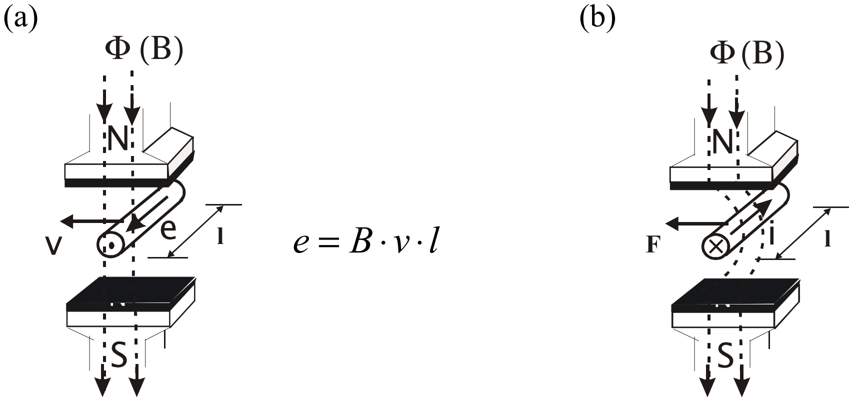
INTRODUCTION TO DC MOTORS

1. Generation electromotive force and mechanical force

Fig.1 illustrate the generation of electromotive force (EMF) voltage ***e***, and mechanical force ***F***. Symbols: ***B*** – magnetic flux density, ***Φ*** – magnetic flux, ***i*** – current, ***v*** - speed



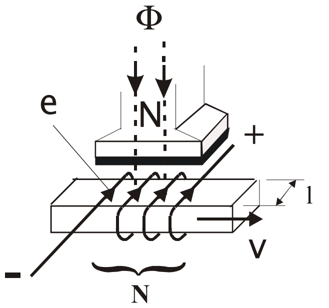
$$e = B \cdot v \cdot l$$

$$F = B \cdot i \cdot l$$

Fig.1 Generation of: (a) EMF ***e*** (**right** hand rule), (b) force ***F*** (**left** hand rule)

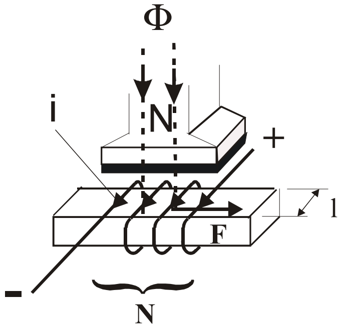
Fig.2 shows linear machines where in Fig.2.b is illustrated the generation of EMF ***e***, in Fig. 2.b – generation of mechanical force ***F***, and in Fig.2.c – linear generator where the both ***e*** and ***F*** are produced if the winding circuit consisting of ***N*** turns is closed through the load impedance $\boldsymbol{Z_l}$.

(a)



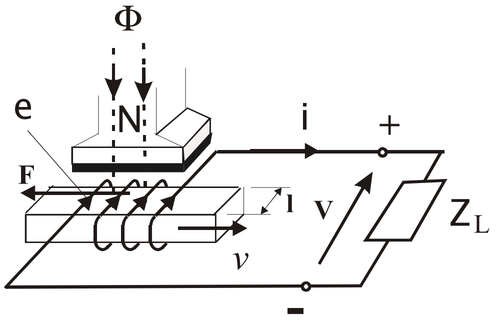
$$E = B \cdot v \cdot l \cdot N = e \cdot N$$

(b)



$$F = B \cdot i \cdot l \cdot N$$

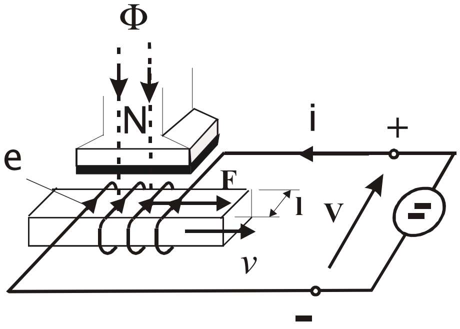
(c)



$E = e \cdot N$

$E > V$ generator

(d)



$E < V$ motor

Fig.2 Linear electric machines: (a) generation of voltage ***e***, (b) generation of force ***F***, (c) linear generator, (d) linear motor

