Chapter 3 DC Machines

Learning Objectives

- Know fundamental equations for DC machines
- Classify different types of DC machines
- Understand types of speed controls

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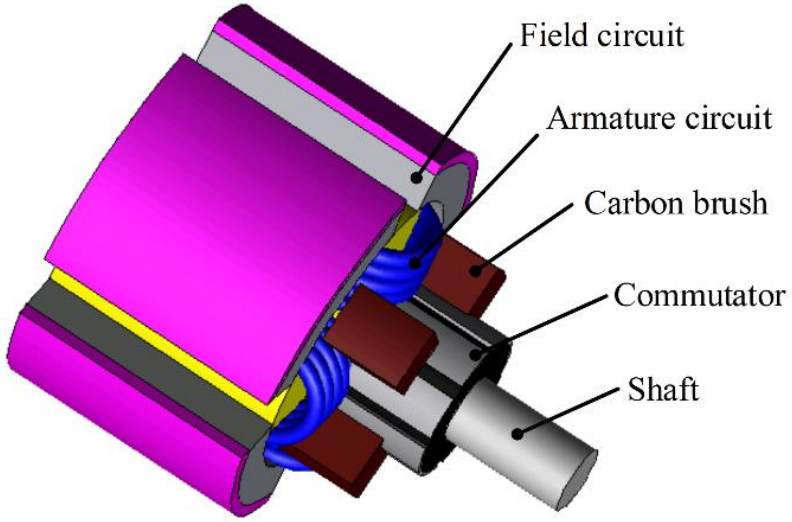
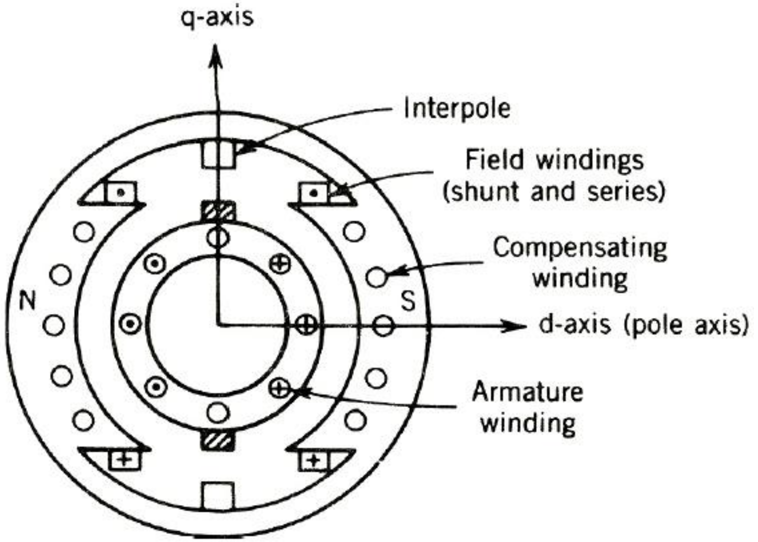
3.1 Fundamentals





- It consists of stator, rotor, commutator and carbon brushes
- The stator is field circuit that incorporates field windings or permanent-magnets (PMs) in order to produce magnetic flux
- The rotor is armature circuit that installs with armature winding
- Upon support by commutator and carbon brushes, the armature current can be switched to flow in bidirectional form

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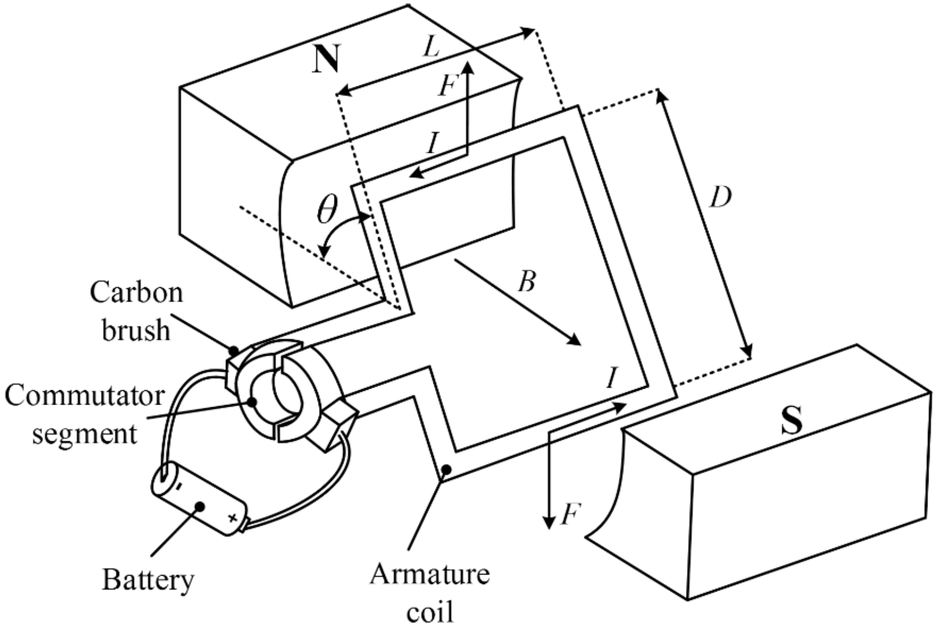
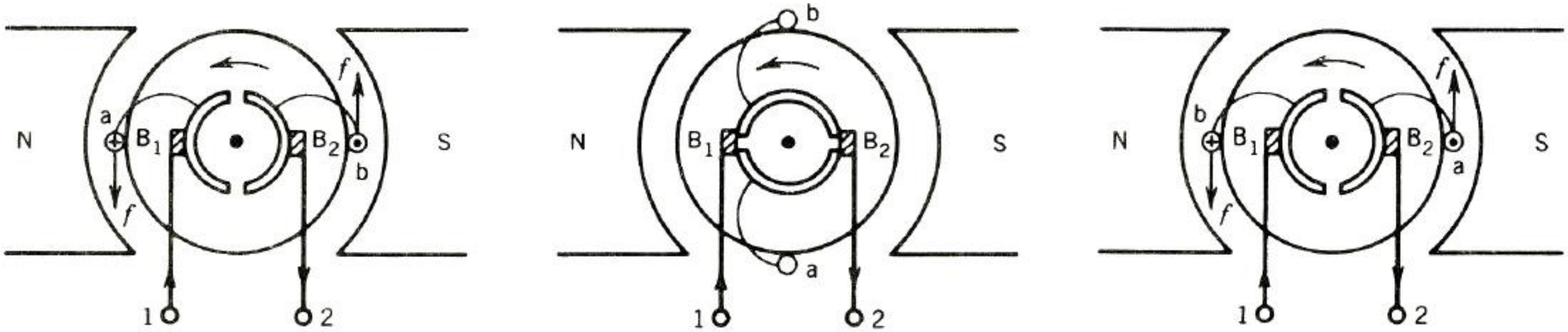
3.1 Fundamentals



