

EE3124 Tutorial 2 (Solution)

DC Machines

Name:

Student No.:

Q1 - Four types of permanent magnets that have been widely used for electric motors.

- What are their names and chemical formulas?
- Which two rare-earth elements are being used for permanent magnets?
- Sketch their demagnetization characteristics. Which magnetic is the strongest? Why?

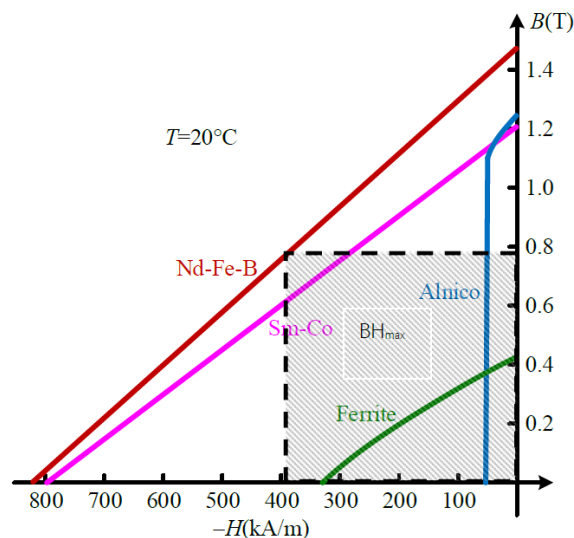
Solution

Four types of permanent magnets:

- neodymium-iron-boron (Compound, $\text{Nd}_2\text{Fe}_{14}\text{B}$),
- samarium-cobalt (Compound, SmCo_5 / $\text{Sm}_2\text{Co}_{17}$)
- aluminium-nickel-cobalt (Alloy, Al-Ni-Co or Alnico),
- ferrite, iron III oxide (Compound, Fe_2O_3)

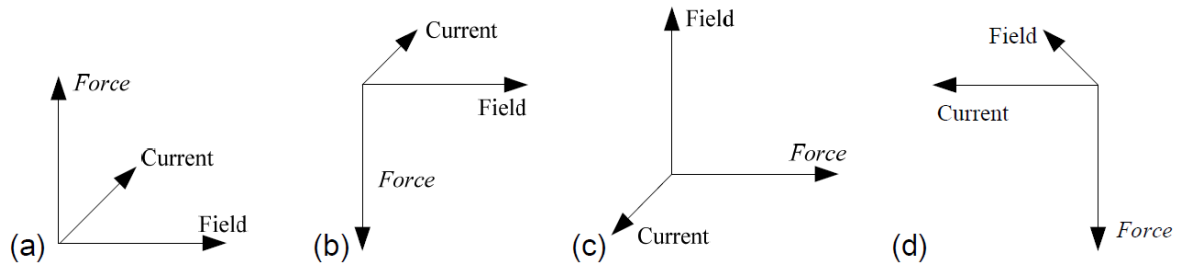
Two-rare-earth elements:

- neodymium (Nd),
- samarium (Sm)



Strongest: neodymium-iron-boron, Highest BH_{max} (largest rectangle that can be inscribed under the normal curve)

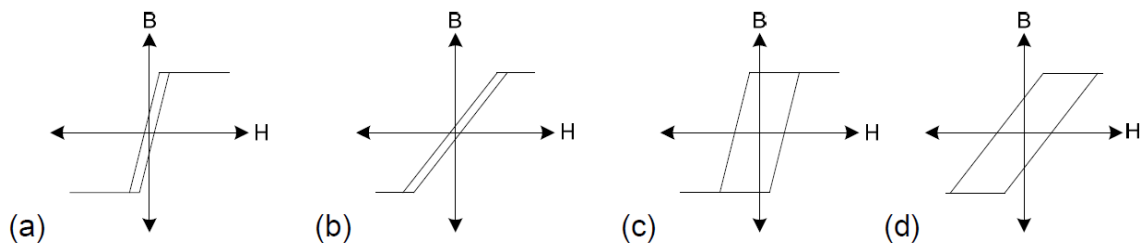
Q2 - Study the Fleming's rule for motor. Which of the following vector diagram represents the Fleming's rule of force creation in a machine.



Solution

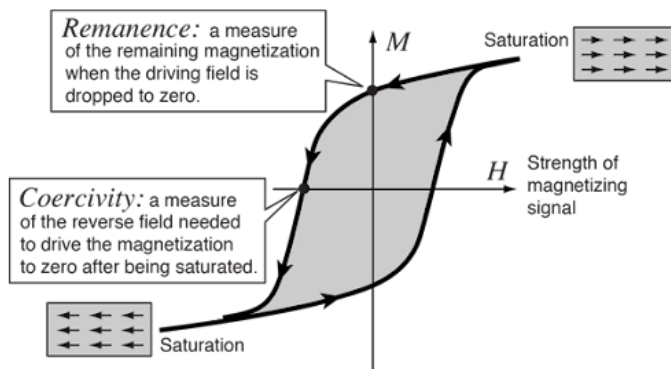
(b)/(d)

Q3 - Which of the following figure represents the BH curve of a good permanent magnetic?



Solution

(c) – higher remanence



Q4 - Use the correct word from the word bank to complete the sentence.