2. Linear DC motor with permanent magnets

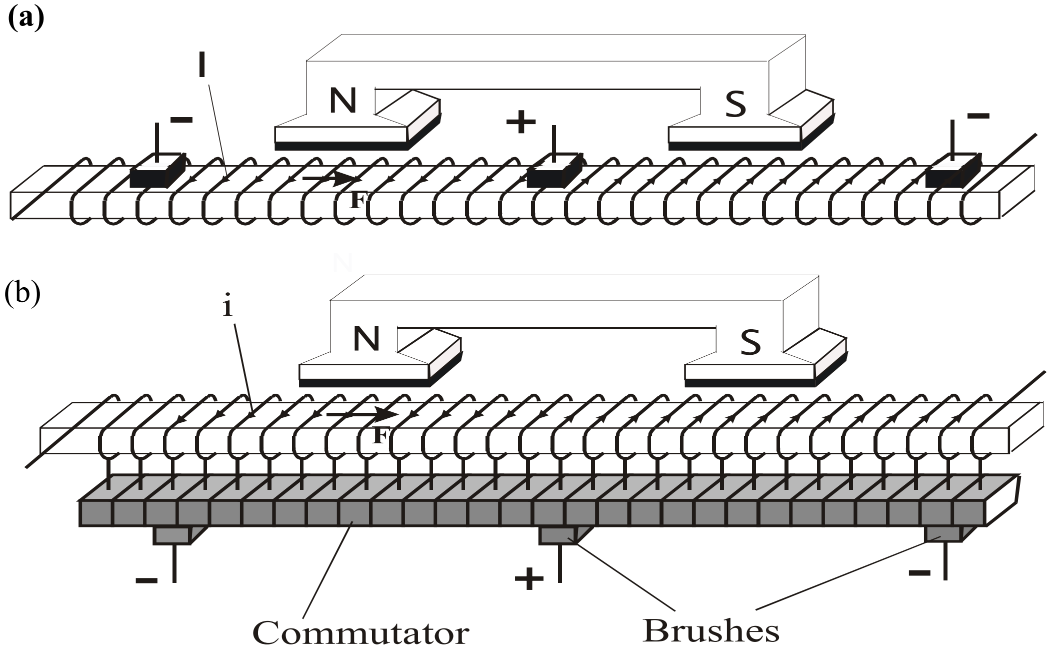


Fig.3.a Brushes placed directly on the wire, b. Brushes placed on the commutator

3. Rotating motor

- Motor with toroidal rotor

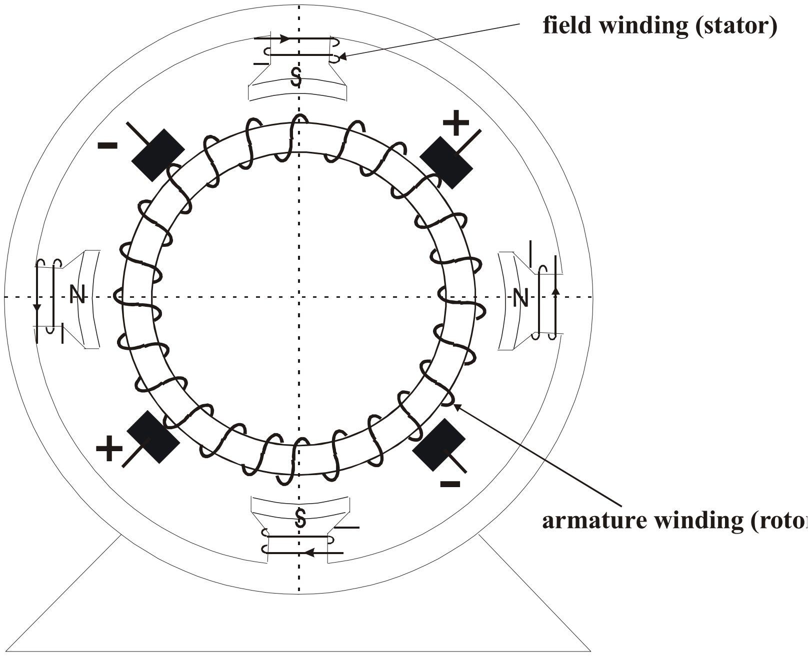


Fig.4 Rotating DC motor

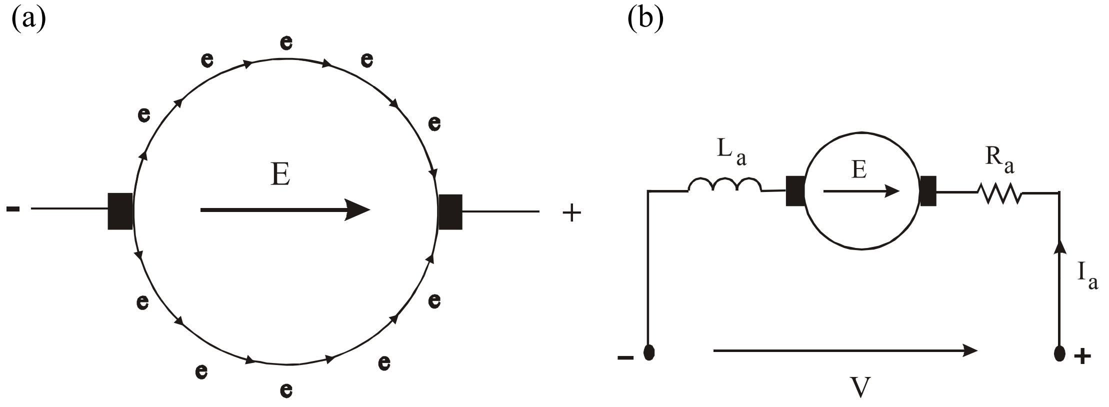

(a)
(b)

Fig.5.(a) Armature winding after removing of toroidal core, (b) diagram of the armature circuit

DIRECT CURRENT MACHINES

1. Construction and principle of operation

A scheme of a primitive, single coil winding dc machine with two magnetic poles is shown in Fig.1. The stator has salient poles that are excited by field winding supplied by the dc source. The field current $\boldsymbol{I_f}$ produces the flux $\boldsymbol{\Phi_f}$. The rotor consists of single-turn coil, which is connected to two semicircle copper segments (moveable with the coil), which together with two (stationary) ***"brushes"*** constitute the ***commutator***. If the coil rotates the emf is induced in both sides of the coil with the direction that can be determined by the right-hand rule. After one half of turn the direction of the induced voltage in the coil sides changes, but due to the commutator the polarity of the voltage across the brushes remains unchanged.

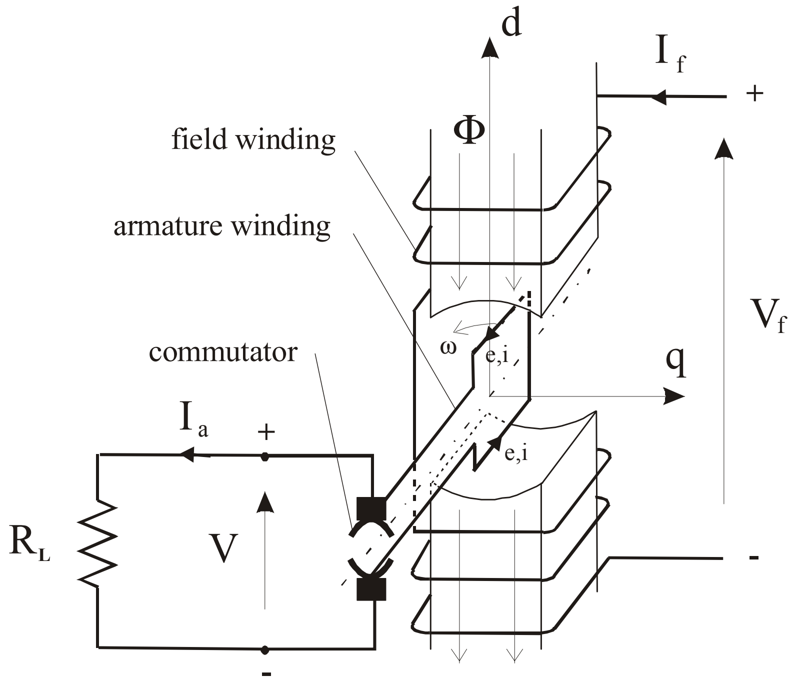


Fig.1 A scheme of the single-turn dc machine

The flux distribution in the air gap is symmetrical about the pole axis called ***direct axis*** or ***d-axis*** (Fig.2). The brushes are placed along ***quadrature*** (or ***q***) ***axis***, perpendicular to the ***d-axis***. The voltage induced in the coil changes with respect to θ angle as shown in Fig.3.b. This voltage is rectified be the commutator, so its shape, when measured across the brushes is as shown in Fig.3.c. When more multi-turn coils are wound on the rotor (Fig.2), each coil is connected to the copper segment of the commutator (Fig.2.b) and the rectified voltage across the brushes is changing more smoothly (Fig.3.d).