- A basic two-pole DC machine is used for illustration
- The armature circuit consists of a simple single-turn coil that is connected to the DC source via a two-segment commutator and a pair of carbon brushes
- The commutator serves to reverse the direction of current flow
- The carbon brushes enables electrical conduction between the rotating commutator and the stationary DC source

3.2 Operating Principle



- Field windings is placed on the stator while armature winding is on rotor
- Current will be fed into the armature through the brushes
- Current will reverse when the turn passes the interpolar where the commutator segments touches the other brushes

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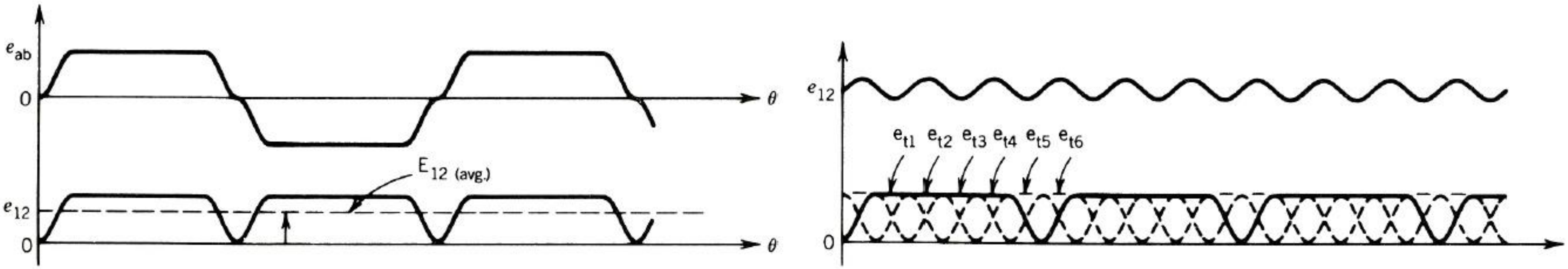
3.2 Operating Principle



- Even though the voltage induced in the turn is alternating, the voltage at the brush terminal is unidirectional
- This unidirectional voltage generally consists of large ripple
- In order to reduced ripples, a large number of turns are placed in several slots

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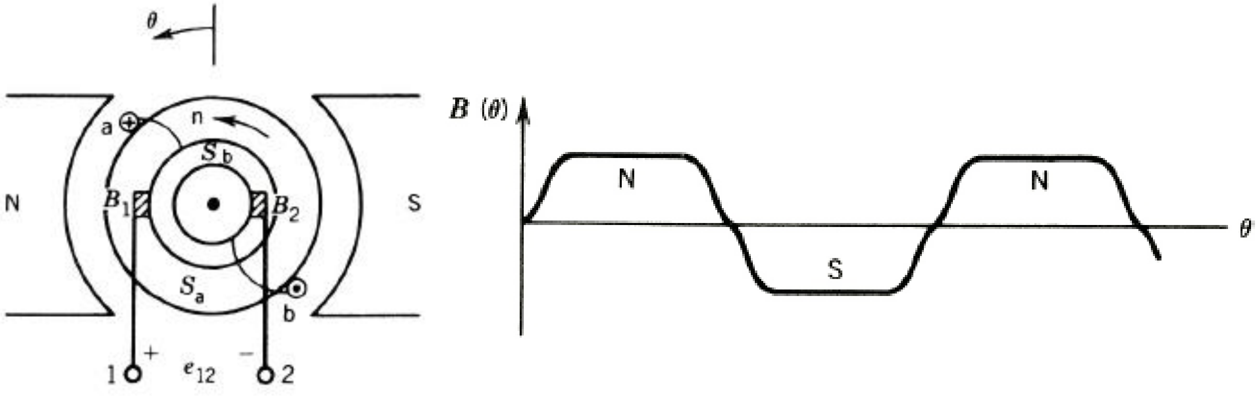
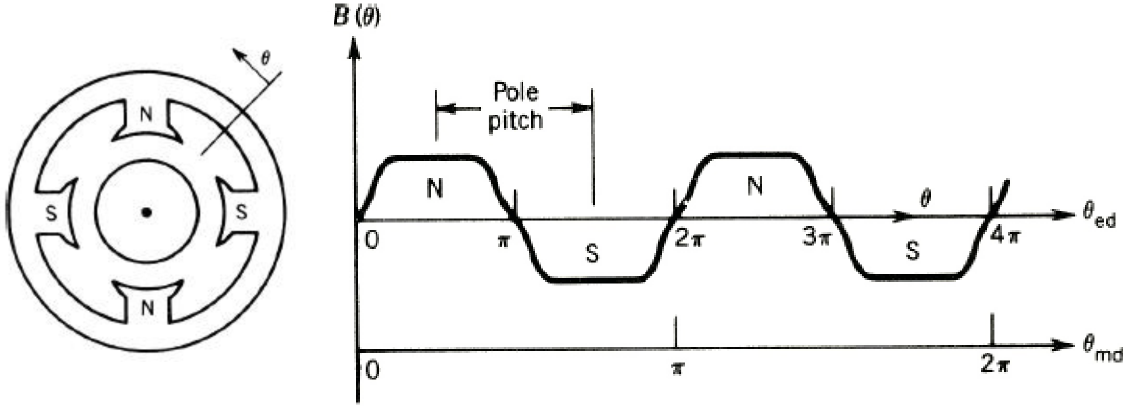
3.2 Operating Principle