Increase	field	small	rotor	reduce	brush
high	transformer	dc-motor	commutator	reversing	rectifying

- i) _____ permeability ferromagnetic materials should be used to _____ the flux density in the transformer core.
- ii) The air gap between the stator and rotor should kept as _____ as possible to _____ the reluctance.
- iii) The induced back-emf of a permanent magnetic dc-motor depends on the magnetic _____ intensity and _____ speed.
- iv) To reduce the eddy current loss, _____ and induction motor (both stator and rotor) are made of laminated stainless steel.
- v) In a DC- motor the _____ applies electric current to the windings. By _____ the current direction in the rotating windings each half turn, a steady rotating force (torque) is produced.

Solution

- i) High permeability ferromagnetic materials should be used to increase the flux density in the transformer core.

Explanation: $B = \mu H$, when μ increases, same H (same current) will induces larger B (flux density)

- ii) The air gap between the stator and rotor should kept as small as possible to reduce the reluctance.

Explanation: Intuitively, it can't be larger. Reluctance, akin to resistance in electrical circuit,

is the “resistance” in a magnetic circuit. $R = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A}$. The smaller the air gap, of course the small “resistance” for the magnetic field flow between the stator and rotor. From the equation, the smaller l . We want the gap to have more steel, less air.

- iii) The induced back-emf of a permanent magnetic dc-motor depends on the magnetic field intensity and rotor speed.

Explanation: $E = K_e \Phi \omega_n$ and $\Phi = \int_A B dA$, where K_e is the parameter determined by the Electrical Machine, $H = \frac{B}{\mu}$ is the magnetic field intensity and ω_n is the rotor speed.

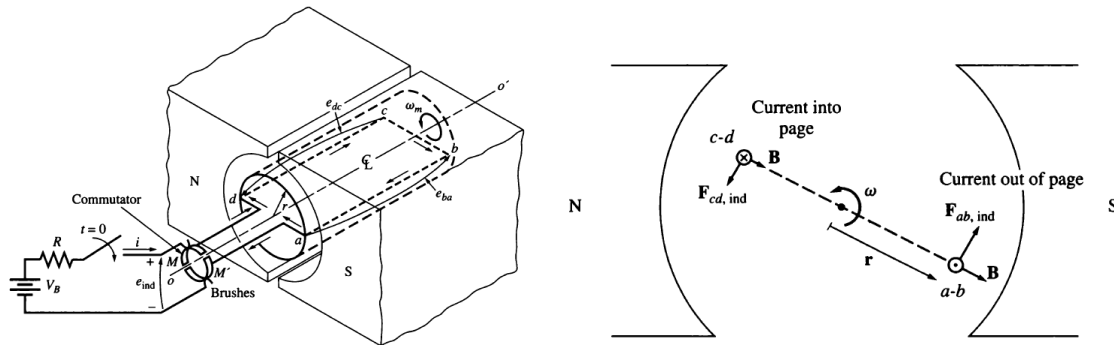
- iv) To reduce the eddy current loss, transformer and induction motor (both stator and rotor) are made of laminated stainless steel.

Explanation: Eddy currents (also called Foucault's currents) are loops of electrical current induced within conductors by a changing magnetic field in the conductor according to Faraday's law of induction. Eddy currents flow in closed loops within conductors, in planes perpendicular to the magnetic field.

Q5 - The following figure shows a simple rotating loop between curved pole faces connected to a battery and a resistor through a switch. The resistor shown models the total resistance of the battery and the wire in the machine. The physical dimensions and characteristics of this machine are

$$r = 0.5 \text{ m} \quad l = 1.0 \text{ m} \quad R = 0.3 \Omega \quad B = 0.25 \text{ T} \quad V_B = 120 \text{ V}$$

- (a) What happens when the switch is closed?
 (b) What is the machine's maximum starting current? What is its steady-state angular velocity at no load?
 (c) Suppose a load is attached to the loop, and the resulting load torque is $10 \text{ N} \cdot \text{m}$. What would the new steady-state speed be? How much power is supplied to the shaft of the machine? How much power is being supplied by the battery? Is this machine a motor or a generator?



Solution

(a)

the loop is initially stationary, $e_{ind} = 0$. Therefore, the current will be given by

$$i = \frac{V_B - e_{ind}}{R} = \frac{V_B}{R}$$

This current flows through the rotor loop, producing a torque

$$\tau_{ind} = \frac{2}{\pi} \phi i \quad \text{CCW}$$

This induced torque produces an angular acceleration in a counterclockwise direction, so the rotor of the machine begins to turn. But as the rotor begins to turn, an induced voltage is produced in the motor, given by

$$e_{ind} = \frac{2}{\pi} \phi \omega_m$$

so the current i falls. As the current falls, $\tau_{ind} = (2/\pi)\phi i \downarrow$ decreases, and the machine winds up in steady state with $\tau_{ind} = 0$, and the battery voltage $V_B = e_{ind}$.

This is the same sort of starting behavior seen earlier in the linear dc machine.

(b) At starting conditions, the machine's current is

$$i = \frac{V_B}{R} = \frac{120 \text{ V}}{0.3 \Omega} = 400 \text{ A}$$

At no-load steady-state conditions, the induced torque τ_{ind} must be zero. But $\tau_{\text{ind}} = 0$ implies that current i must equal zero, since $\tau_{\text{ind}} = (2/\pi)\phi i$, and the flux is nonzero. The fact that $i = 0 \text{ A}$ means that the battery voltage $V_B = e_{\text{ind}}$. Therefore, the speed of the rotor is

$$\begin{aligned} V_B &= e_{\text{ind}} = \frac{2}{\pi} \phi \omega_m \\ \omega &= \frac{V_B}{(2/\pi)\phi} = \frac{V_B}{2rLB} \\ &= \frac{120 \text{ V}}{2(0.5 \text{ m})(1.0 \text{ m})(0.25 \text{ T})} = 480 \text{ rad/s} \end{aligned}$$

(c) If a load torque of $10 \text{ N} \cdot \text{m}$ is applied to the shaft of the machine, it will begin to slow down. But as ω decreases, $e_{\text{ind}} = (2/\pi)\phi \omega$ decreases and the rotor current increases [$i = (V_B - e_{\text{ind}})/R$]. As the rotor current increases, $|\tau_{\text{ind}}|$ increases too, until $|\tau_{\text{ind}}| = |\tau_{\text{load}}|$ at a lower speed ω .