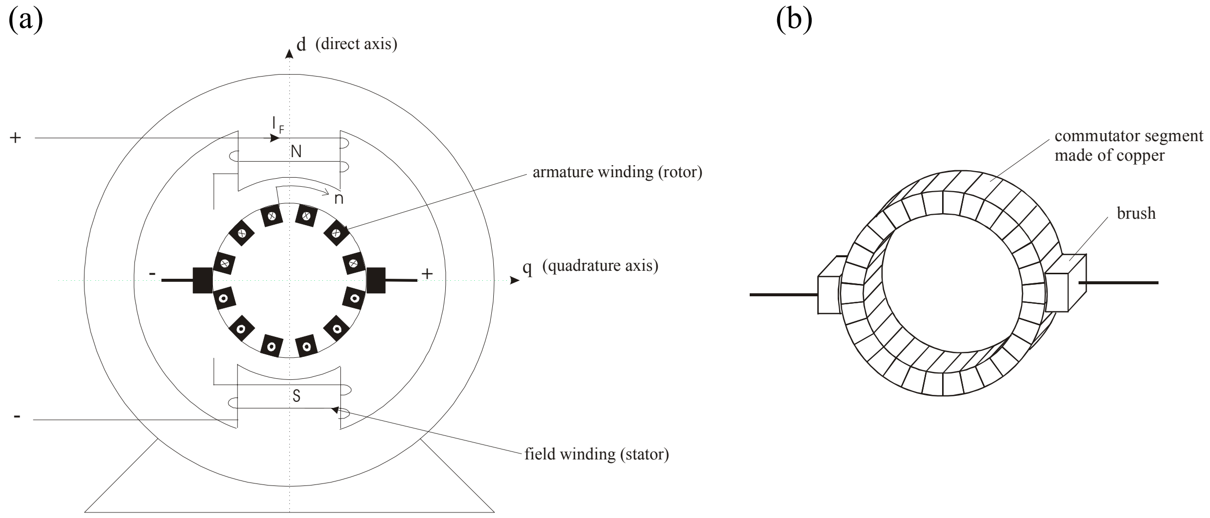
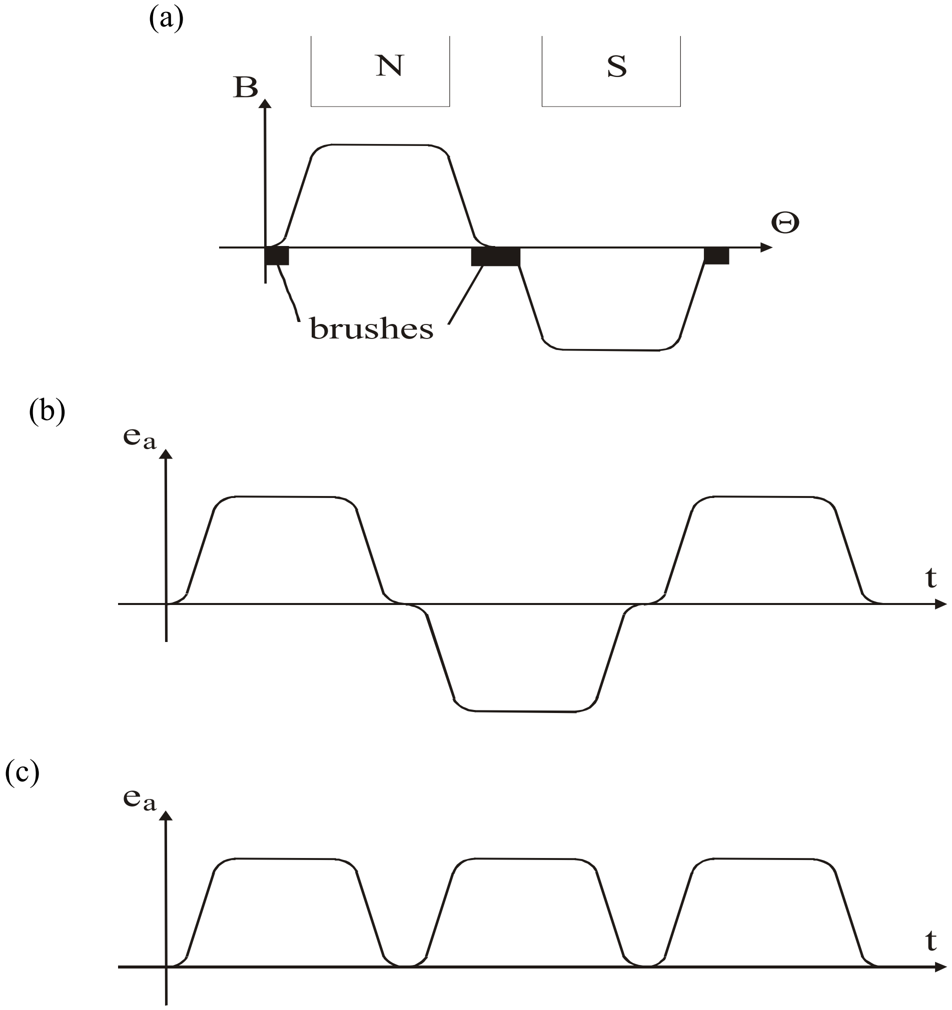


Fig.2.a A scheme of the multi-coil dc machine; b - commutator



(d)

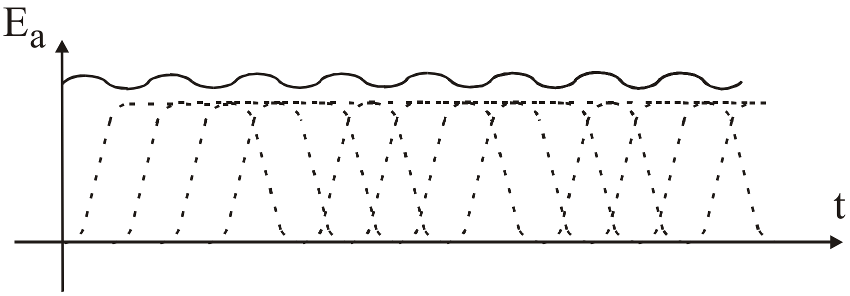


Fig.3.(a) Distribution of the magnetic flux density on the rotor circumference; waveforms of: (b) the voltage induced in the coil, (c) voltage across the brushes – for single-coil armature winding; (d) voltage waveform across the armature terminals for multi-turn armature winding