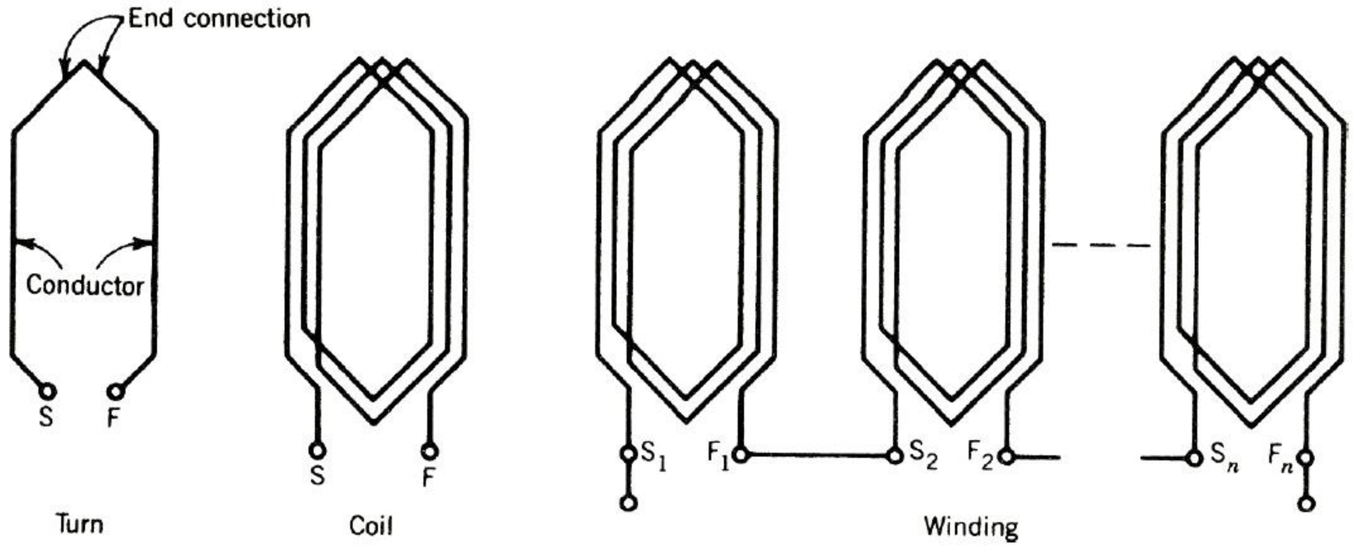




- The resultant MMF wave can make one revolution per cycle of current variation in a two-pole machine
- In a *p*-pole machine, one cycle of current variation will make MMF wave instead rotate by 2 / *p* revolutions
- Distance between the centers of two adjacent poles is known as *pole pitch*

$$One\ pole\ pitch = 180°_{ed} = \frac{360°_{md}}{p}$$

3.2 Operating Principle



- A turn means two conductors are connected to one end by an other
- A coil means several turns are connected in series
- A winding means several coils are connected in series

3.2 Operating Principle

- According to Faraday's Law, average value of induced voltage

$$\bar{e_t} = \overline{2B(\theta)}l\omega_m r$$

$$= \frac{\Phi p}{\pi}\omega_m$$

- Assume total of turns N in the armature winding, voltage induced in all the turns connected in series for one parallel path a will contribute average terminal voltage

$$E_a = \frac{N}{a}\bar{e_t}$$

$$= \frac{Np}{\pi a}\Phi\omega_m$$

$$= K_a\Phi\omega_m$$

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3.2 Operating Principle

- Force acting on a conductor

$$f_c = B(\theta)l\frac{I_a}{a}$$

- Average torque produced by a conductor

\

$$\bar{T_c} = \frac{\Phi I_a}{2\pi a}$$

- Total torque by all conductors in the armature windings

$$T = 2NT_c = \frac{N\Phi I_a}{\pi a}$$

$$= K_a\Phi I_a$$

- Energy conversion can be described as

$$E_a I_a = K_a\Phi\omega_m I_a = T\omega_m$$

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Concept Check 3.1

A four-pole DC machine consists of an armature of radius of 12.5 cm and effective length of 25 cm. The poles cover 75 % of the armature periphery. The armature windings consist of 33 coil, with each coil of 7 turns. The coils are accommodated in 33 slots. The average flux density in each pole is 0.75 T.

(a) Find the armature constant K_a (Ans: 73.53)

(b) Find the induced armature voltage when it rotates at 1000 rpm (Ans: 212.5 V)

(c) Find the electromagnetic torque when the armature current is 400 A (Ans: 811.8 Nm)

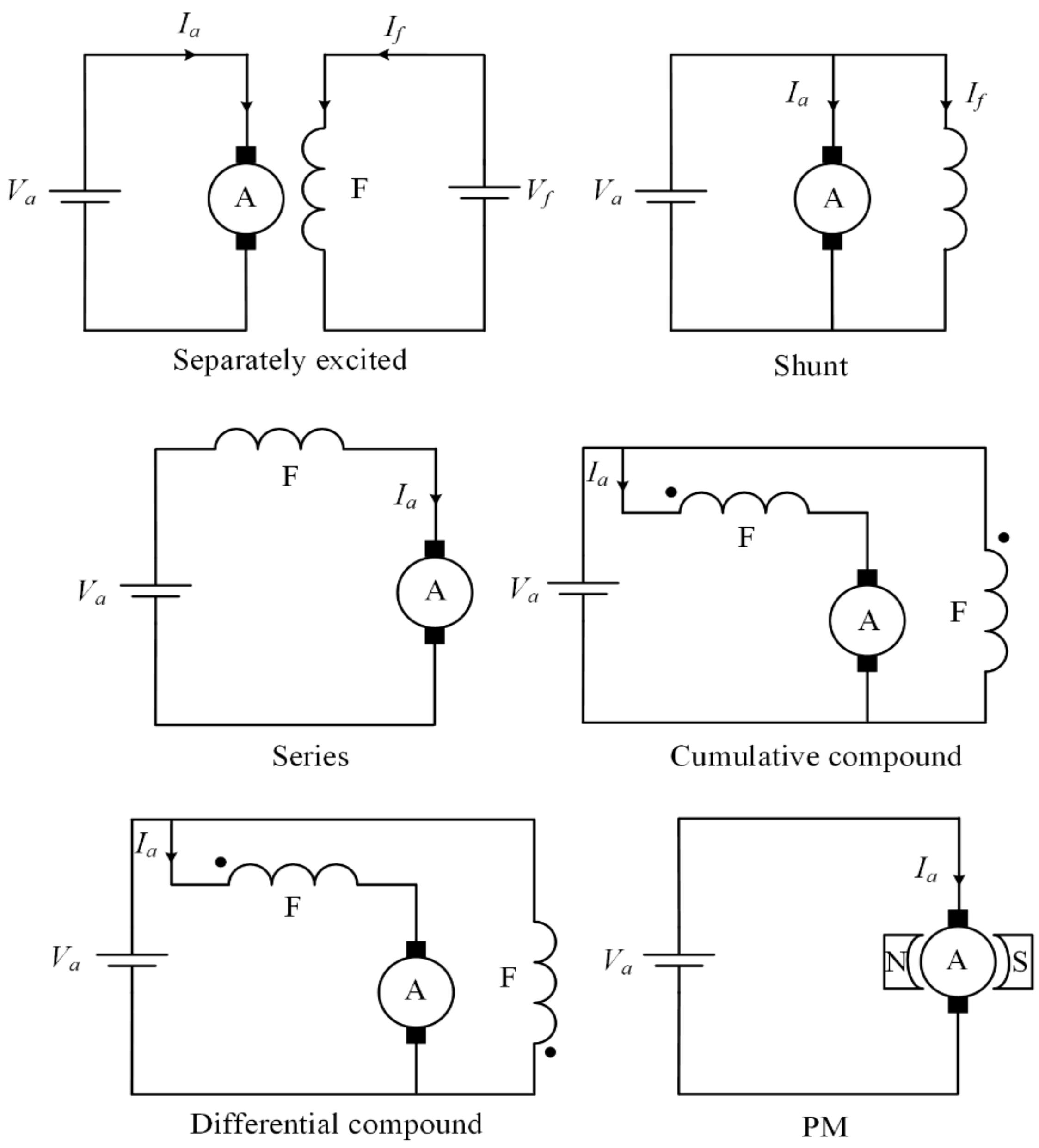
(d) Find the power developed by the armature (Ans: 85 kW)