At steady state, $|\tau_{\text{load}}| = |\tau_{\text{ind}}| = (2/\pi)\phi i$. Therefore,

$$\begin{aligned} i &= \frac{\tau_{\text{ind}}}{(2/\pi)\phi} = \frac{\tau_{\text{load}}}{2rLB} \\ &= \frac{10 \text{ N} \cdot \text{m}}{(2)(0.5 \text{ m})(1.0 \text{ m})(0.25 \text{ T})} = 40 \text{ A} \end{aligned}$$

By Kirchhoff's voltage law, $e_{\text{ind}} = V_B - iR$, so

$$e_{\text{ind}} = 120 \text{ V} - (40 \text{ A})(0.3 \Omega) = 108 \text{ V}$$

Finally, the speed of the shaft is

$$\begin{aligned} \omega &= \frac{e_{\text{ind}}}{(2/\pi)\phi} = \frac{e_{\text{ind}}}{2rLB} \\ &= \frac{108 \text{ V}}{(2)(0.5 \text{ m})(1.0 \text{ m})(0.25 \text{ T})} = 432 \text{ rad/s} \end{aligned}$$

The power supplied to the shaft is

$$\begin{aligned} P &= \tau \omega_m \\ &= (10 \text{ N} \cdot \text{m})(432 \text{ rad/s}) = 4320 \text{ W} \end{aligned}$$

The power out of the battery is

$$P = V_B i = (120 \text{ V})(40 \text{ A}) = 4800 \text{ W}$$

This machine is operating as a *motor*, converting electric power to mechanical power.

Q6 - A 25-kW 125-V separately excited dc machine is operated at a constant speed of 3000 r/min with a constant field current such that the open-circuit armature voltage is 125 V. The armature resistance is 0.02Ω .

Compute the armature current, terminal power, and electromagnetic power and torque when the terminal voltage is (a) 128 V and (b) 124 V.

Solution

a.

with $V_t = 128 \text{ V}$ and $E_a = 125 \text{ V}$, the armature current is

$$I_a = \frac{V_t - E_a}{R_a} = \frac{128 - 125}{0.02} = 150 \text{ A}$$

in the motor direction, and the power input at the motor terminal is

$$V_t I_a = 128 \times 150 = 19.20 \text{ kW}$$

The electromagnetic power is given by

$$E_a I_a = 125 \times 150 = 18.75 \text{ kW}$$

In this case, the dc machine is operating as a motor and the electromagnetic power is hence smaller than the motor input power by the power dissipated in the armature resistance.

Finally, the electromagnetic torque is given by

$$T_{\text{mech}} = \frac{E_a I_a}{\omega_m} = \frac{18.75 \times 10^3}{100\pi} = 59.7 \text{ N} \cdot \text{m}$$

b. In this case, E_a is larger than V_t and hence armature current will flow out of the machine, and thus the machine is operating as a generator. Hence

$$I_a = \frac{E_a - V_t}{R_a} = \frac{125 - 124}{0.02} = 50 \text{ A}$$

and the terminal power is

$$V_t I_a = 124 \times 50 = 6.20 \text{ kW}$$

The electromagnetic power is

$$E_a I_a = 125 \times 50 = 6.25 \text{ kW}$$

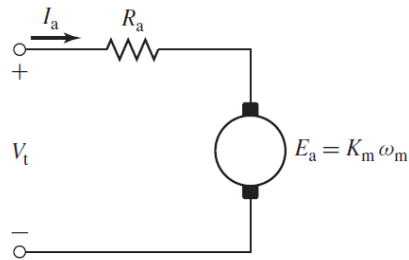
and the electromagnetic torque is

$$T_{\text{mech}} = \frac{6.25 \times 10^3}{100\pi} = 19.9 \text{ N} \cdot \text{m}$$

Q7 - A permanent-magnet dc motor is known to have an armature resistance of $1.03 \, \Omega$. When operated at no load from a dc source of 50 V, it is observed to rotate at a speed of 2100 r/min and to draw a current of 1.25 A. Find

- the torque constant K_m
- the no-load rotational losses of the motor, and
- the power output of the motor when it is operating at 1700 r/min from a 48-V source.