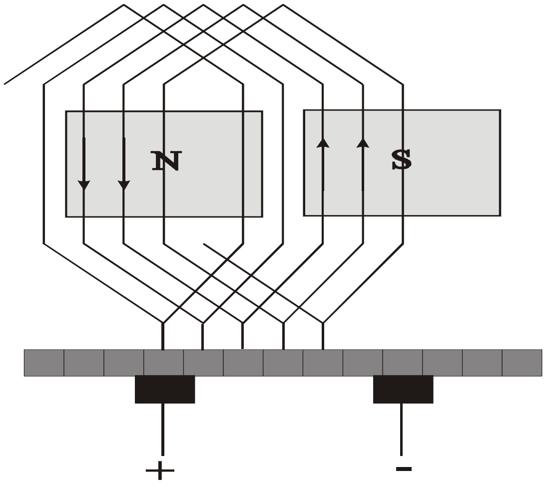


Fig.4 Lap-type winding of the armature

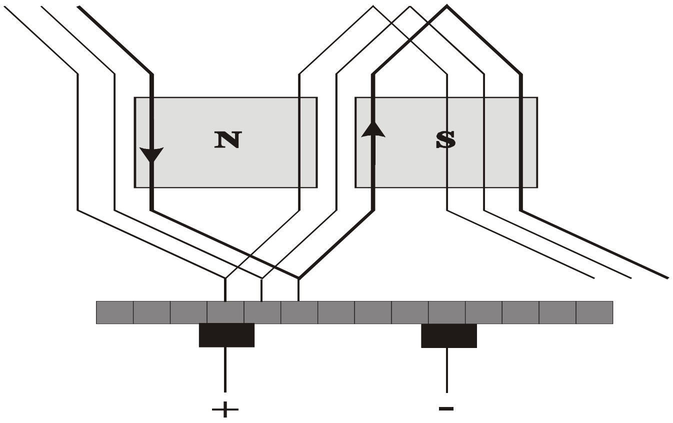


Fig.5 Wave-type winding of the armature

The coils are connected in series and there are no end terminals. There are two types of armature winding:

- Lap winding (Fig.4), and
- Wave winding (Fig.5).

Fig.6 shows the circuit diagram of the dc machine with both windings:

- field winding and
- armature winding.

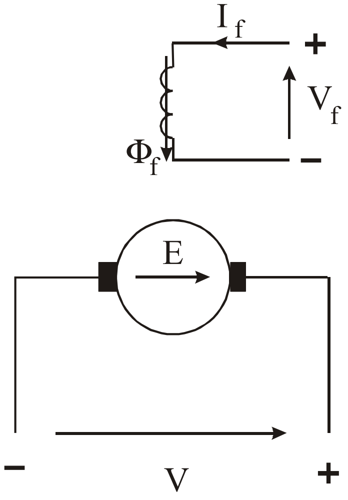


Fig.6 Circuit diagram of the dc machine

The induced emf in one side of the coil is:

$$e = Blv \tag{1}$$

where: ***B*** is the flux density in the air gap,
l is the active length of the coil side,
v is the speed of the coil related to the flux density ***B***.

For multi-coil winding the electromotive force across the brushes is:

$$E = K\omega\Phi_f \tag{2}$$

where: ***K*** - is the constant,
Φ_f - is the flux produced by the field winding,
ω - is the angular speed of the rotor.

When the current ***i*** flows in the coil it is affected by the force

$$f = Bli \tag{3}$$

For multi-coil winding the torque acting on the rotor is

$$T = KI\Phi_f \tag{4}$$

2. Classification of dc machines

The field circuit and the armature circuit can be interconnected in various ways:

- in parallel - a ***shunt field winding*** and
- in series - a ***series field winding***

Also the field poles can be excited by two field windings. The various connections of the field circuit and armature circuit are shown in Fig.7. These various connections provide a wide variety of performance characteristics, what is an outstanding advantage of dc machines. There are following types of dc machines:

- separately excited dc machine (Fig.7.a),
- self-excited dc machines: a) – shunt dc machine (Fig.7.b)
  b) – series dc machine (Fig.7.c)
  c) – compound dc machine (Fig.7.d)

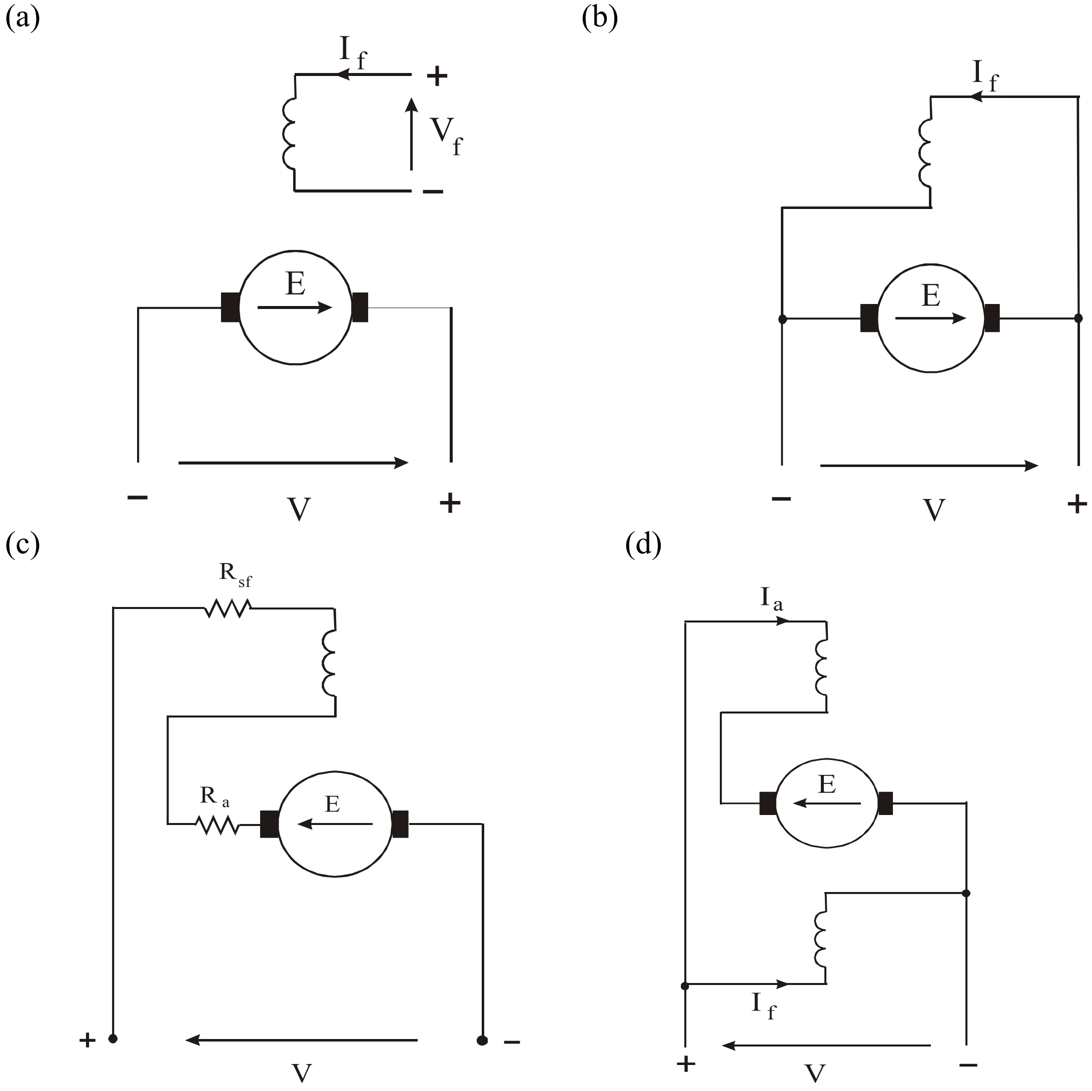


Fig.7 Types of dc machines: (a) - separately excited machine, self-excited dc machines: (b) – shunt dc machine, (c) – series dc machine, (c) – compound dc machine