Concept Check 3.1

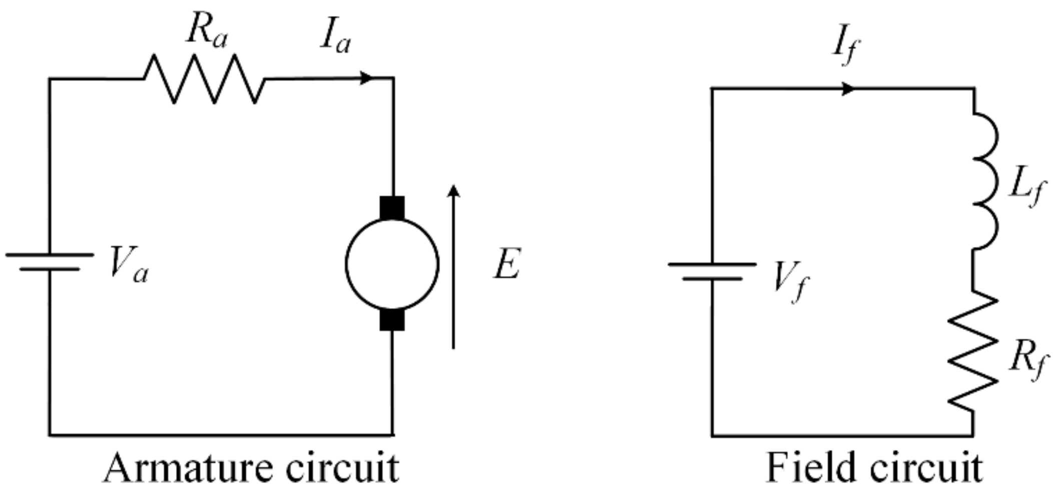
Concept Check 3.1

3.3 Types of DC Machines

- Separately excited DC
- Series DC
- Shunt DC
- Cumulative compound DC
- Differential compound DC
- Permanent-magnet DC



3.4 Separately Excited DC Machine



- A separately excited DC machine is used for illustration
- Consider magnetic flux generated by field circuit is

$$\Phi = K_f I_f$$

where K_f is field constant

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3.4 Separately Excited DC Machine

- Back electromotive force (EMF) generated in DC machine becomes

$$E_a = K_a \Phi \omega_m = K_v I_f \omega_m$$

where K_a is armature constant
K_v is voltage constant

- Hence, armature voltage becomes

$$V_a = \pm E_a + R_a I_a$$

where + is for motor while – is for generator

- Meanwhile, generated torque from excitation of field circuit is

$$T_e = K_a \Phi I_a = K_t I_f I_a$$

where K_t is torque constant

- Output power can be

$$P = T_e \omega_m$$

Motoring

$$P = V_a I_a$$

Regenerative

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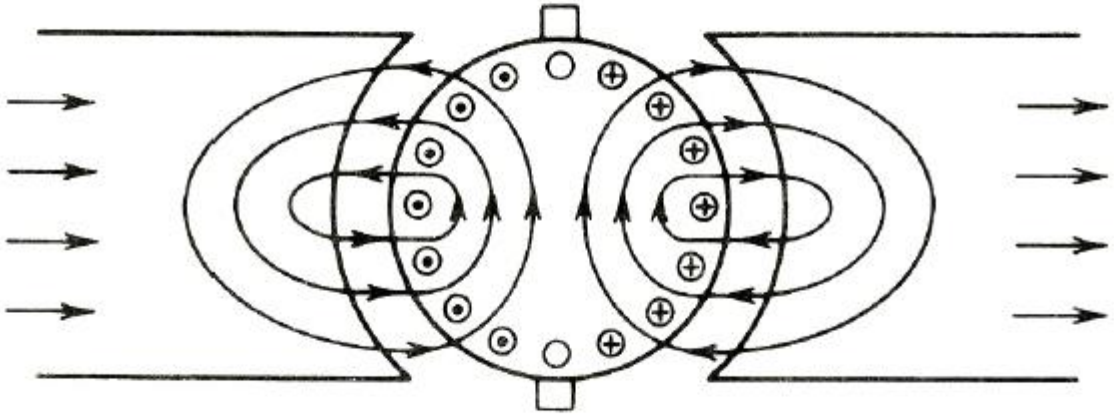
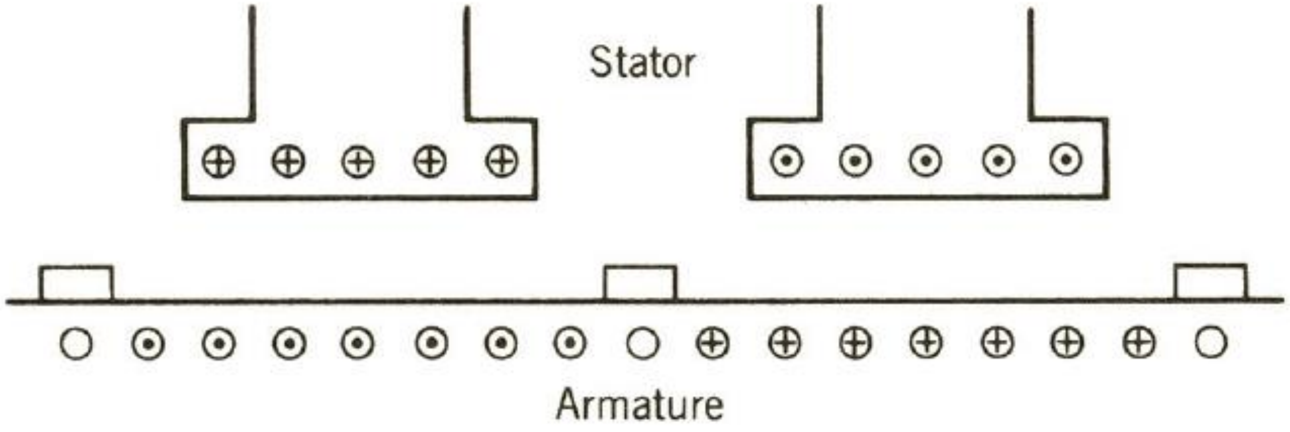
3.5 Armature Reaction