Solution



- From the equivalent circuit of Fig. 7.25, the generated voltage E_a can be found as

$$\begin{aligned} E_a &= V_t - I_a R_a \\ &= 50 - 1.25 \times 1.03 = 48.7 \text{ V} \end{aligned}$$

At a speed of 2100 r/min,

$$\begin{aligned} \omega_m &= \left(\frac{2100 \text{ r}}{\text{min}} \right) \times \left(\frac{2\pi \text{ rad}}{\text{r}} \right) \times \left(\frac{1 \text{ min}}{60 \text{ sec}} \right) \\ &= 220 \text{ rad/sec} \end{aligned}$$

Therefore, from Eq. 7.31,

$$K_m = \frac{E_a}{\omega_m} = \frac{48.7}{220} = 0.22 \text{ V/(rad/sec)}$$

- b. At no load, all the power supplied to the generated voltage E_a is used to supply rotational losses. Therefore

$$\text{Rotational losses} = E_a I_a = 48.7 \times 1.25 = 61 \text{ W}$$

- c. At 1700 r/min,

$$\omega_m = 1700 \left(\frac{2\pi}{60} \right) = 178 \text{ rad/sec}$$

and

$$E_a = K_m \omega_m = 0.22 \times 178 = 39.2 \text{ V}$$

The input current can now be found as

$$I_a = \frac{V_t - E_a}{R_a} = \frac{48 - 39.2}{1.03} = 8.54 \text{ A}$$

The electromagnetic power can be calculated as

$$P_{\text{mech}} = E_a I_a = 39.2 \times 8.54 = 335 \text{ W}$$

Assuming the rotational losses to be constant at their no-load value (certainly an approximation), the output shaft power can be calculated:

$$P_{\text{shaft}} = P_{\text{mech}} - \text{rotational losses} = 274 \text{ W}$$

CHAPTER 7

DC MACHINERY FUNDAMENTALS

LEARNING OBJECTIVES

- Understand how voltage is induced in a rotating loop.
- Understand how curved pole faces contribute to a constant flux, and thus more constant output voltages.
- Understand and be able to use the equation for induced voltage and torque in a dc machine.
- Understand commutation.
- Understand problems with commutation, including armature reaction and $L \frac{di}{dt}$ effects.
- Understand the power flow diagram for dc machines.

DC machines are generators that convert mechanical energy to dc electric energy and motors that convert dc electric energy to mechanical energy. Most dc machines are like ac machines in that they have ac voltages and currents within them—dc machines have a dc output only because a mechanism exists that converts the internal ac voltages to dc voltages at their terminals. Since this mechanism is called a commutator, dc machinery is also known as *commutating machinery*.

The fundamental principles involved in the operation of dc machines are very simple. Unfortunately, they are usually somewhat obscured by the complicated construction of real machines. This chapter will first explain the principles of dc machine operation by using simple examples and then consider some of the complications that occur in real dc machines.

7.1 A SIMPLE ROTATING LOOP BETWEEN CURVED POLE FACES

The linear machine studied in Section 1.8 served as an introduction to basic machine behavior. Its response to loading and to changing magnetic fields closely

resembles the behavior of the real dc generators and motors that we will study in Chapter 8. However, real generators and motors do not move in a straight line—they *rotate*. The next step toward understanding real dc machines is to study the simplest possible example of a rotating machine.

The simplest possible rotating dc machine is shown in Figure 7–1. It consists of a single loop of wire rotating about a fixed axis. The rotating part of this machine is called the *rotor*, and the stationary part is called the *stator*. The magnetic field for the machine is supplied by the magnetic north and south poles shown on the stator in Figure 7–1.

Notice that the loop of rotor wire lies in a slot carved in a ferromagnetic core. The iron rotor, together with the curved shape of the pole faces, provides a constant-width air gap between the rotor and stator. Remember from Chapter 1 that the reluctance of air is much higher than the reluctance of the iron in the machine. To minimize the reluctance of the flux path through the machine, the magnetic flux must take the shortest possible path through the air between the pole face and the rotor surface.

Since the magnetic flux must take the shortest path through the air, it is *perpendicular* to the rotor surface everywhere under the pole faces. Also, since the air gap is of uniform width, the reluctance is the same everywhere under the pole faces. The uniform reluctance means that the magnetic flux density is constant everywhere under the pole faces.

The Voltage Induced in a Rotating Loop

If the rotor of this machine is rotated, a voltage will be induced in the wire loop. To determine the magnitude and shape of the voltage, examine Figure 7–2. The loop of wire shown is rectangular, with sides *ab* and *cd* perpendicular to the plane of the page and with sides *bc* and *da* parallel to the plane of the page. The magnetic field is constant and perpendicular to the surface of the rotor everywhere under the pole faces and rapidly falls to zero beyond the edges of the poles.

To determine the total voltage e_{tot} on the loop, examine each segment of the loop separately and sum all the resulting voltages. The voltage on each segment is given by Equation (1–45):

$$e_{\text{ind}} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \quad (1-45)$$

1. *Segment ab*. In this segment, the velocity of the wire is tangential to the path of rotation. The magnetic field $\mathbf{B}$ points out perpendicular to the rotor surface everywhere under the pole face and is zero beyond the edges of the pole face. Under the pole face, velocity $\mathbf{v}$ is perpendicular to $\mathbf{B}$, and the quantity $\mathbf{v} \times \mathbf{B}$ points into the page. Therefore, the induced voltage on the segment is

$$\begin{aligned} e_{ba} &= (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \\ &= \begin{cases} vBl & \text{positive into page} & \text{under the pole face} \\ 0 & & \text{beyond the pole edges} \end{cases} \quad (7-1) \end{aligned}$$