3. Separately excited dc motor (and shunt motor)

The dc machines, like other machines can operate both as a generator and as a motor. When it operates as a generator, the input to the machine is mechanical power and the output is electrical power. When the dc machine operates as a motor, the input to the machine is electrical power and the output is mechanical power. If the armature and the field winding are connected to a dc supply the motor will develop electromagnetic torque:

$$T = K\Phi_f I_a \tag{22}$$

and the mechanical power:

$$\begin{aligned} P_m &= \frac{T}{\omega_m} = \frac{K\Phi_f I_a}{\omega_m} \\ &= EI_a \end{aligned} \tag{23}$$

A schematic diagram of a shunt dc motor is shown in Fig.8. The equations for motor circuit are as follows:

$$V = E + R_a I_a \tag{24}$$

and

$$I = I_f + I_a \tag{25}$$

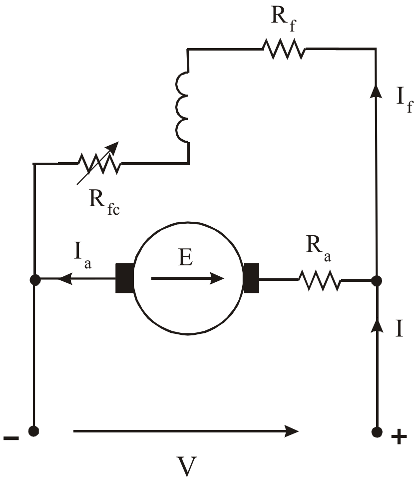


Fig.8 circuit diagram of shunt dc motor

Combining equation 24 and 9 we get:

$$n = \frac{V - R_a I_a}{K_E \Phi_f} \tag{26}$$

If $\Phi_f \sim I_f$ then:

$$n = \frac{V - R_a I_a}{K_{fE} I_f} \tag{27}$$

According to Eq.27 if the terminal voltage ***V*** and the field current I_f are kept constant the speed-current (or speed-torque – since $T \sim I_a$) characteristic is as shown in Fig.9.

Equation 27 suggests that speed control in a shunt motor can be achieved by the following methods:

1) Armature voltage control (***V***)
2) Field control (Φ or I_f)
3) Armature resistance control (R_a).

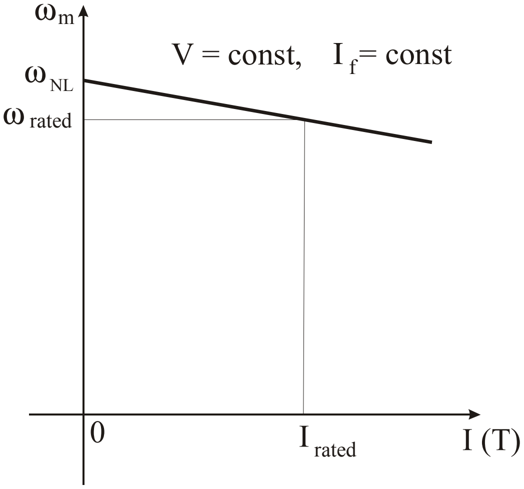


Fig.9 Mechanical characteristic of shunt dc motor

Armature voltage control

In this method the armature circuit resistance remains unchanged, the field current is kept constant, and the armature terminal voltage is varied to change the speed. The family speed-torque characteristics at various voltages are shown in Fig.10. As the voltage ***V*** decreases, the speed decreases linearly. This method is applied for the separately excited motor. For shunt motor the change of terminals voltage influences also the field current.

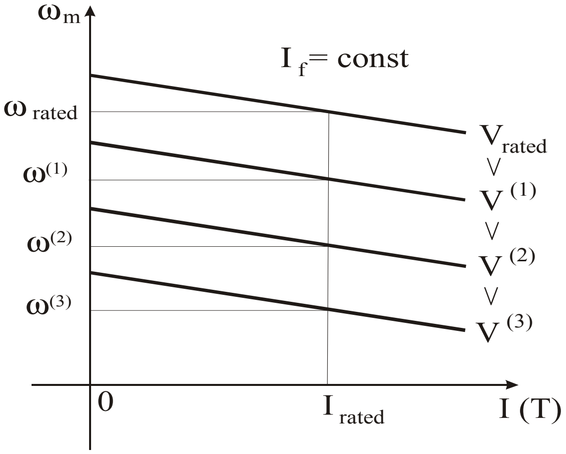


Fig.10 Speed control by the change of armature voltage ***V***

Field control

In this method the armature circuit resistance $\boldsymbol{R_a}$ and the terminal voltage ***V*** remain fixed and the speed is controlled by varying the current $\boldsymbol{I_f}$ of the field circuit. This is normally achieved in shunt motor by using a field circuit rheostat $\boldsymbol{R_{fc}}$ as shown in Fig.8. Fig.11 shows the speed-torque characteristics drawn for different field currents. If the field current decreases the speed will increase.

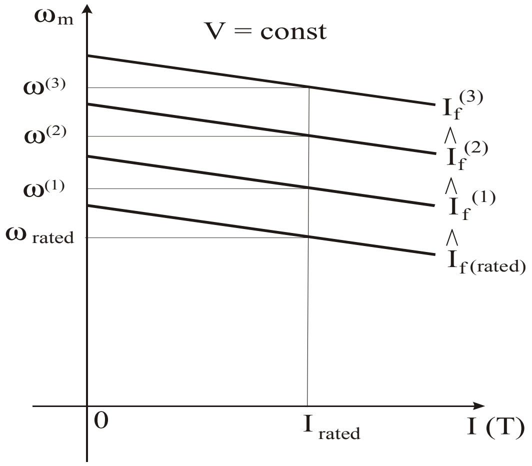


Fig.11 Speed control by the change of field current $\boldsymbol{I_f}$

Armature resistance control

In this method the armature terminal voltage ***V*** and the field current $\boldsymbol{I_f}$ (hence $\boldsymbol{\Phi_f}$) are kept constant at their rated values. The speed is controlled by changing resistance in the armature circuit. An armature circuit rheostat $\boldsymbol{R_{ac}}$ as shown in Fig.12 is used for this purpose. The speed-torque characteristics for various values of the external armature circuit resistance are shown in Fig.13. When the resistance $\boldsymbol{R_{ac}}$ goes up the rotor speed goes down.