- When current flows in the armature circuit, it produces its own mmf
- The original flux distribution is reduced and known as *armature reaction*
- The net effect of armature reaction can be considered as reduction of field current

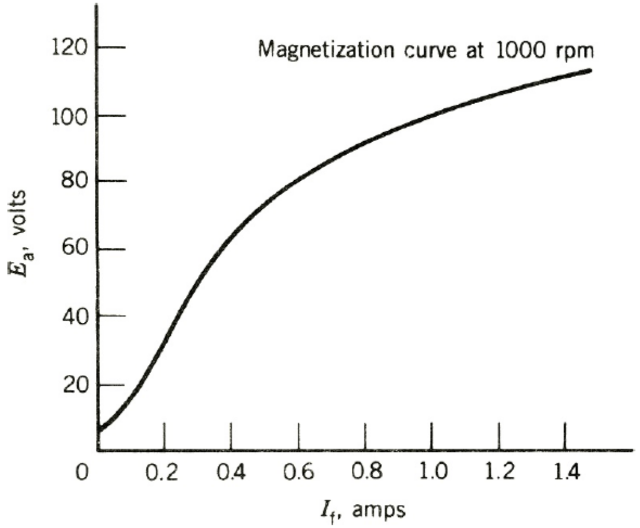
$$I_{f(eff)} = I_{f(actual)} - I_{f(AR)}$$

3.5 Armature Reaction



- The armature mmf distorts and demagnetizes the original flux density distribution
- It shirts zero flux density region and leads to sparking
- The armature reaction can be neutralized by a compensating winding

Concept Check 3.2



A 12 kW, 100 V, 1000 rpm dc shunt generator consists of armature resistance of 0.1 Ω, shunt field winding resistance of 80 Ω and field turns of 1200 turns per pole. The rated field current is 1 A. The magnetization characteristics at 1000 rpm is shown above. The machine is operated as a separately excited dc generator at 1000 rpm with rated field current.

(a) Find the terminal voltage at full load (Ans: 88 V)
(b) If the armature reaction is at full load of equivalent of 0.06 field amperes, find the full-load terminal voltage (Ans: 86 V)
(c) Find the field current so as V_t = 100 V at full-load condition (Ans: 1.46 A)

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Concept Check 3.2

Concept Check 3.2

Concept Check 3.3

The DC machine in Concept Check 3.2 is now provided with series winding to become a compound DC machine. It is required to provide a terminal voltage of 100 V at no-load as well as full-load by cumulatively compounding the generator. Assume the series winding consists of resistance of 0.01 Ω.

If the shunt field winding consists of 1200 turns per pole, how many series turns per pole are required to obtain zero voltage regulation, i.e., full load? (Ans: 5.04 turns per pole)

Concept Check 3.3

Concept Check 3.3

Concept Check 3.4

The DC machine (12 kW, 100 V, 1000 rpm) in Concept Check 3.2 is connected to a 100 V DC supply and operated as a DC shunt motor. At no-load condition, the motor runs at 1000 rpm with armature of 6 A.

(a) Find the value of resistance of the shunt field control rheostat (Ans: 21 Ω)

(b) Find the rotation losses at 1000 rpm (Ans: 596.4 W)

(c) Find the speed, electromagnetic torque and efficiency at rated condition if the air gap remains the same as that at no-load (Ans: 885.3 rpm; 113.9 Nm; 82.4 %)

(d) Repeat (c) if the air gap flux is reduced by 5 % because of armature reaction (Ans: 931.9 rpm; 108.2 Nm; 82.4 %)

(e) Find the stating torque if armature is limited to 150 % of its rated value (Ans: 170.8 Nm)

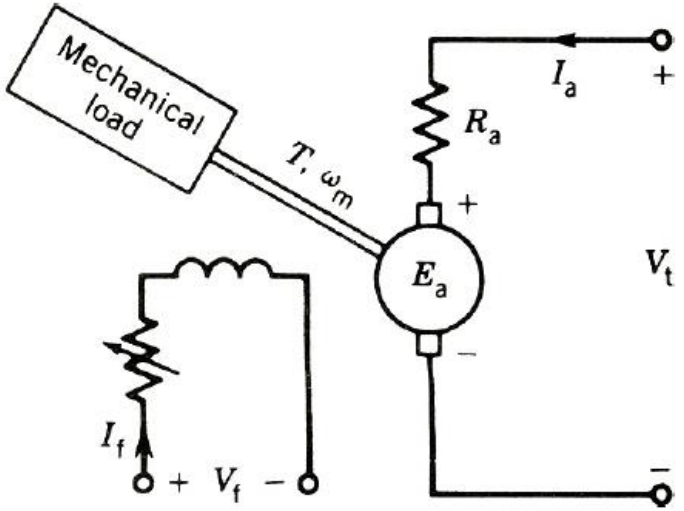
(f) Repeated (e) if armature reaction is considered to be 0.16 A (Ans: 160.7 Nm)

Concept Check 3.4

Concept Check 3.4

Concept Check 3.4

3.6 Speed Control

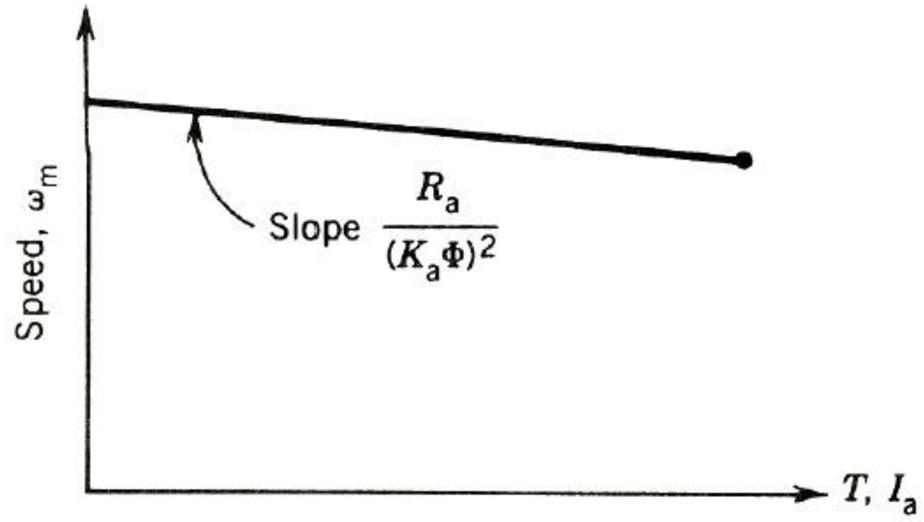


- DC motors are used to drive mechanical loads with speed controllability
- Consider a separately excited DC motor

