

EEE 321

Electromechanical Energy Conversion – I

By

Prof. Dr. A. Mete VURAL

mvural@gantep.edu.tr

1

CHAPTER 3

DC MACHINERY FUNDAMENTALS

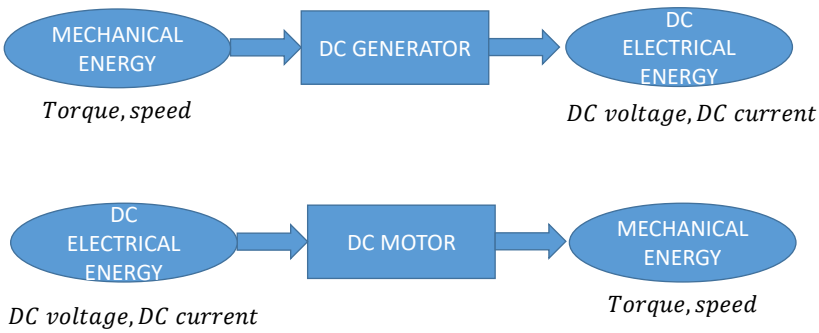
2

Introduction

- DC machines are **generators** that convert mechanical energy to DC electric energy.
- DC machines are **motors** that convert DC electric energy to mechanical energy.
- Most DC machines are like AC machines in that they have AC voltages and currents.
- DC machines have 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**».
- This chapter explains the principles of DC machine operation by using simple examples and then consider some of the complications that occur in real DC machines.

3

Introduction



4

Introduction



24VDC 150W, 2750 RPM DC MOTOR

Source: https://www.motiondynamics.com.au



1/2 HP 90 Volt DC Motor

Source: https://www.surpluscenter.com

5

What are applications of DC motors?



Drill



Spinning and Weaving machines (textile industry)



Crane



Lathe



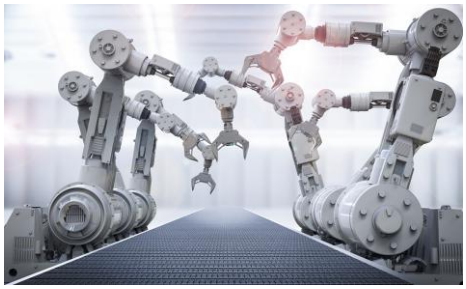
Electric traction



Air compressor

6

What are applications of DC motors?



Robotic applications



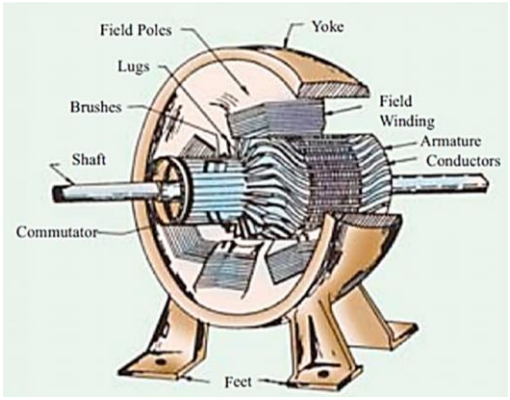
conveyors

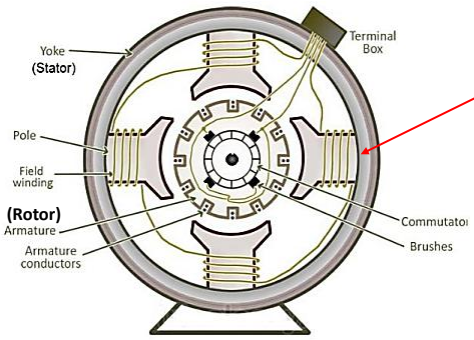


tachogenerators

7

Construction of DC Machines





Air gap is the small clearance between stator and rotor to allow the rotor to rotate freely

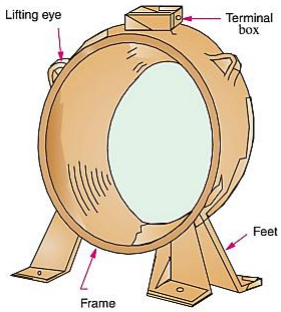
Basic components of a DC Machine

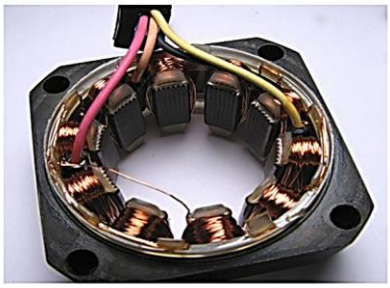
8

Construction of DC Machines

Stator or Yoke:

- The outer frame or yoke is shown in the figure.
- Its function is to provide mechanical support for the poles and act as a protecting cover for the whole machine.
- It also carries the magnetic flux produced by the poles.
- In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron.
- But for large machines, yokes are usually made of cast steel or rolled steel.





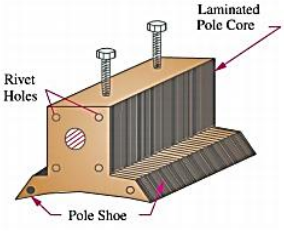
Stator

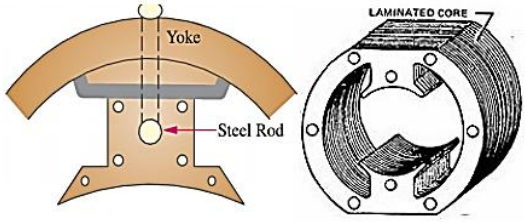
9

Construction of DC Machines

Pole-Cores and Pole-Shoes:

- The field magnets consist of pole cores and pole shoes as shown in the figure.
- The pole shoes serve two purposes:
  - They spread out the flux in the air gap.
  - They reduce the reluctance of the magnetic path due to the larger cross-section.
- They also mechanically support the field coils.



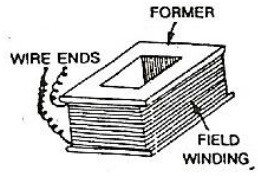


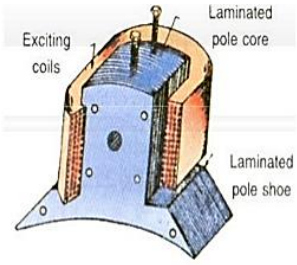
10

Construction of DC Machines

Exciting Coils or Field Coils:

- The field coils, which consist of copper wire, are former-wound for the correct dimension.
- Then, the former is removed, and wound coil is put into place over the core as shown in the figure.
- When current is passed through these coils, they electromagnetise the poles which produce the necessary flux for the DC machine.



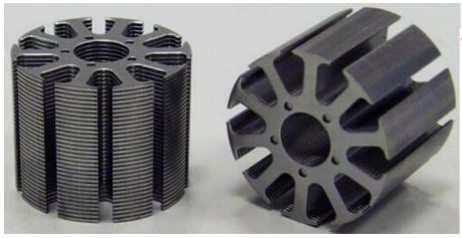


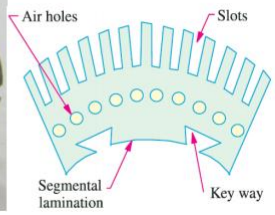
11

Construction of DC Machines

Armature Core:

- It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of the field magnets.
- In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a N-pole to a S-pole.
- It is cylindrical shaped and is built up of usually circular laminations approximately 0.5 mm thick as shown in the figure.
- It is keyed to the shaft. Usually, these laminations include holes for air ducts which permits axial flow of air through the armature for cooling purposes.