Armature resistance control is simple to implement. However, this method is less efficient because of losses in $\boldsymbol{R_{ac}}$.

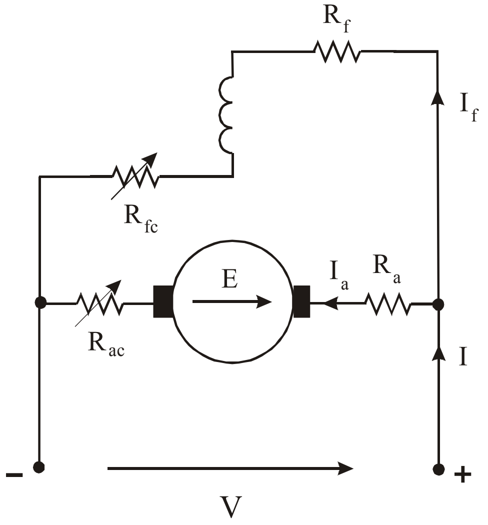


Fig.12 Circuit diagram of the shunt dc motor with armature rheostat $\boldsymbol{R_{ac}}$

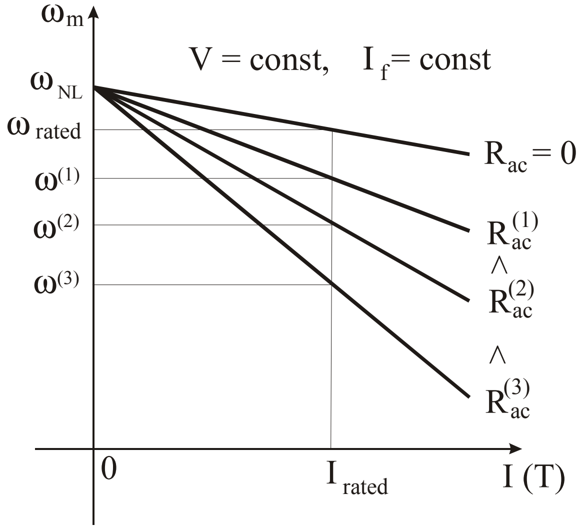
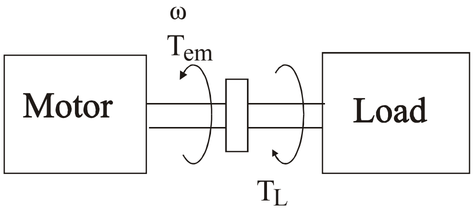


Fig.13 Speed control by the change of resistance $\boldsymbol{R_{ac}}$ in the armature circuit

4. Four quadrant operation of dc motors



Mechanical power: $P = T_{em}\omega$

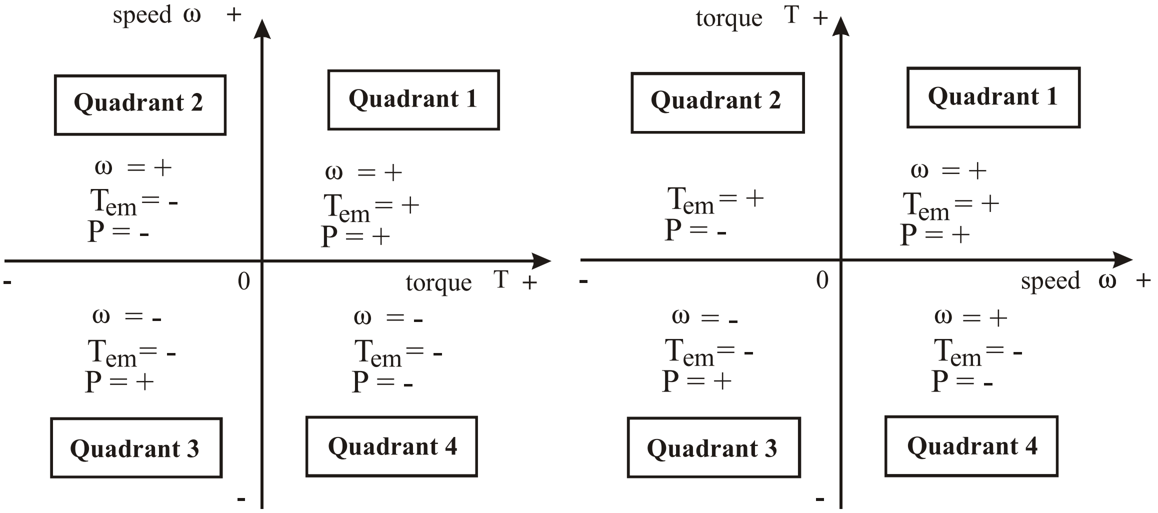


Fig.14 Four quadrant operation of electric drives

The motor in some industrial drives, (in electric locomotives, for example) may run clockwise or counter-clockwise, and the torque may be with or against the direction of rotation. In general, the speed and torque may be positive or negative. This can be illustrated graphically by means of a four-quadrant diagram shown in Fig.15. Suppose, the separately excited DC machine is considered. It may operate in four quadrants as:

- motor: **quadrant 1**- torque and speed are directed clockwise (CW) (Fig.17.a),
- generator or brake: **quadrant 4**- torque – CW, speed - directed counter clockwise (CCW) (**generator** - Fig.18.b and Fig.16 – dashed line; **brake** – Fig.17.c and Fig.16 – solid line),
- motor: **quadrant 3** - torque and speed - CCW (Fig.16 - dashed line),
- generator or brake: **quadrant 2** - torque – CCW, speed - CW (**generator** - Fig.17.b and Fig.16 – solid line; **brake** – Fig.18.c and Fig.16 – dashed line).

If the armature voltage is fixed then the complete torque-speed characteristic (Fig.17 – solid line) cover three quadrants: 1 – motor, 2 – brake, 3 – generator. If the armature voltage is reversed the dashed line illustrates the motor operation in quadrants: 2 – generator, 3 – motor, 4 – brake.