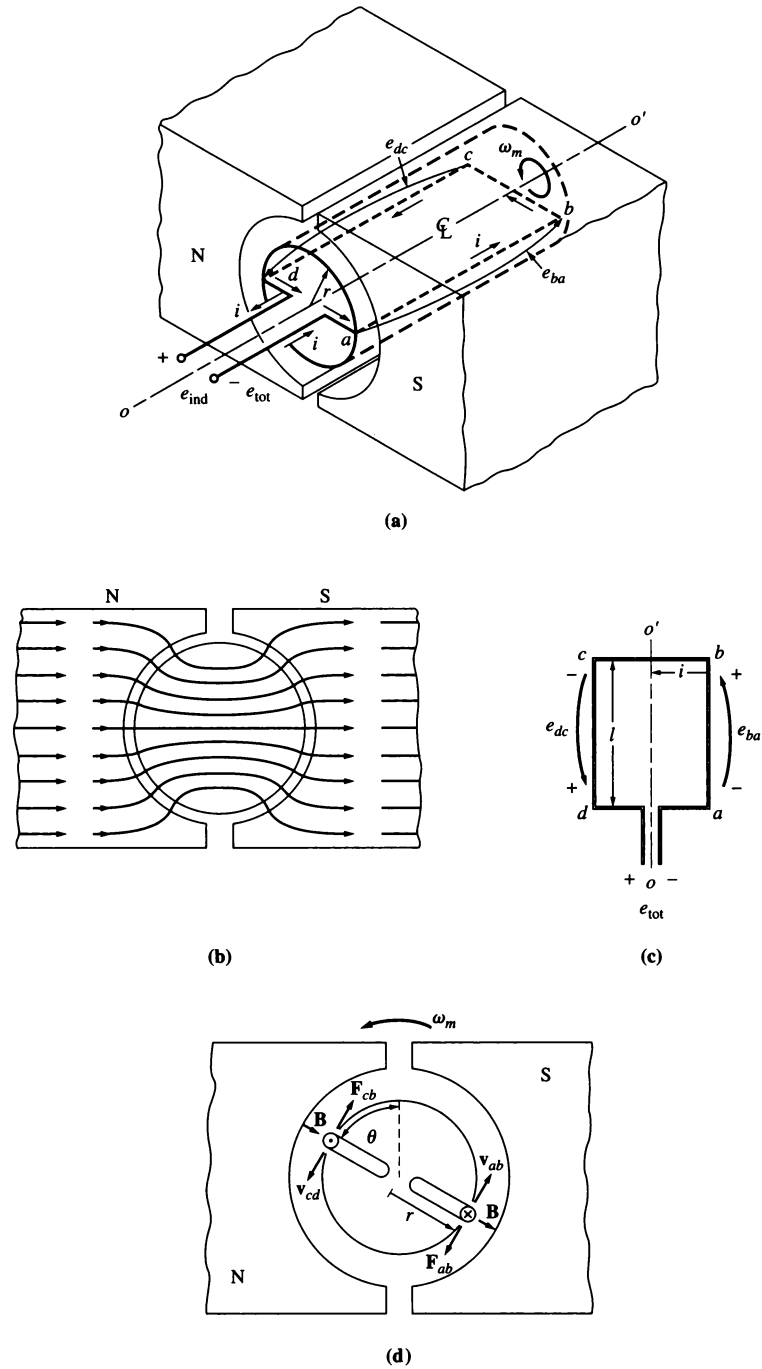


FIGURE 7-1
A simple rotating loop between curved pole faces. (a) Perspective view; (b) view of field lines; (c) top view; (d) front view.

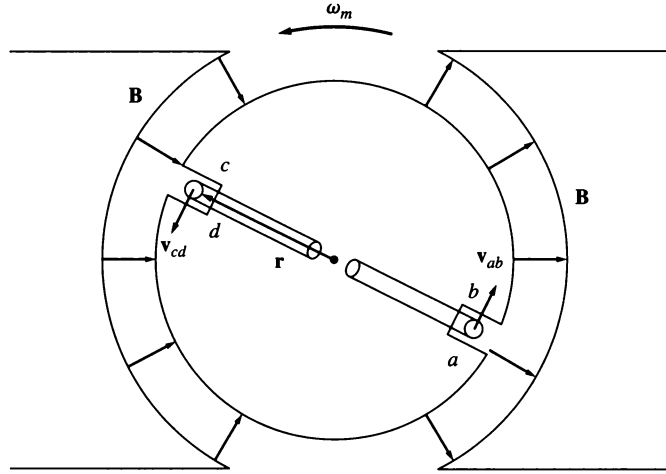


FIGURE 7-2
Derivation of an equation for the voltages induced in the loop.

2. *Segment bc.* In this segment, the quantity $\mathbf{v} \times \mathbf{B}$ is either into or out of the page, while length $\mathbf{l}$ is in the plane of the page, so $\mathbf{v} \times \mathbf{B}$ is perpendicular to $\mathbf{l}$. Therefore the voltage in segment bc will be zero:

$$e_{cb} = 0 \quad (7-2)$$

3. *Segment cd.* In this segment, the velocity of the wire is tangential to the path of rotation. The magnetic field $\mathbf{B}$ points *in* perpendicular to the rotor surface everywhere under the pole face and is zero beyond the edges of the pole face. Under the pole face, velocity $\mathbf{v}$ is perpendicular to $\mathbf{B}$, and the quantity $\mathbf{v} \times \mathbf{B}$ points out of the page. Therefore, the induced voltage on the segment is

$$\begin{aligned} e_{dc} &= (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \\ &= \begin{cases} vBl & \text{positive out of page} & \text{under the pole face} \\ 0 & & \text{beyond the pole edges} \end{cases} \quad (7-3) \end{aligned}$$