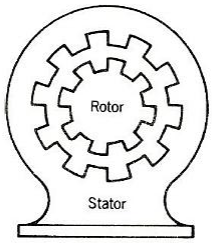




12

Construction of DC Machines

- Both **stator** and **rotor** are made of **ferromagnetic materials**.
- In most machines, slots are cut on the **inner periphery of the stator** and **outer periphery of the rotor** structure, as shown below.
- Copper conductors are placed in both of these slots.



13

Construction of DC Machines

Commutator:

- The function of the commutator is to facilitate collection of current from the armature conductors.
- It converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit.
- It is of copper cylindrical structure and is built up of wedge-shaped segments.
- These segments are insulated from each other by thin layers of mica.
- Each commutator segment is connected to the armature conductor.



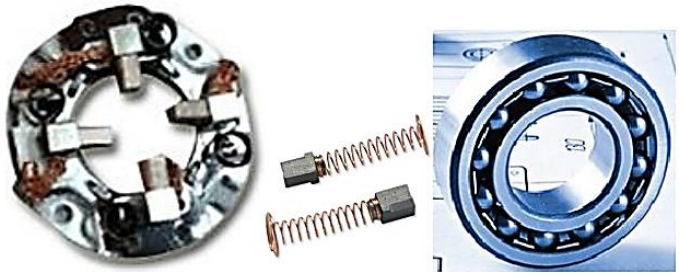


14

Construction of DC Machines

Brushes and Bearings:

- The function of brushes is to collect current from commutator.
- Brushes are usually made of carbon or graphite and its shape is rectangular.
- These brushes are housed in brushholders usually of the box-type variety.
- As shown in the figure, the brushes are made to bear down on the commutator by a spring.
- Roller bearings are used for quiet operation and to reduce bearing wear.



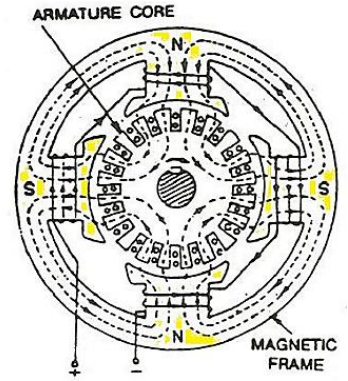
brushes *bearing*

15

Construction of DC Machines

Magnetic circuit of DC Machines:

- In DC machines, there are as **many magnetic paths** as the **number of poles**.
- For example, there are **4 magnetic paths and 4 poles** of the DC machine as shown in the figure.
- Each complete path includes yoke, pole core, pole shoe, air gaps (*stator to rotor & rotor to stator*), armature teeth, armature core, pole shoe of adjacent pole, pole core of adjacent pole, yoke.



16

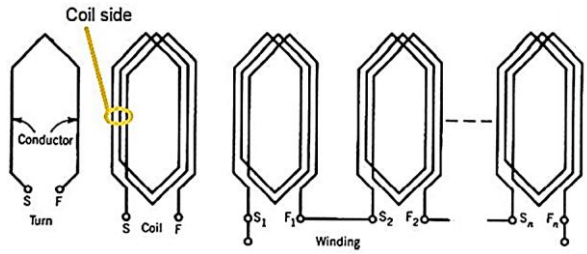
Construction of DC Machines

Armature windings:

- **Armature windings** are available on the **rotor** of the DC machine.
- A **turn** consists of **two conductors**.
- A **coil** is formed by connecting several turns **in series**, with **two ends** (*S=start & F=finish*).
- Therefore, each coil has **two coil sides**.
- A **winding** is formed by connecting **several coils in series**.



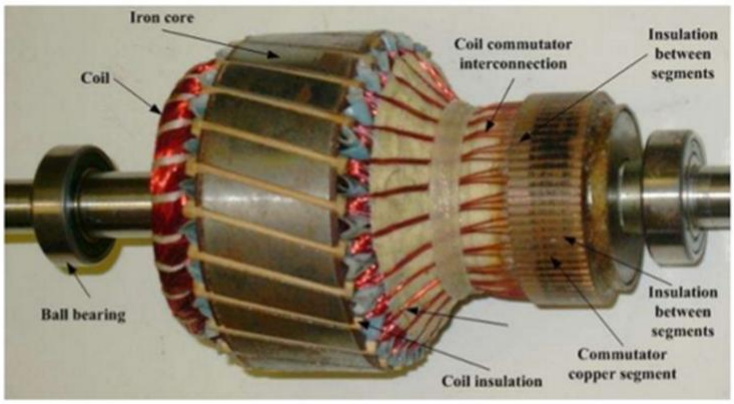
Rotor



17

Construction of DC Machines

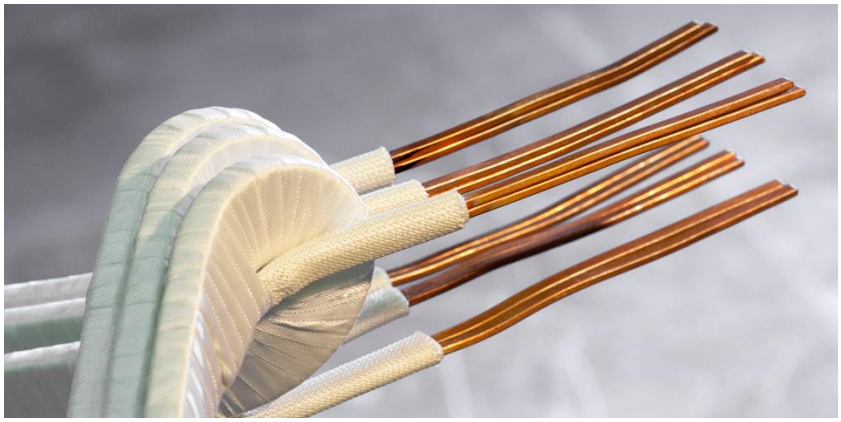
Armature of a DC machine:



18

Construction of DC Machines

Rotor Coils:



Source: https://jayelectric.com

19

Construction of DC Machines

Rotor Coils:

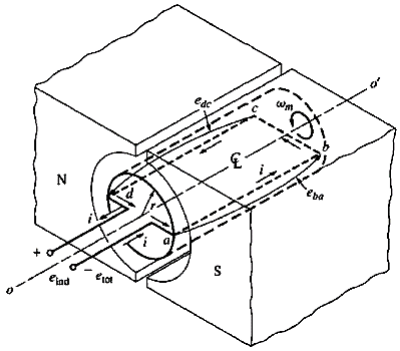


Source: https://jayelectric.com

20

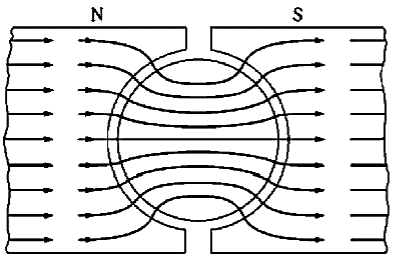
Simple Rotating Loop Between Curved Pole Faces

- The simplest possible rotating dc machine is shown in the figure.
- It consists of a single loop of wire rotating about a fixed axis.
- The **rotating part** of this machine is called the «**rotor**».
- The **stationary part** is called the «**stator**».
- The **magnetic field** for the machine is supplied by the **magnetic north** and **south poles** as shown in the figure.