Example: The permanent magnet DC motor drives a battery-operated electric car; three modes of operation:

1) **Quadrant 1** – the car accelerates to full speed in a forward (CW) direction, up a steep hill **(Fig.16 – solid line**, and Fig.17.(a)) – electric power P_{el} directed to the motor and mechanical power P_m (on the rotor shaft) directed out of motor,

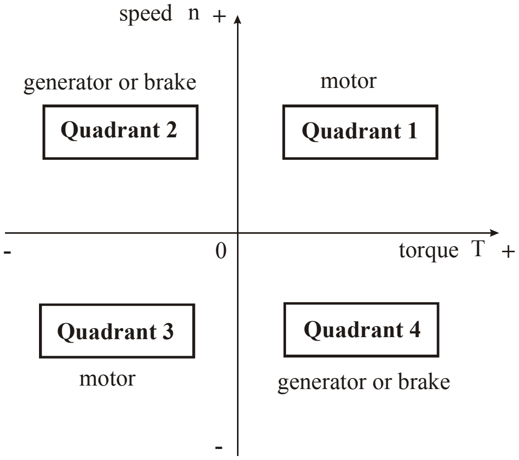


Fig.15 Four quadrant diagram the electric machine can operate

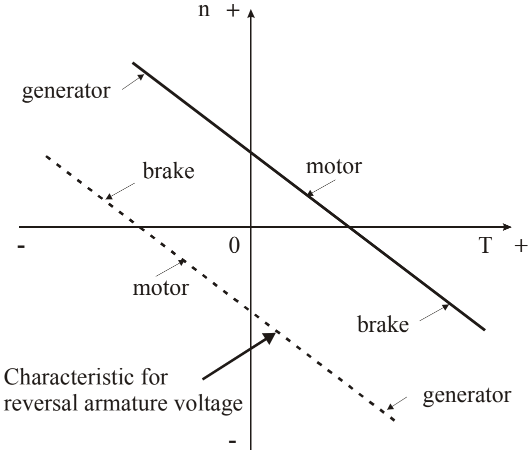
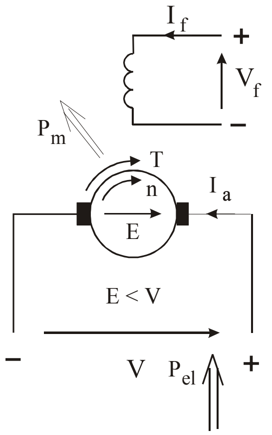
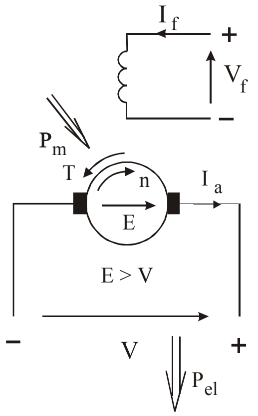


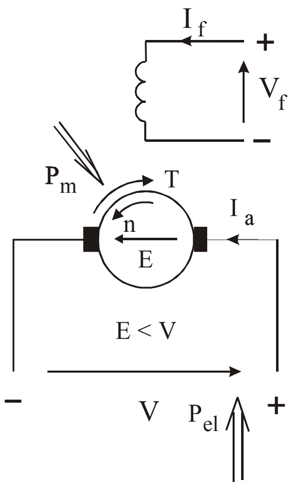
Fig.16 Torque-speed characteristics of separately excited motor



(a) quadrant 1 – motor operation



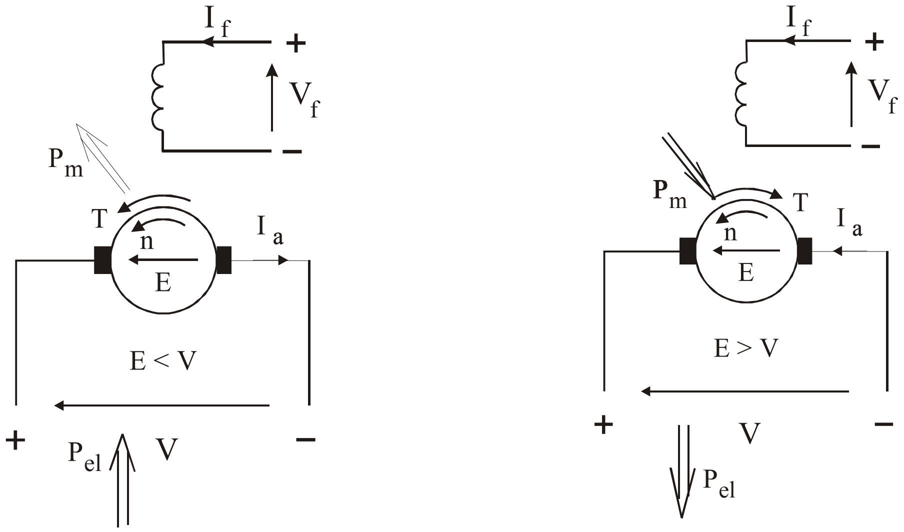
(b) quadrant 2 – generator operation (regenerative braking)



(c) quadrant 4 – brake operation (plugging braking)

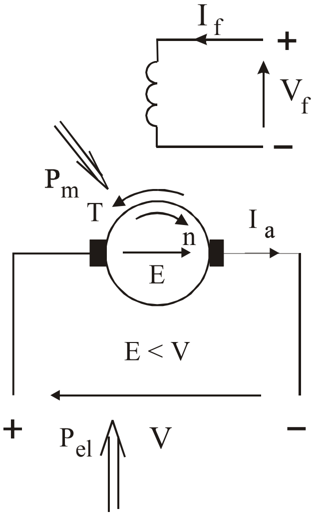
Fig.17 Three modes of operation of separately excited (or permanent magnet) DC motor (see Fig.16 – solid line)

2) **Quadrant 2** – the car descends downhill, it tends to accelerate and now going faster above the no-load motor speed; E becomes greater than V, what reverses the armature current and, in consequence, torque T and electric power P_{el} (**Fig.16 – solid line**, **and Fig.17.(b)**); the P_{el} is now "pumped back" to the battery from the motor armature. The motor becomes a generator and the car – prime mover. The motor brakes (**regenerative braking**) the car, but it is insufficient to stop the car.
3) **Quadrant 4** – To bring the car to a complete standstill **plugging braking** should be applied by reversing the battery supply to the armature (**Fig.16 – dashed line, Fig.18.c));** the torque T brake the car and the P_m, as well as P_{el} are directed into the motor.