4. *Segment da.* Just as in segment bc , $\mathbf{v} \times \mathbf{B}$ is perpendicular to $\mathbf{l}$. Therefore the voltage in this segment will be zero, too:

$$e_{ad} = 0 \quad (7-4)$$

The total induced voltage on the loop e_{ind} is given by

$$e_{\text{ind}} = e_{ba} + e_{cb} + e_{dc} + e_{ad}$$

$$e_{\text{ind}} = \begin{cases} 2vBl & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases} \quad (7-5)$$

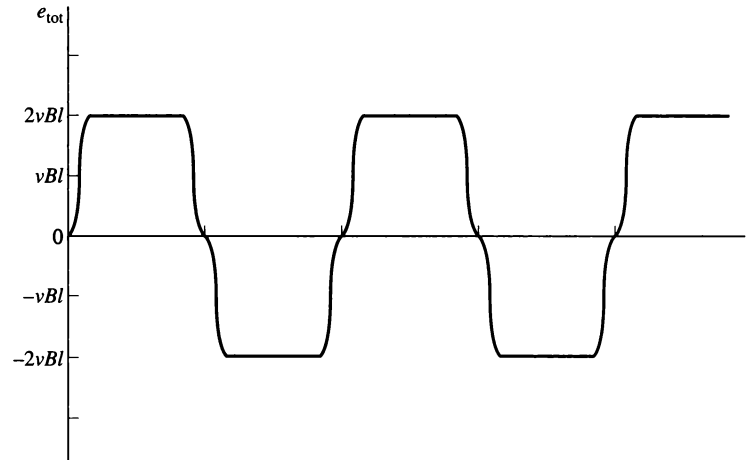


FIGURE 7-3
The output voltage of the loop.

When the loop rotates through 180° , segment ab is under the north pole face instead of the south pole face. At that time, the direction of the voltage on the segment reverses, but its magnitude remains constant. The resulting voltage e_{tot} is shown as a function of time in Figure 7-3.

There is an alternative way to express Equation (7-5) which clearly relates the behavior of the single loop to the behavior of larger, real dc machines. To

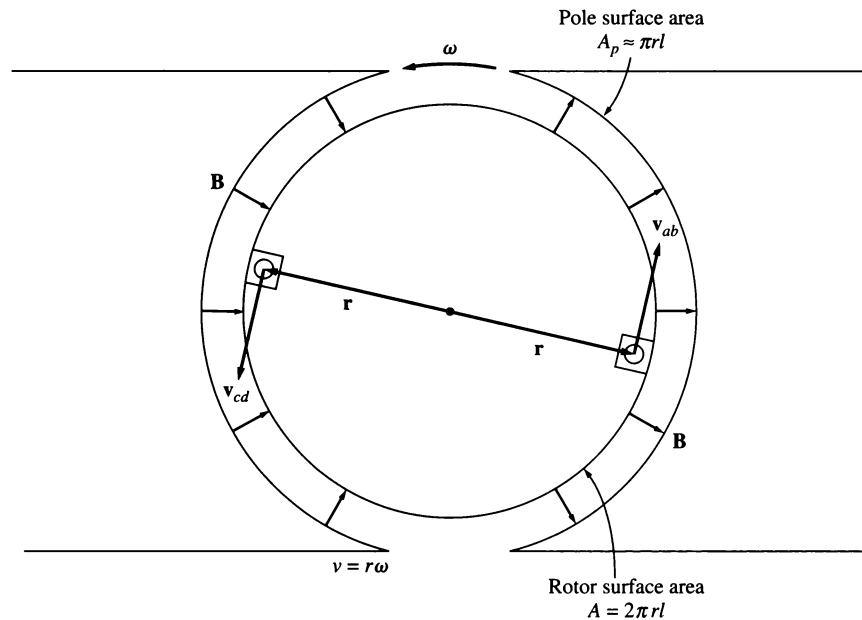


FIGURE 7-4
Derivation of an alternative form of the induced voltage equation.

derive this alternative expression, examine Figure 7–4. Notice that the tangential velocity v of the edges of the loop can be expressed as

$$v = r\omega_m$$

where r is the radius from the axis of rotation out to the edge of the loop and ω_m is the angular velocity of the loop. Substituting this expression into Equation (7–5) gives

$$e_{\text{ind}} = \begin{cases} 2r\omega_m Bl & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

$$e_{\text{ind}} = \begin{cases} 2rlB\omega_m & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

Notice also from Figure 7–4 that the rotor surface is a cylinder, so the area of the rotor surface A is just equal to $2\pi rl$. Since there are two poles, the area of the rotor *under each pole* (ignoring the small gaps between poles) is $A_p = \pi rl$. Therefore,

$$e_{\text{ind}} = \begin{cases} \frac{2}{\pi} A_p B \omega_m & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

Since the flux density B is constant everywhere in the air gap under the pole faces, the total flux under each pole is just the area of the pole times its flux density:

$$\phi = A_p B$$

Therefore, the final form of the voltage equation is

$$e_{\text{ind}} = \begin{cases} \frac{2}{\pi} \phi \omega_m & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases} \quad (7-6)$$