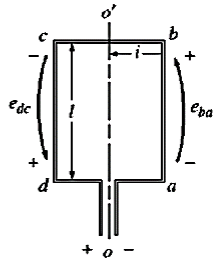


21

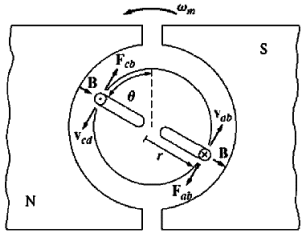
Simple Rotating Loop Between Curved Pole Faces



view of field lines.



top view.

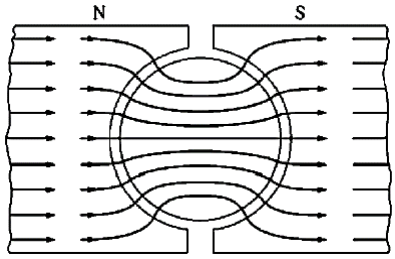


front view.

22

Simple Rotating Loop Between Curved Pole Faces

- As seen in the figure, there is a **constant-width air gap** between the **rotor** and **stator**.
- From previous chapter, we know that the reluctance of air is **much 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**.



23

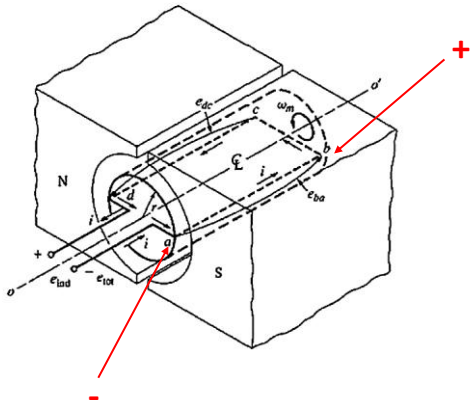
The Voltage Induced in a Rotating Loop

Segment ab:

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$e_{ba} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$= \begin{cases} vBl & \text{under the pole face} \\ 0 & \text{beyond the pole edges} \end{cases}$$



24

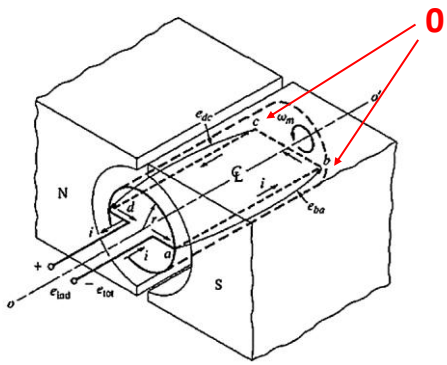
The Voltage Induced in a Rotating Loop

Segment bc:

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$e_{cb} = 0$$

(**v x B** is ***perpendicular*** to **l**)



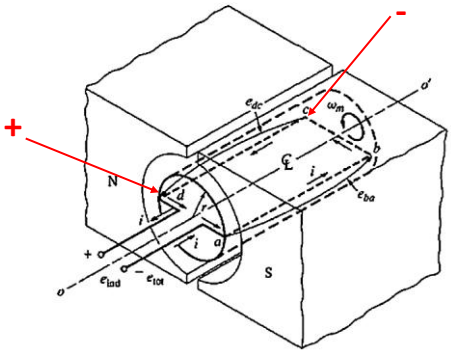
25

The Voltage Induced in a Rotating Loop

Segment cd:

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$e_{dc} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} = \begin{cases} vBl & \text{under the pole face} \\ 0 & \text{beyond the pole edges} \end{cases}$$



26

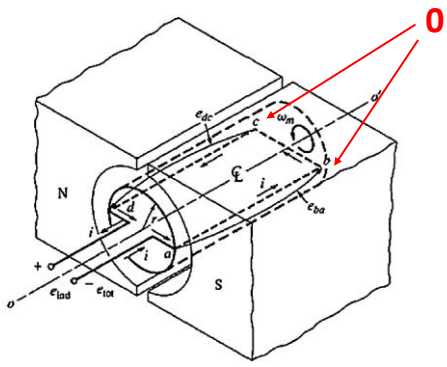
The Voltage Induced in a Rotating Loop

Segment da:

$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$

$e_{ad} = 0$

(**v x B** is ***perpendicular*** to **l**)



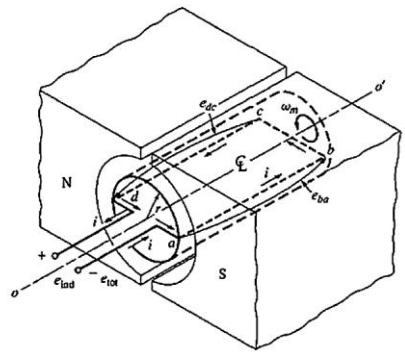
27

The Voltage Induced in a Rotating Loop

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

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

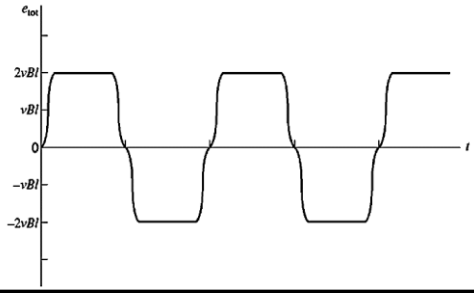
$$e_{ind} = \begin{cases} 2vBl & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

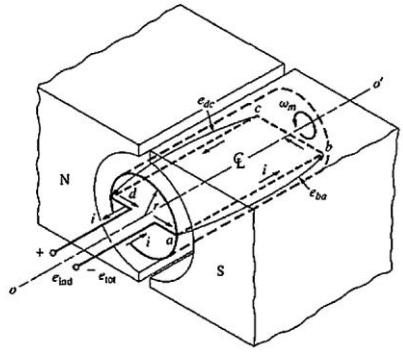


28

The Voltage Induced in a Rotating Loop

- When the loop rotates through **180°**, se**gment 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 induced voltage is shown in the figure as a function of time.





29

The Voltage Induced in a Rotating Loop

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

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

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

Since;

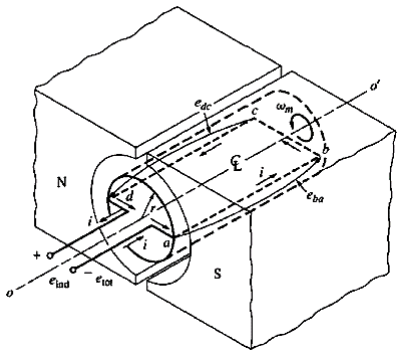
$v = r\omega$

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

30

The Voltage Induced in a Rotating Loop

- Notice also from the Figure, the rotor surface is a **cylinder**.
- so the area of the **rotor surface A** is just equal to **2πrl**.
- Since there are **two poles**, the area of the rotor under each pole (ignoring the small gaps between poles) is **Ap = πrl**.
- Therefore,



