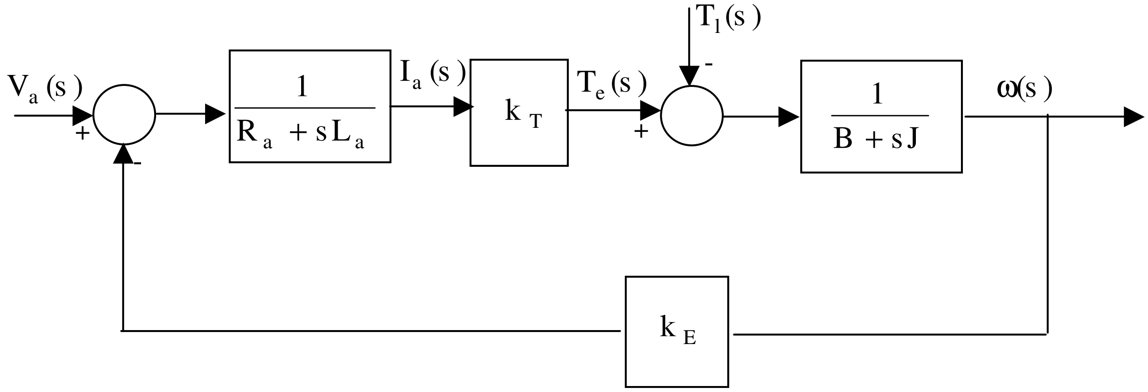
$$V_t(s) = I_a(s)R_a + L_a s Ia + E_a(s) \quad (12)$$

$$T_e(s) = k_E I_a(s) \quad (13)$$

$$E_a(s) = k_E \omega(s) \quad (14)$$

$$T_e(s) = T_L(s) + B\omega(s) + sJ\,\omega(s) \quad (15)$$

Thus the block diagram representing the DC motor is shown:



Power electronic converters in DC drives

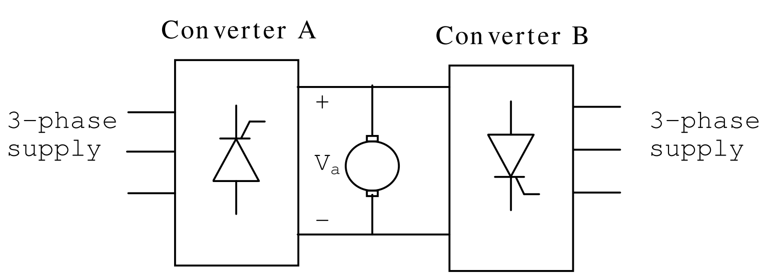
The power electronic converters are used to obtain an adjustable DC voltage applied to the armature of a DC motor. There are basically two types of converter normally employed in DC drives: (i) controlled rectifier (ii) switch–mode converter.

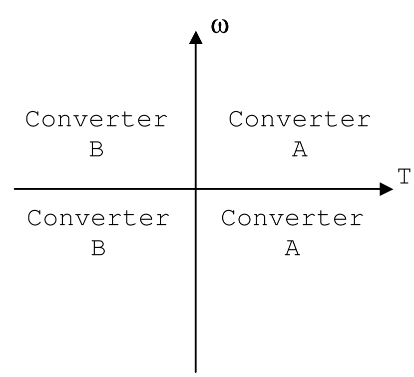
<u>(i) Controlled rectifier</u>

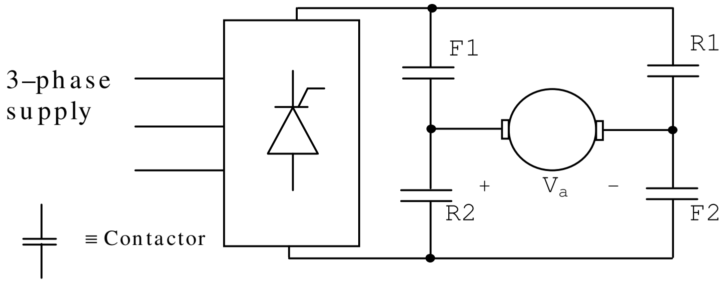
Controlled rectifier can be operated from a single phase or three phase input