(a) quadrant 3 – motor operation

(b) quadrant 4 – generator operation (regenerative braking)



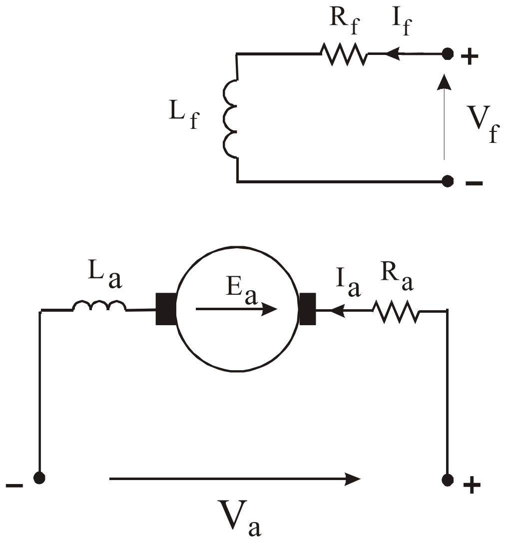
(c) quadrant 2 – brake operation (plugging braking)

Fig.18 Three modes of operation of separately excited (or permanent magnet) DC motor **with reversed supply terminals** to the armature (see Fig.16 – dushed line)

In variable-speed drives we try to vary the speed and torque smoothly. It can be accomplished by shifting the entire torque-speed characteristic back and forth along x-axis. Practically, it is done by varying the armature voltage.

4. Dynamic simulation of dc motor

Equations of electric circuit and mechanical system



Field circuit:

$$v_f = R_f i_f + L_f \frac{di_f}{dt} \text{ or } v_f = (R_f + L_f s) i_f$$

armature circuit

$$v_a = e_a + R_a i_a + L_a \frac{di_a}{dt} \text{ or } v_a - e_a = (R_a + L_a s) i_a$$

If I_f = const

$e_a = k_E \omega_m$ and $T_{em} = k_T i_a$

where

$k_E = k_T$

Fig.19

Mechanical system (port):

$$T_{em} = T_L + (J_M + J_L)\frac{d\omega_m}{dt} + B\omega_m \text{, or}$$

$$T_{em} - T_L = (J_M + J_L) s\omega_m + B\omega_m \text{, or}$$

$$T_{em} - T_L = (Js + B)\omega_m$$

Block diagram of dc permanent magnet motor

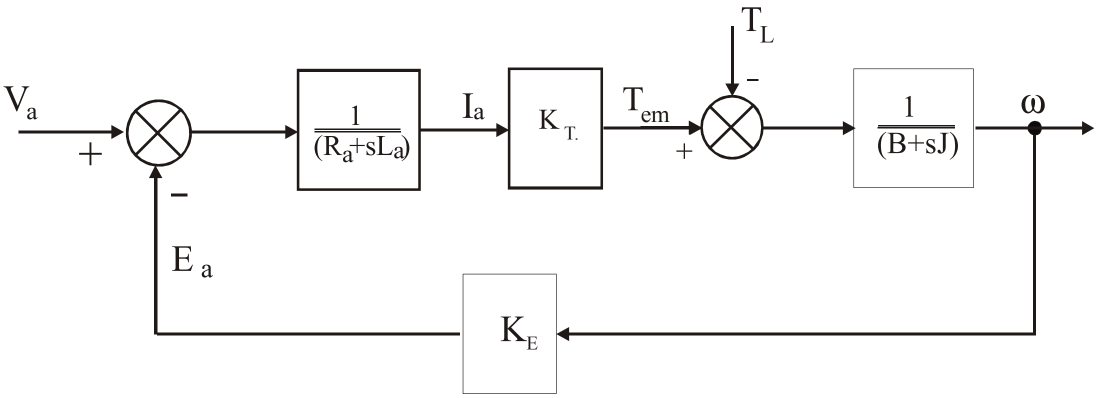


Fig.20

Block diagram in SIMULING

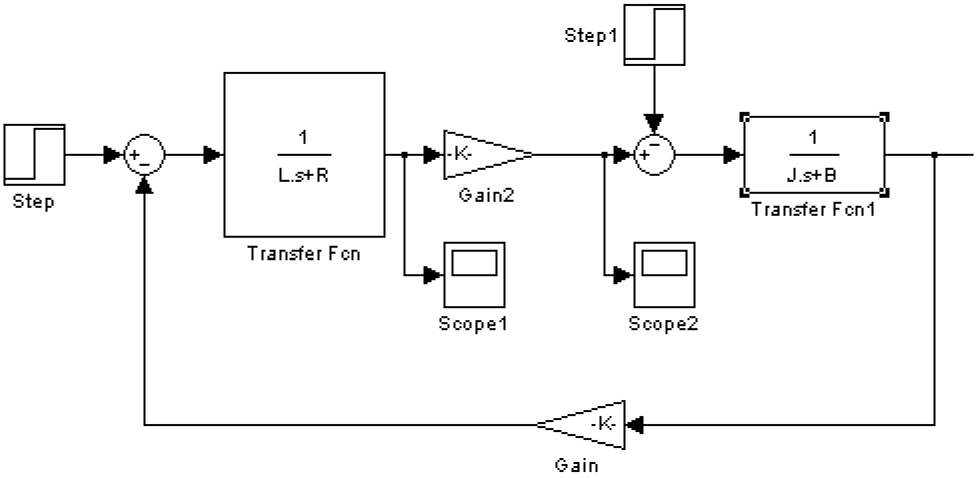


Fig.21

if $T_L = K_L \omega_m^2$ for centrifugal load (fan)

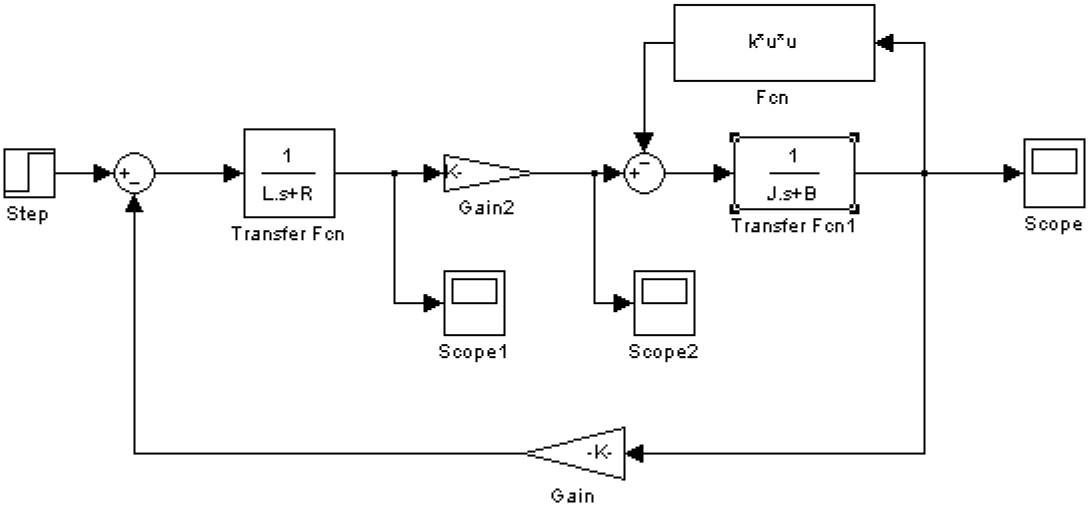


Fig.22