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

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

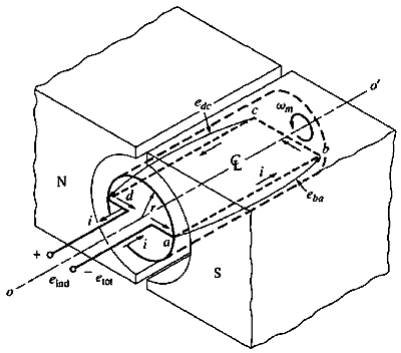
The Voltage Induced in a Rotating Loop

- 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:

$$\phi = A_P B$$

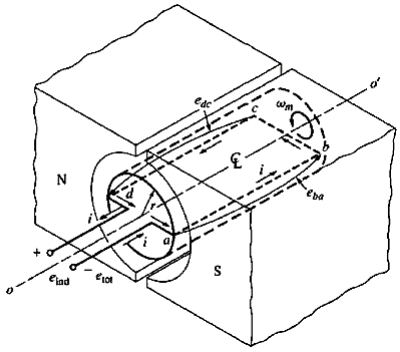
$$e_{\text{ind}} = \begin{cases} \frac{2}{\pi} A_P B\omega & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

$$\boxed{e_{\text{ind}} = \begin{cases} \frac{2}{\pi} \phi\omega & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}}$$



The Voltage Induced in a Rotating Loop

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

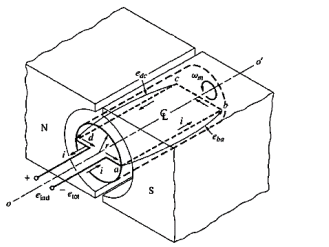


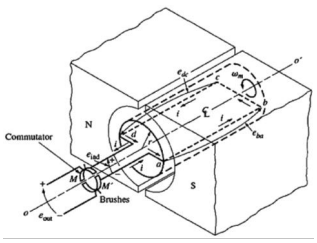
- The voltage generated in the machine is equal to the product of the **flux** inside the machine and the **speed of rotation** of the machine, multiplied by a **constant** representing the mechanical construction of the machine.
- In general, the voltage in any real machine will depend on the **three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

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

33

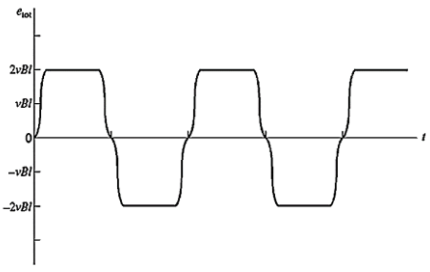
Getting DC Voltage out of the Rotating Loop

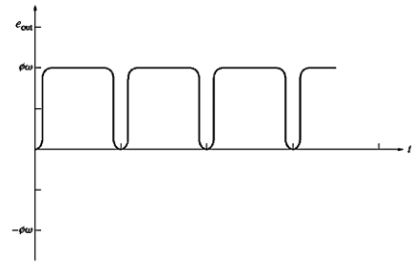








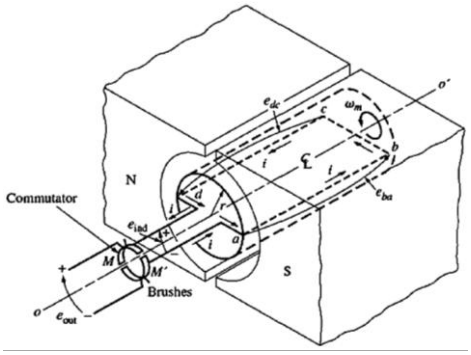




34

Getting DC Voltage out of the Rotating Loop

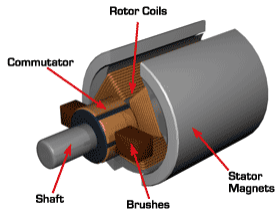
- Using «**commutator+brush**» combination is known as «**commutation**».
- The rotating semicircular segments are called «**commutator segments»**
- The fixed contacts are called «**brushes**».



The **commutator segments** in real machines are typically made of **copper bars**. The **brushes** are made of a **mixture containing graphite**, so that they cause very **little friction** as they rub over the rotating commutator segments.

35

Getting DC Voltage out of the Rotating Loop

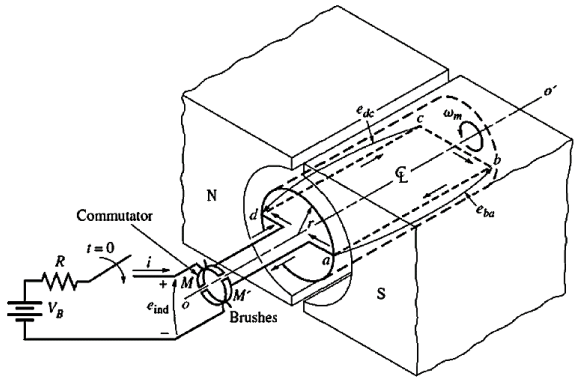


Source: electrical4u.com

36

The Induced Torque in the Rotating Loop

- Suppose that a **battery** is now connected to the machine as shown in the figure.
- The questions are
  - How much torque will be produced in the loop when the switch is closed ?
  - Is the conductor loop rotating or not due to the torque ?



37

The Induced Torque in the Rotating Loop

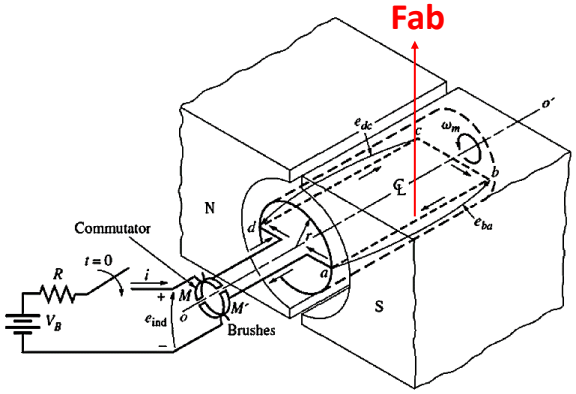
Segment ab:

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{F}_{ab} = i(\mathbf{l} \times \mathbf{B}) \quad \text{(Direction is upside)}$$
$$= ilB$$

The torque on the rotor caused by this force is

$$\tau_{ab} = rF \sin\theta$$
$$= r(ilB) \sin 90^\circ$$
$$= rilB \qquad \text{CCW}$$



38

The Induced Torque in the Rotating Loop

Segment bc:

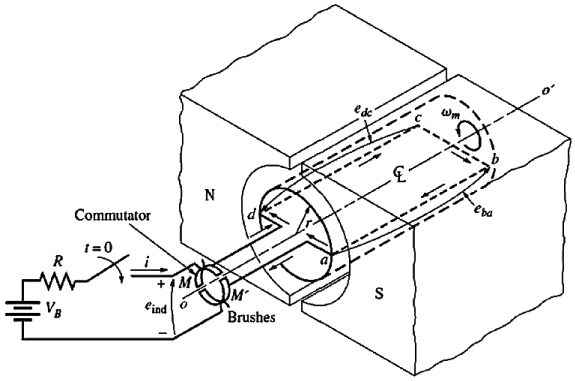
$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{F}_{bc} = i(\mathbf{l} \times \mathbf{B})$$
$$= 0 \quad \text{since } \mathbf{l} \text{ is parallel to } \mathbf{B}$$

$$\tau = rF \sin\theta$$

Therefore,

$$\tau_{bc} = 0$$



The Induced Torque in the Rotating Loop

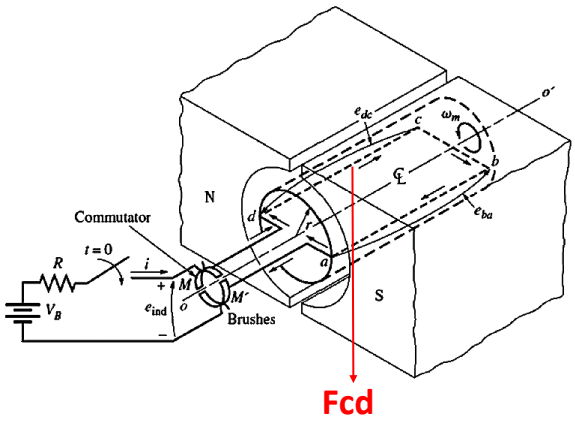
Segment cd:

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{F}_{cd} = i(\mathbf{l} \times \mathbf{B}) \quad \text{(Direction is downside)}$$
$$= ilB$$

The torque on the rotor caused by this force is

$$\tau_{cd} = rF \sin\theta$$
$$= r(ilB) \sin 90°$$
$$= rilB \quad \text{CCW}$$



The Induced Torque in the Rotating Loop

Segment da:

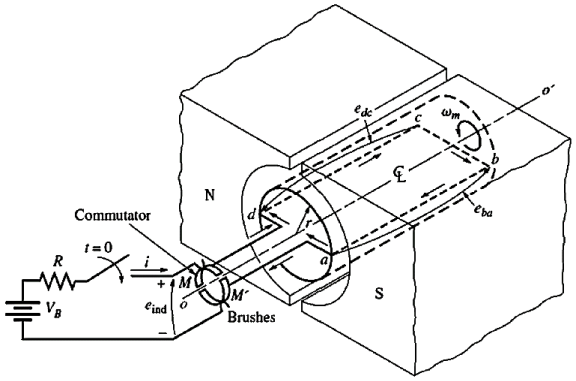
$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{F}_{da} = i(\mathbf{l} \times \mathbf{B})$$
$$= 0 \quad \text{since } \mathbf{l} \text{ is parallel to } \mathbf{B}$$

$$\tau = rF \sin\theta$$

Therefore,

$$\tau_{da} = 0$$



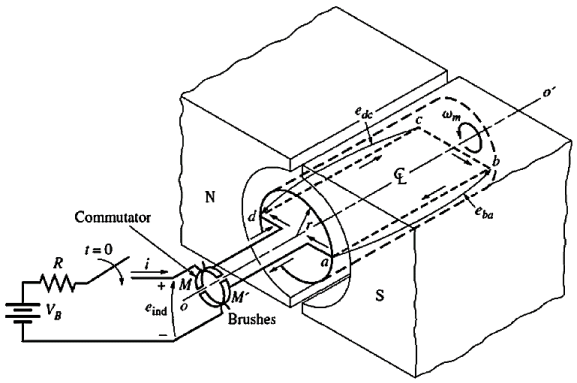
41

The Induced Torque in the Rotating Loop

The resulting total induced torque on the loop is given by

$$\tau_{ind} = \tau_{ab} + \tau_{bc} + \tau_{cd} + \tau_{da}$$

$$\tau_{ind} = \begin{cases} 2rilB & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$



42

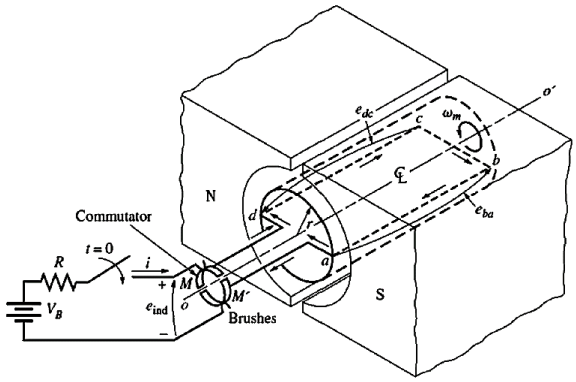
The Induced Torque in the Rotating Loop

- 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:

$\phi = A_P B$ where **Ap = πrl**

$$\tau_{ind} = \begin{cases} 2rilB & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

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



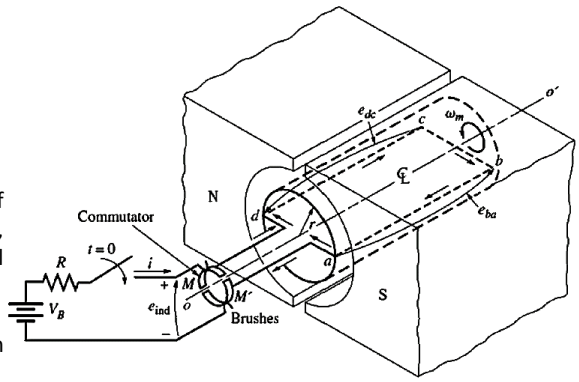
43

The Induced Torque in the Rotating Loop

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

- 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.
- In general, the **torque** in any real machine will depend on **three factors**:

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



44

Example

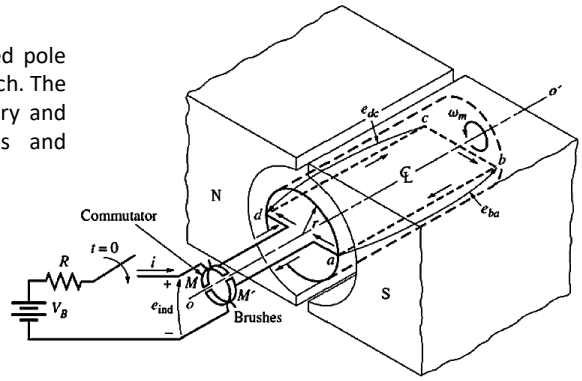
- The Figure shows a simple rotating loop between curved pole faces connected to a battery and a resistor through a switch. The resistor shown models the total resistance of the battery and the wire in the machine. The physical dimensions and characteristics of this machine are as follows:

$r = 0.5$ m $\quad l = 1.0$ m

$R = 0.3\ \Omega \quad B = 0.25$ T

$V_B = 120$ V

Answer the questions:



45

Example

(a) What happens when the switch is closed?

(a) When the switch in Figure 8–6 is closed, a current will flow in the loop. Since the loop is initially stationary, $e_{ind} = 0$. Therefore, the current will be given by

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

This current flows through the rotor loop, producing a torque

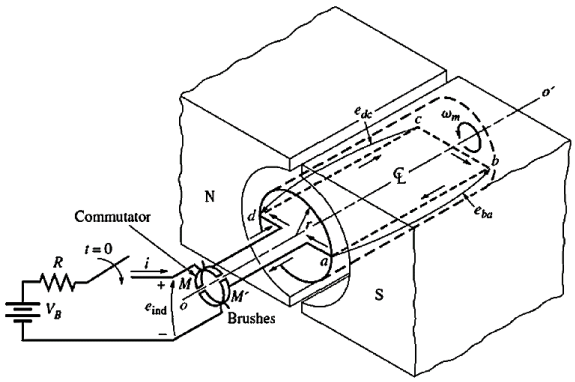
$$\tau_{\text{ind}} = \frac{2}{\pi}\phi i \qquad \text{CCW}$$

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

$$e_{\text{ind}} = \frac{2}{\pi}\phi\omega$$

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

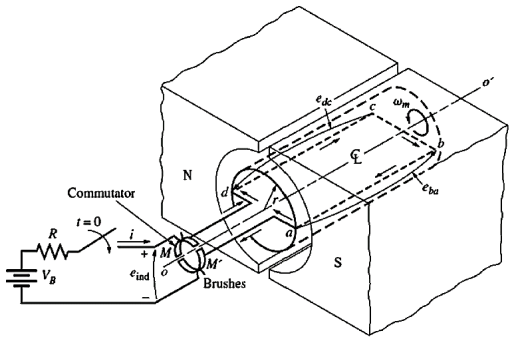
This is the same sort of starting behavior seen earlier in the linear dc machine.