$$E_a = K_a\Phi\omega_m = V_t - I_aR_a \qquad\qquad T = K_a\Phi I_a$$

$$\omega_m = \frac{V_t}{K_a\Phi} - \frac{R_a}{(K_a\Phi)^2}T$$

3.6 Speed Control



- The drop in speed as applied torque increases is small, and hence providing a good speed regulation
- Speed control can be achieved based on
  1. Armature voltage control
  2. Field control
  3. Armature resistance control

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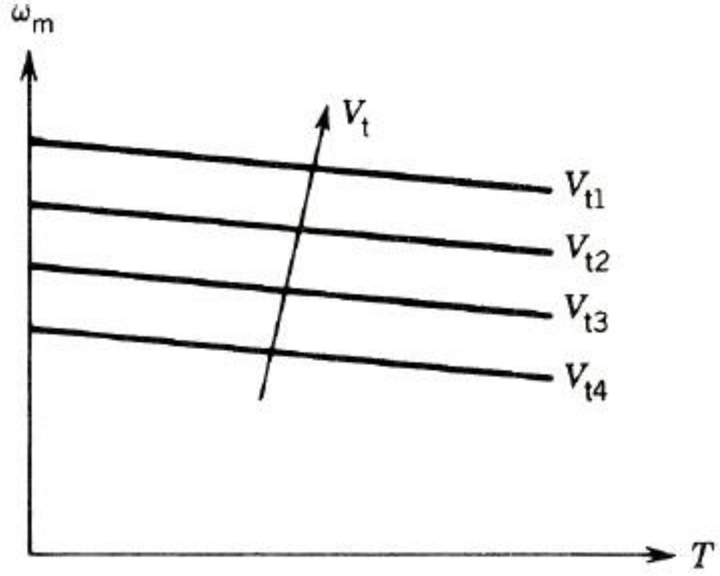
3.6.1 Armature Voltage Control



- Armature circuit resistance and field current are kept constant
- Armature terminal voltage is varied to change the speed linearly
- It provides smooth control from zero to base speed
- However, it is expensive because it needs a variable DC supply

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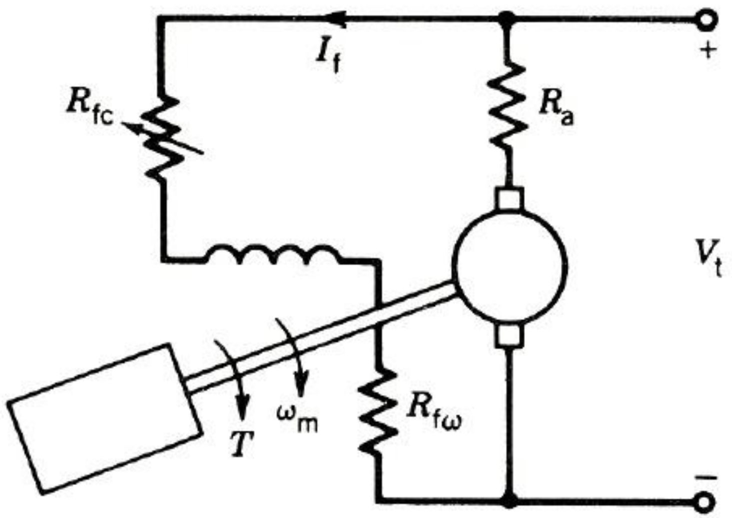
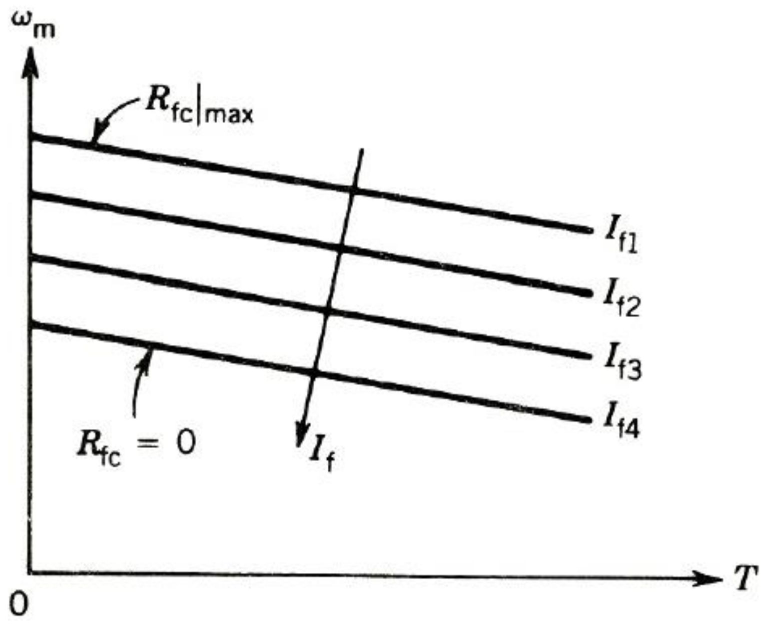
3.6.1 Field Weakening





- Armature circuit resistance and terminal voltage are kept constant
- Field current is varied to change the speed linearly
- It can be achieved by using a field circuit rheostat
- Field current control is also known as *Field Weakening*