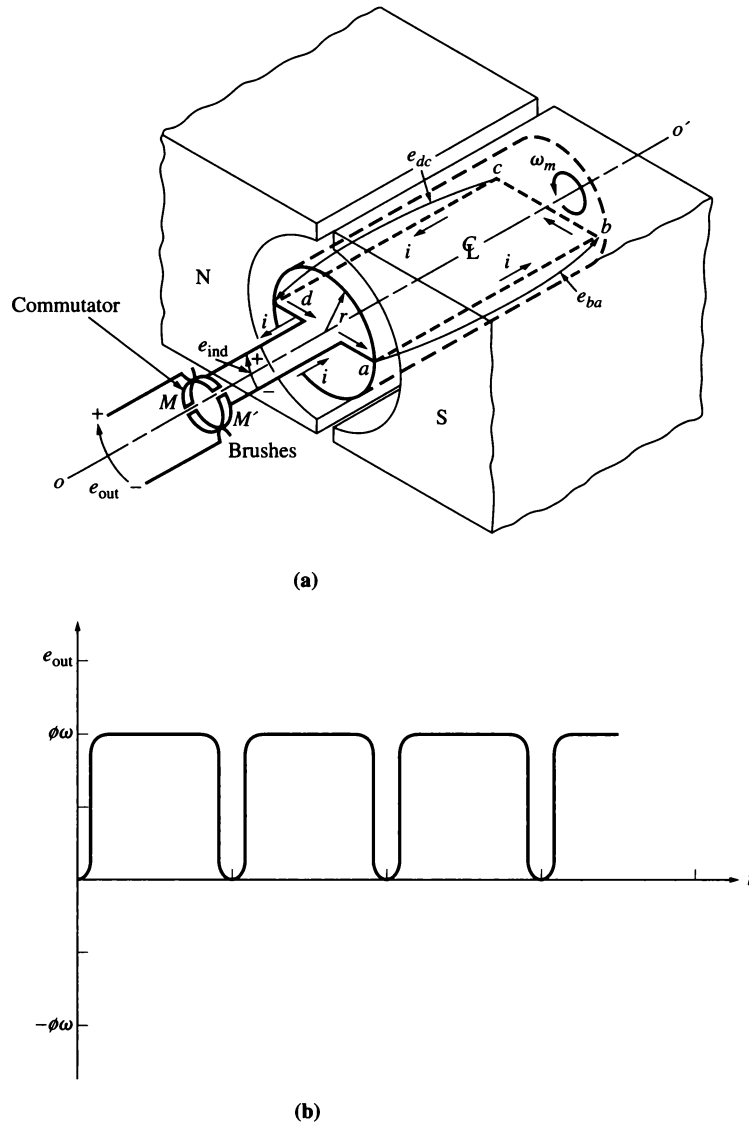
Thus, *the voltage generated in the machine is equal to the product of the flux inside the machine and the speed of rotation of the machine*, multiplied by a constant representing the mechanical construction of the machine. In general, the voltage in any real machine will depend on the same three factors:

1. The flux in the machine
2. The speed of rotation
3. A constant representing the construction of the machine

Getting DC Voltage Out of the Rotating Loop

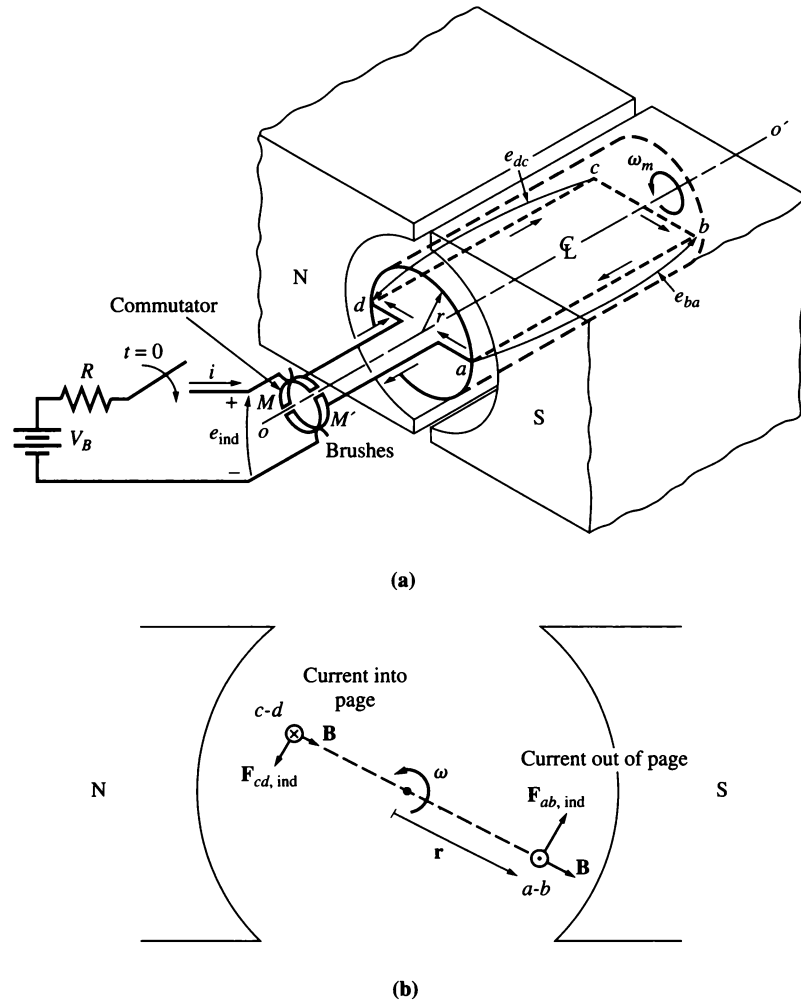
Figure 7–3 is a plot of the voltage e_{tot} generated by the rotating loop. As shown, the voltage out of the loop is alternately a constant positive value and a constant negative value. How can this machine be made to produce a dc voltage instead of the ac voltage it now has?