46

Example

(b) What is the machine's maximum starting current? What is its steady-state angular velocity at no load?



(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 $\tau_{ind} = 0$ implies that current i must equal zero, since $\tau_{ind} = (2/\pi)\phi i$, and the flux is nonzero. The fact that $i = 0$ A means that the battery voltage $V_B = e_{ind}$. Therefore, the speed of the rotor is

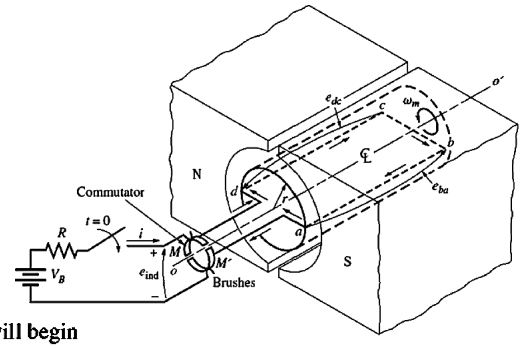
$$V_B = e_{ind} = \frac{2}{\pi}\phi\omega$$

$$\omega = \frac{V_B}{(2/\pi)\phi} = \frac{V_B}{2rlB}$$

$$= \frac{120\ \text{V}}{2(0.5\ \text{m})(1.0\ \text{m})(0.25\ \text{T})} = 480\ \text{rad/s}$$

Example

(c) Suppose a load is attached to the loop, and the resulting **load torque** is **10 Nm**. 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?



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

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

$$i = \frac{\tau_{ind}}{(2/\pi)\phi} = \frac{\tau_{ind}}{2rlB}$$

$$= \frac{10\ \text{N} \cdot \text{m}}{(2)(0.5\ \text{m})(1.0\ \text{m})(0.25\ \text{T})} = 40\ \text{A}$$

Example

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

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

Finally, the speed of the shaft is

$$\omega = \frac{e_{ind}}{(2/\pi)\phi} = \frac{e_{ind}}{2rlB}$$

$$= \frac{108\ \text{V}}{(2)(0.5\ \text{m})(1.0\ \text{m})(0.25\ \text{T})} = 432\ \text{rad/s}$$

The power supplied to the shaft is

$$P = \tau\omega$$

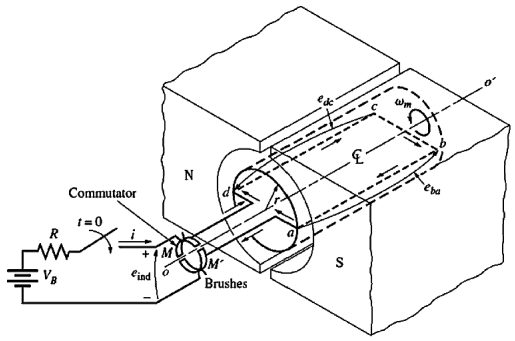
$$= (10\ \text{N} \cdot \text{m})(432\ \text{rad/s}) = 4320\ \text{W}$$

The power out of the battery is

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

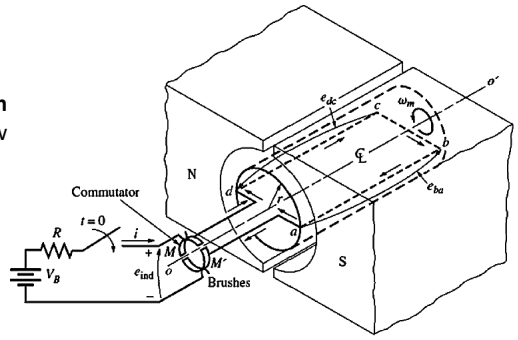
Why difference ?

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



Example

(d) Suppose the machine is again **unloaded**, and a torque of **7.5 Nm** is applied to the shaft **in the direction of rotation**. What is the new steady-state speed? Is this machine now a motor or a generator?



Example

(d) If a torque is applied in the direction of motion, the rotor accelerates. As the speed increases, the internal voltage e_{ind} increases and exceeds V_B, so the current flows out of the top of the bar and into the battery. This machine is now a *generator*. This current causes an induced torque opposite to the direction of motion. The induced torque opposes the external applied torque, and eventually $|\tau_{load}| = |\tau_{ind}|$ at a higher speed ω.

The current in the rotor will be

$$i = \frac{\tau_{ind}}{(2/\pi)\phi} = \frac{\tau_{ind}}{2rlB}$$

$$= \frac{7.5 \text{ N} \cdot \text{m}}{(2)(0.5 \text{ m})(1.0 \text{ m})(0.25 \text{ T})} = 30 \text{ A}$$

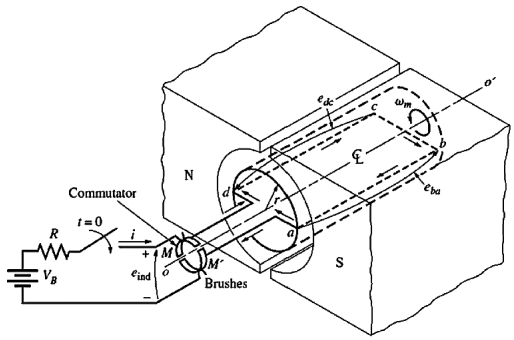
The induced voltage e_{ind} is

$$e_{ind} = V_B + iR$$
$$= 120 \text{ V} + (30 \text{ A})(0.3 \ \Omega)$$
$$= 129 \text{ V}$$

Finally, the speed of the shaft is

$$\omega = \frac{e_{ind}}{(2/\pi)\phi} = \frac{e_{ind}}{2rlB}$$

$$= \frac{129 \text{ V}}{(2)(0.5 \text{ m})(1.0 \text{ m})(0.25 \text{ T})} = 516 \text{ rad/s}$$



Example

(e) Suppose that the machine is running **unloaded** again. What would the final steady-state speed of the rotor be if the flux density were reduced to 0.20 T?

(e) Since the machine is initially unloaded at the original conditions, the speed $\omega = 480$ rad/s. If the flux decreases, there is a transient. However, after the transient is over, the machine must again have zero torque, since there is still no load on its shaft. If $\tau_{ind} = 0$, then the current in the rotor must be zero, and $V_B = e_{ind}$. The shaft speed is thus

$$\omega = \frac{e_{ind}}{(2/\pi)\phi} = \frac{e_{ind}}{2rlB}$$

$$= \frac{120 \text{ V}}{(2)(0.5 \text{ m})(1.0 \text{ m})(0.20 \text{ T})} = 600 \text{ rad/s}$$

Notice that when the flux in the machine is decreased, its speed increases. This is the same behavior seen in the linear machine and the same way that real dc motors behave.