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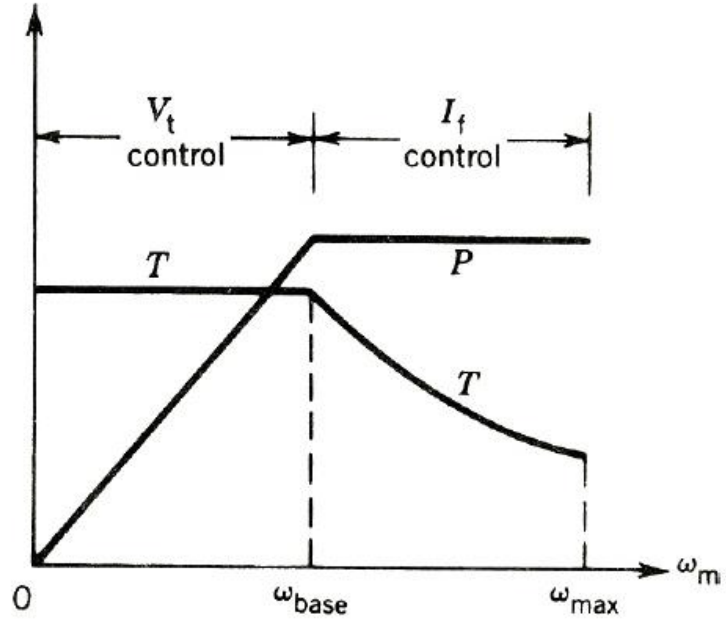
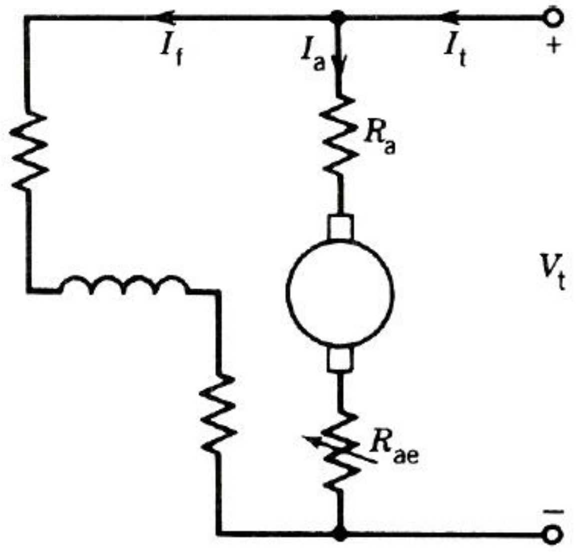
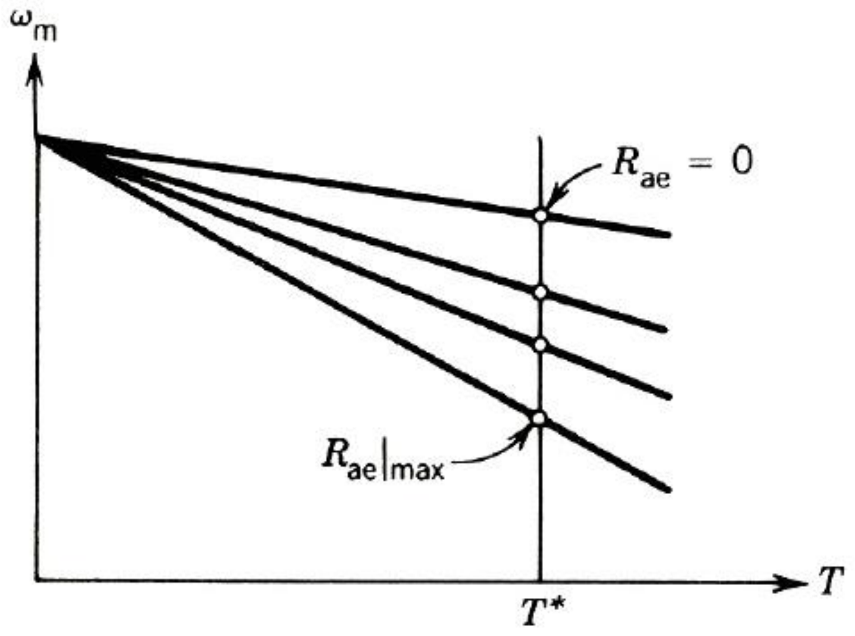
3.6.3 Combined Control



- Speed control from zero to base speed is obtained by armature voltage control, while this region is known as constant-torque region
- At the base speed, the armature terminal voltage is at rated value
- Speed control beyond the base speed is obtained by field weakening, while this region is known as constant-power region

3.6.4 Armature Resistance Control





- Armature terminal voltage and field current are kept constant
- The speed is controlled by changing resistance in the armature circuit

$$\omega_m = \frac{V_t}{K_a\Phi} - \frac{R_a + R_{ae}}{(K_a\Phi)^2}T$$

- Less efficient than other two methods and more expensive than field control

Concept Check 3.5

A variable-voltage source is supplied to a DC motor. By armature terminal voltage control from 0 to 500 V, the drive speed is varied from 0 to 1500 rpm, i.e., base speed.

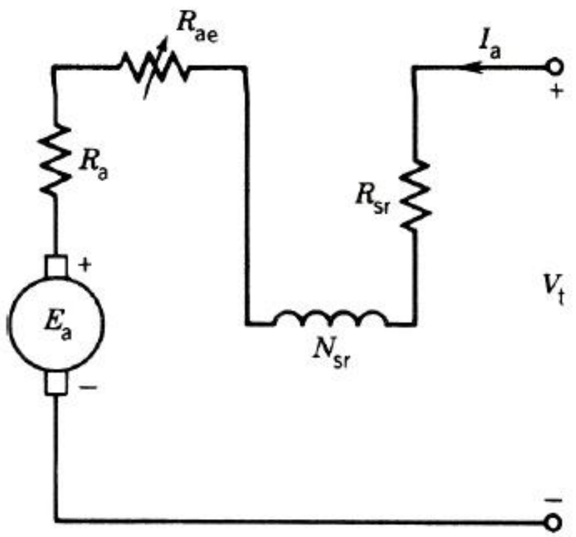
(a) Find the motor armature current if the torque is held constant at 300 Nm (Ans: 94.2 A)

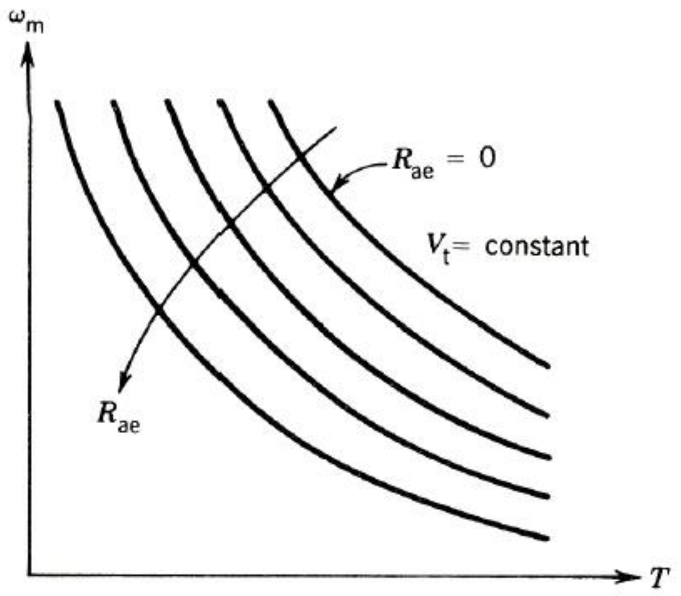
(b) Field weakening is applied when the speed is beyond its base speed while the armature voltage is held constant at 500 V. Find the torque available at a speed of 3000 rpm if the armature current is held constant at the value at (a) (Ans: 150 Nm)