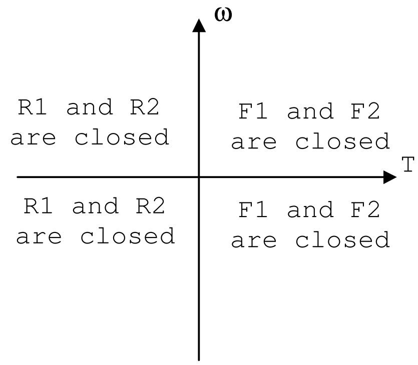
Output voltage contain low frequency ripple which may require a large inductor inserted in armature circuit, in order to reduce the armature current ripple. A large armature current ripple is undesirable since it may be reflected in speed response if the inertia of the motor–load is not large enough. Controlled rectifier has low bandwidth. The average output voltage response to a control signal, which is the delay angle, is relatively slow. Therefore controlled rectifier is not suitable for drives requiring fast response, e.g. in servo applications.

In terms of quadrant of operations, a single phase or a three phase rectifier is only capable of operating in first and fourth quadrants – which is not suitable for drives requiring forward breaking mode. To be able to operate in all four quadrants, configurations using back to back rectifiers or contactors shown below must be employed.



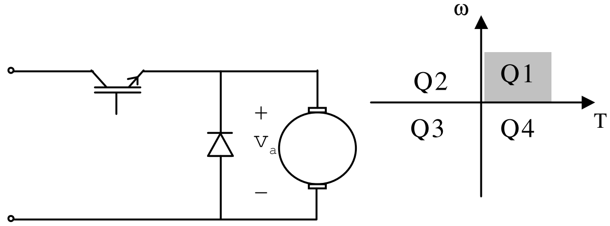




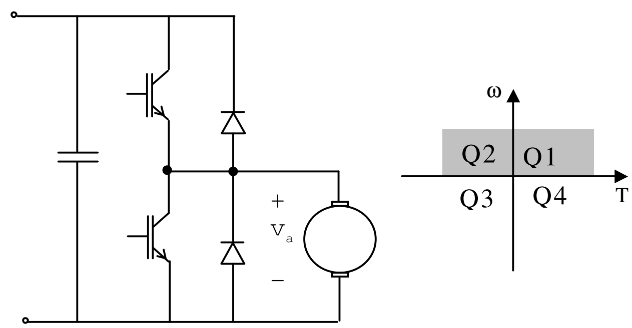


(ii) Switch–mode converter

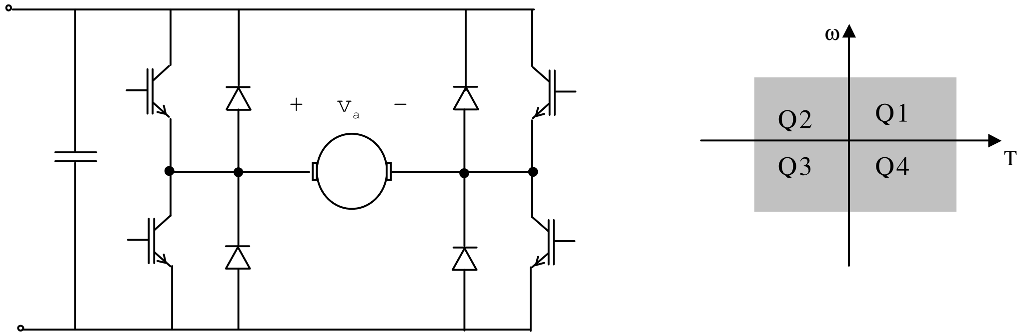
Switch–mode converters normally operate at high frequency. As a result of this, (i) the average output voltage response is significantly faster than the controlled rectifier, in other words the bandwidth of a switch–mode rectifier is higher compared to the controlled rectifier, and (ii) the armature current ripple is relatively less than the controlled rectifier circuit when the same amount of inductance present in the armature circuit. The switch-mode converter is therefore suitable for applications requiring position control or fast response, for example in servo applications, robotics, etc. In terms of quadrant of operations, 3 possible configurations are possible: single quadrant, two–quadrant and four–quadrant converters – these are shown below.



Single-quadrant



Two-quadrant



Four-quadrant

Reference:
N. Mohan, "Electric Drives: An integrative approach", University of Minnesota Printing services, 2000.
N. Mohan, "Power Electronics: Converters, applications and design" John Wiley and Sons, 1995.