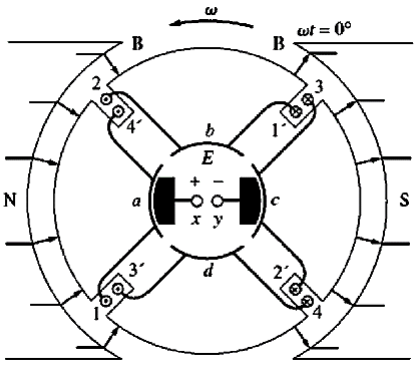
Commutation in a Simple Four-Loop DC Machine

- **Commutation** is the process of converting the ac voltages and currents in the rotor of a dc machine to dc voltages and currents at its terminals.
- It is the most critical part of the **design** and **operation** of any dc machine.
- A more detailed study is necessary to determine just how this conversion occurs and to discover the problems associated with it.
- Here the analysis is extended to the four loops which is more physically complex than only a single loop.

53

Commutation in a Simple Four-Loop DC Machine

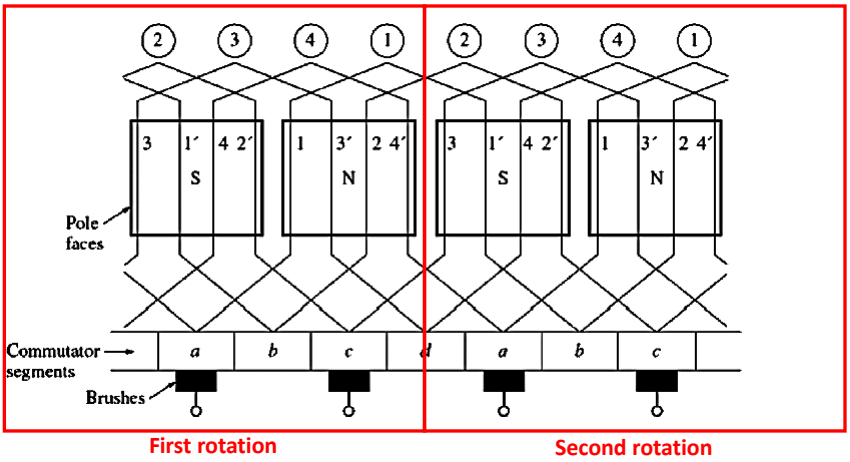
- A simple **four-loop**, **two-pole** dc machine is shown in the figure.
- This machine has **four complete loops** buried in slots carved in the **laminated steel of its rotor**.
- The pole faces of the machine are **curved** to provide a **uniform air-gap width** and to give a **uniform flux density** everywhere under the faces.



A four-loop two-pole dc machine shown at time wt=0°

54

Commutation in a Simple Four-Loop DC Machine



Winding diagram of this machine showing the interconnections of the rotor loops at time wt=0°.

55

Commutation in a Simple Four-Loop DC Machine

At the instant shown in Figure 8–7, the 1, 2, 3′, and 4′ ends of the loops are under the north pole face, while the 1′, 2′, 3, and 4 ends of the loops are under the south pole face. The voltage in each of the 1, 2, 3′, and 4′ ends of the loops is given by

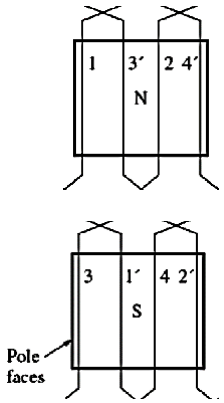
$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \qquad (1\text{–}45)$$

$$e_{ind} = vBl \quad \text{positive out of page} \qquad (8\text{–}17)$$

The voltage in each of the 1′, 2′, 3, and 4 en … en by

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

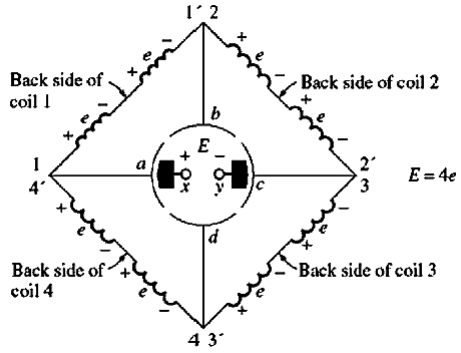
$$= vBl \quad \text{positive into the page} \qquad (8\text{–}18)$$



Check the polarities using slides 8 and 10 !

56

Commutation in a Simple Four-Loop DC Machine



The voltages on the rotor conductors at wt=0°.

- Notice that there are **two parallel paths** for current in the armature.
- The existence of two or more parallel paths for rotor current is a common feature of all commutation schemes.

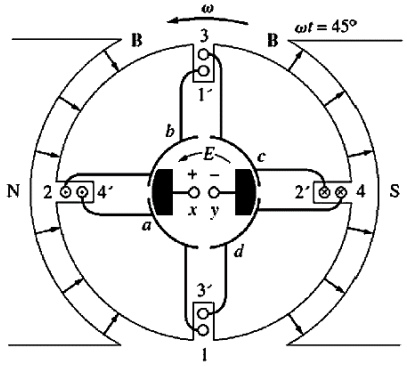
The total voltage at the brushes of the machine is

$$E = 4e \qquad \omega t = 0^\circ$$

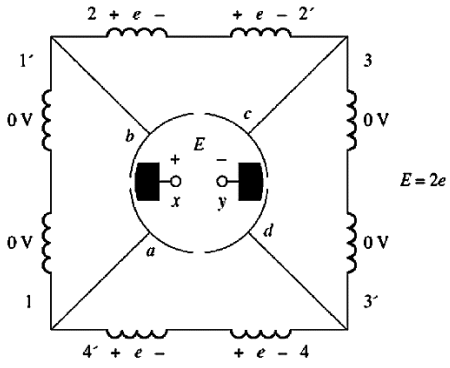
57

Commutation in a Simple Four-Loop DC Machine

What happens to the voltage of the terminals as the rotor **continues to rotate**?



A four-loop two-pole dc machine shown at time wt=45°



The voltages on the rotor conductors at wt=45°.

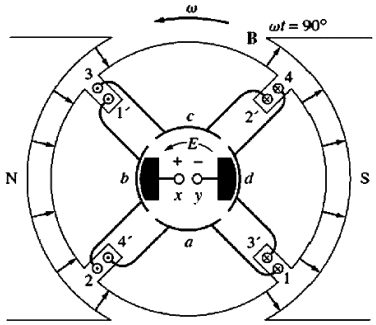
The total voltage at the brushes of the machine is

$$E = 2e \qquad \omega t = 45^\circ$$

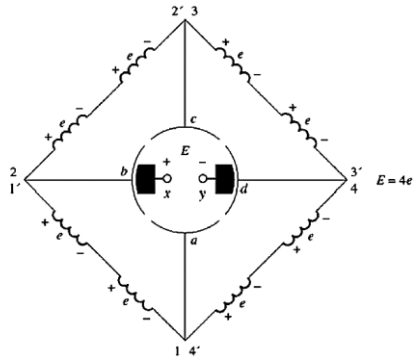
58

Commutation in a Simple Four-Loop DC Machine

What happens to the voltage of the terminals as the rotor **continues to rotate**?



A four-loop two-pole dc machine shown at time wt=90°.



The voltages on the rotor conductors at wt=90°.