One way to do this is shown in Figure 7–5a. Here two semicircular conducting segments are added to the end of the loop, and two fixed contacts are set up at

**FIGURE 7-5**

Producing a dc output from the machine with a commutator and brushes. (a) Perspective view; (b) the resulting output voltage.

an angle such that at the instant when the voltage in the loop is zero, the contacts short-circuit the two segments. In this fashion, *every time the voltage of the loop switches direction, the contacts also switch connections, and the output of the contacts is always built up in the same way* (Figure 7-5b). This connection-switching process is known as *commutation*. The rotating semicircular segments are called *commutator segments*, and the fixed contacts are called *brushes*.

**FIGURE 7-6**

Derivation of an equation for the induced torque in the loop. Note that the iron core is not shown in part b for clarity.

The Induced Torque in the Rotating Loop

Suppose a battery is now connected to the machine in Figure 7-5. The resulting configuration is shown in Figure 7-6. How much torque will be produced in the loop when the switch is closed and a current is allowed to flow into it? To determine the torque, look at the close-up of the loop shown in Figure 7-6b.

The approach to take in determining the torque on the loop is to look at one segment of the loop at a time and then sum the effects of all the individual segments. The force on a segment of the loop is given by Equation (1-43):

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B}) \quad (1-43)$$

and the torque on the segment is given by

$$\tau = rF \sin \theta \quad (1-6)$$

where θ is the angle between $\mathbf{r}$ and $\mathbf{F}$. The torque is essentially zero whenever the loop is beyond the pole edges.

While the loop is under the pole faces, the torque is

1. *Segment ab.* In segment *ab*, the current from the battery is directed out of the page. The magnetic field under the pole face is pointing radially out of the rotor, so the force on the wire is given by

$$\begin{aligned} \mathbf{F}_{ab} &= i(\mathbf{l} \times \mathbf{B}) \\ &= ilB \quad \text{tangent to direction of motion} \end{aligned} \quad (7-7)$$

The torque on the rotor caused by this force is

$$\begin{aligned} \tau_{ab} &= rF \sin \theta \\ &= r(ilB) \sin 90^\circ \\ &= rilB \quad \text{CCW} \end{aligned} \quad (7-8)$$

2. *Segment bc.* In segment *bc*, the current from the battery is flowing from the upper left to the lower right in the picture. The force induced on the wire is given by

$$\begin{aligned} \mathbf{F}_{bc} &= i(\mathbf{l} \times \mathbf{B}) \\ &= 0 \quad \text{since } \mathbf{l} \text{ is parallel to } \mathbf{B} \end{aligned} \quad (7-9)$$

Therefore,

$$\tau_{bc} = 0 \quad (7-10)$$

3. *Segment cd.* In segment *cd*, the current from the battery is directed into the page. The magnetic field under the pole face is pointing radially into the rotor, so the force on the wire is given by

$$\begin{aligned} \mathbf{F}_{cd} &= i(\mathbf{l} \times \mathbf{B}) \\ &= ilB \quad \text{tangent to direction of motion} \end{aligned} \quad (7-11)$$

The torque on the rotor caused by this force is

$$\begin{aligned} \tau_{cd} &= rF \sin \theta \\ &= r(ilB) \sin 90^\circ \\ &= rilB \quad \text{CCW} \end{aligned} \quad (7-12)$$

4. *Segment da.* In segment *da*, the current from the battery is flowing from the upper left to the lower right in the picture. The force induced on the wire is given by

$$\begin{aligned}\mathbf{F}_{da} &= i(\mathbf{l} \times \mathbf{B}) \\ &= 0 \quad \text{since } \mathbf{l} \text{ is parallel to } \mathbf{B}\end{aligned}\quad (7-13)$$

Therefore,

$$\tau_{da} = 0 \quad (7-14)$$

The resulting total induced torque on the loop is given by

$$\begin{aligned}\tau_{\text{ind}} &= \tau_{ab} + \tau_{bc} + \tau_{cd} + \tau_{da} \\ \tau_{\text{ind}} &= \begin{cases} 2rilB & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}\end{aligned}\quad (7-15)$$

By using the facts that $A_p \approx \pi rl$ and $\phi = A_p B$, the torque expression can be reduced to

$$\tau_{\text{ind}} = \begin{cases} \frac{2}{\pi} \phi i & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}\quad (7-16)$$

Thus, *the torque produced in the machine is the product of the flux in the machine and the current in the machine*, times some quantity representing the mechanical construction of the machine (the percentage of the rotor covered by pole faces). In general, the torque in *any* real machine will depend on the same three factors:

1. The flux in the machine
2. The current in the machine
3. A constant representing the construction of the machine

Example 7-1. Figure 7-6 shows a simple rotating loop between curved pole faces connected to a battery and a resistor through a switch. The resistor shown models the total resistance of the battery and the wire in the machine. The physical dimensions and characteristics of this machine are

$$\begin{aligned}r &= 0.5 \text{ m} & l &= 1.0 \text{ m} \\ R &= 0.3 \, \Omega & B &= 0.25 \text{ T} \\ V_B &= 120 \text{ V}\end{aligned}$$

- (a) What happens when the switch is closed?
- (b) What is the machine's maximum starting current? What is its steady-state angular velocity at no load?
- (c) Suppose a load is attached to the loop, and the resulting load torque is $10 \text{ N} \cdot \text{m}$. What would the new steady-state speed be? How much power is supplied to the shaft of the machine? How much power is being supplied by the battery? Is this machine a motor or a generator?