Concept Check 3.5

Concept Check 3.5

3.6.5 Series Motor





- An external resistance is connected in series to control the speed

$$\omega_m = \frac{V_t}{\sqrt{K_{sr}}\sqrt{T}} - \frac{R_a + R_{sr} + R_{ae}}{K_{sr}}$$

- A high torque is obtained at low speed and low torque at high speed

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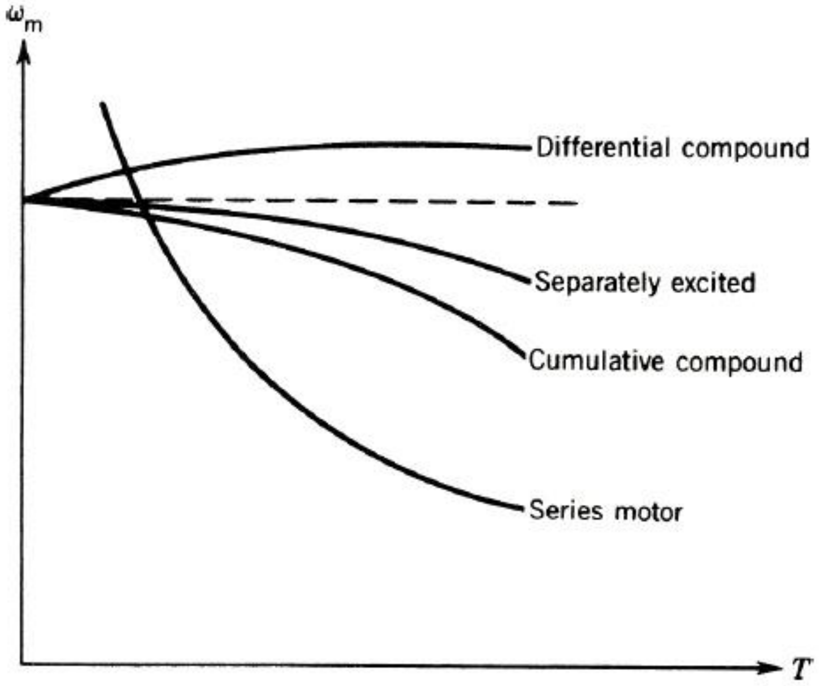
3.6.6 Types of Motor Controls



- Series can provide a variable speed characteristic over a very wide range

Concept Check 3.6

A 220 V, 7 hp series motor is connected to a fan. It draws 25 A and spins at 300 rpm when it is connected to a 220 V supply with no external resistance. The required torque is proportional to the square of the speed. It consists of R_a = 6.0 and R_{sr} = 0.4 . Neglect armature reaction and rotational loss.

(a) Find the power delivered to the fan and the torque developed by the machine (Ans: 6.54 hp; 155.2 Nm)

(b) If the speed is reduced to 200 rpm by adding a resistance in armature circuit, find the value of this resistance and the power delivered by the fan (Ans: 69.0 Nm; 1.94 hp)

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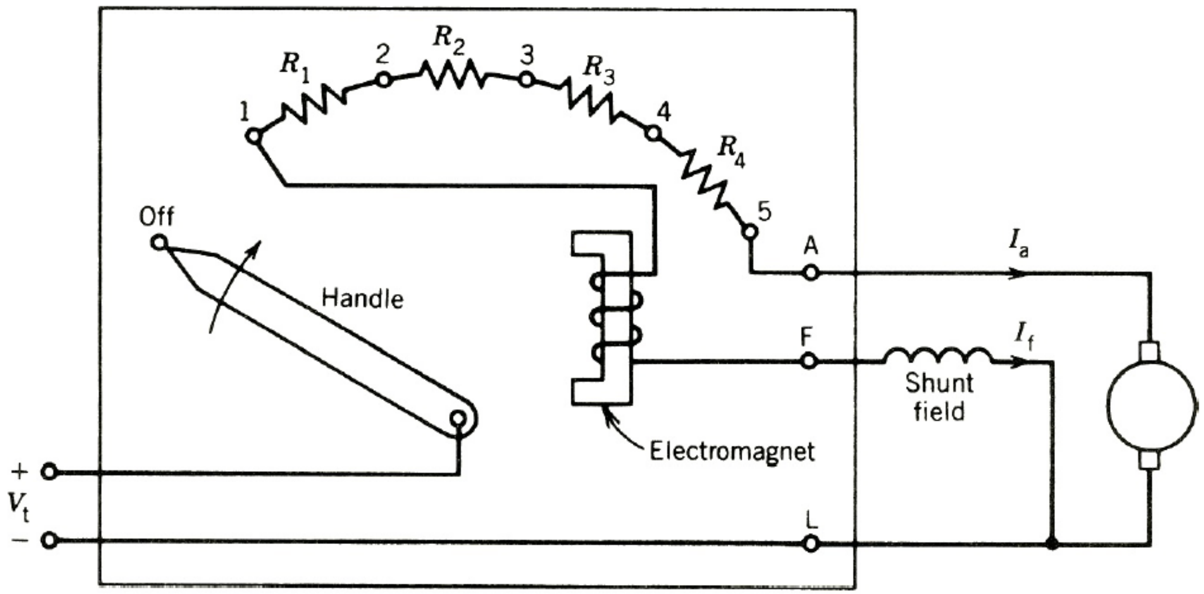
Concept Check 3.6

Concept Check 3.6

3.7 Starting Resistance



- If DC motor is connected to a DC source directly, the starting current will be too large
- An external resistance is purposely added when starting a DC motor
- Since back EMF increases as speed, the external resistance can be gradually taken off

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Concept Check 3.7

A 10 kW, 100 V, 1000 rpm DC machine has R_a = 0.1 Ω and connected to a 100 DC source

(a) Find the starting current if no starting resistance is used (Ans: 1000 A)

(b) Find the value of the starting resistance if the starting current is limited to twice of the rated current (Ans: 0.4 Ω)

(c) By using a starter box, the DC machine is to be operated as a motor. Find the values of required resistances such that the armature current is kept to be within 100 to 200 % of the rated value during starting up (Ans: 0.25 Ω; 0.125 Ω; 0.025 Ω)

Concept Check 3.7

Concept Check 3.7