The total voltage at the brushes of the machine is → $E = 4e \qquad \omega t = 90^{o}$

59

Commutation and Armature Construction in Real DC Machines

- In real dc machines, there are several ways in which the loops on the rotor (*also called the "**armature**"*) can be connected to its **commutator segments**.
- These different connections affect the number of **parallel current paths** within the rotor, the **output voltage** of the rotor, and **the number and position** of the **brushes** riding on the **commutator segments**.
- Different connection configurations affect the **voltage** and the **current** values of the **armature**, hence **power rating** of the DC machine.





Different types of DC motor armatures

60

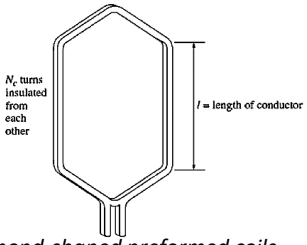
Commutation and Armature Construction in Real DC Machines

Rotor Coils:

- **Rotor coils** of **DC machines** are usually made of **copper conductors**.
- There are different shapes for rotor coils.
- One popular arrangement is the **diamond-shaped preformed coils** as seen in the figure.
- Each coil consists of a **number of turns** (***loops***) **of wire**.
- Each turn is taped and insulated from the other turns and from the rotor slot.
- Each side of a turn is called a "***conductor***".
- The **number of conductors** on a machine's armature is given by

$$Z = 2CN_C$$

where Z = number of conductors on rotor
C = number of coils on rotor
N_C = number of turns per coil



diamond-shaped preformed coils

61

Commutation and Armature Construction in Real DC Machines

Rotor Coils:



diamond-shaped preformed coils

Source: http://www.swigercoil.com



diamond-shaped preformed coils

Source: http://www.swcoils.com



Rotor coils connected to commutator segments

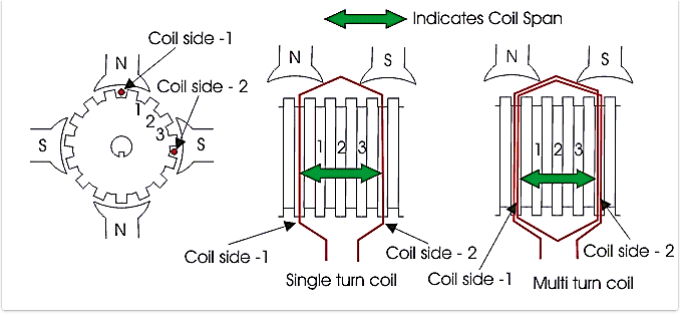
Source: http://www.electricaledition.com

62

Commutation and Armature Construction in Real DC Machines

Rotor Coils:

- Normally, a coil spans **180 electrical degrees**.
- This means that when **one side** is **under the center** of a given magnetic pole, the **other side** is **under the center** of a pole of **opposite polarity**.



Source: https://electricalstudy.sarutech.com

63

Commutation and Armature Construction in Real DC Machines

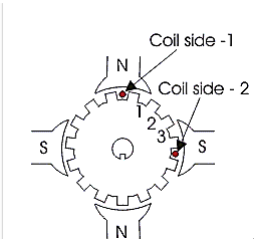
Rotor Coils:

- The relationship between the **electrical angle** and **mechanical angle** in a machine is given by

$$\theta_e = \frac{P}{2}\theta_m$$

where θ_e = electrical angle, in degrees
θ_m = mechanical angle, in degrees
P = number of magnetic poles on the machine

Example:



Pole number = 4
Electrical angle = 180°
Mechanical angle = 90°

Source: https://electricalstudy.sarutech.com

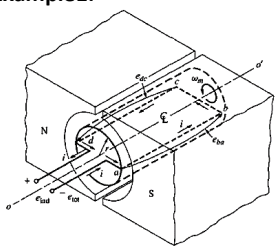
64

Commutation and Armature Construction in Real DC Machines

Full-Pitch Coil:

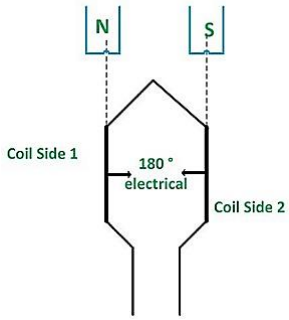
- If a coil spans **180 electrical degrees**, the voltages in the conductors on either side of the coil will be exactly the **same in magnitude** and **opposite in direction** at all times.
- Such a coil is called "***full-pitch coil***".

Example1:



Full-Pitch Coil

Example2:



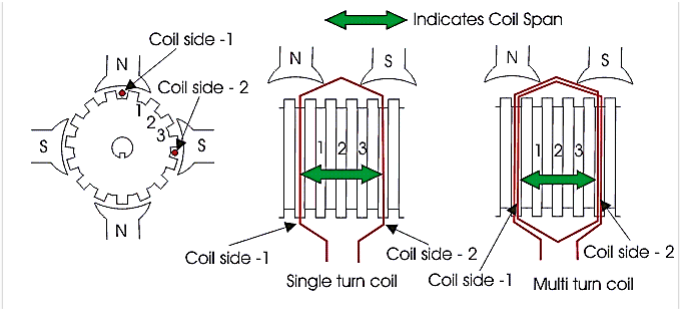
Full-Pitch Coil

Commutation and Armature Construction in Real DC Machines

Full-Pitch Coil:

- If a coil spans **180 electrical degrees**, the voltages in the conductors on either side of the coil will be exactly the same in magnitude and opposite in direction at all times.
- Such a coil is called "***full-pitch coil***".

Example3:



Full-Pitch Coil

Source: https://electricalstudy.sarutech.com

Commutation and Armature Construction in Real DC Machines

Fractional-Pitch Coil:

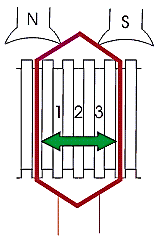
- Sometimes a coil is built that spans **less than 180 electrical degrees**.
- Such a coil is called "***fractional-pitch coil***".
- The rotor winding wound with **fractional-pitch coils** is called a "**chorded winding**"
- The **amount of chording** in a winding is described by a "**pitch factor, *p"***, which is defined by the following equation.
- **Fractional-pitch** coil is used in DC machines to **improve commutation**.

$$p = \frac{\text{electrical angle of coil}}{180^{o}} \times 100\%$$

67

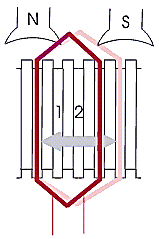
Commutation and Armature Construction in Real DC Machines

Comparison of Full-Pitch Coil and Fractional-Pitch Coil:



Full-Pitch Coil

$p = 100\%$



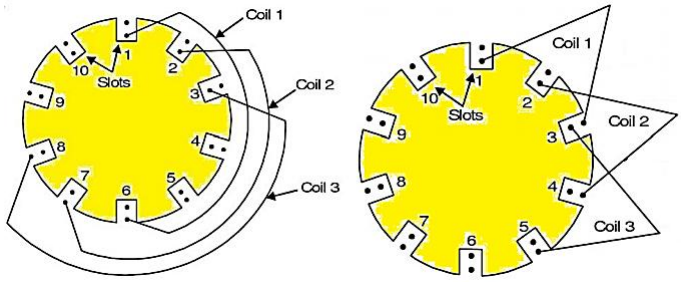
Fractional-Pitch Coil

$p = 75\%$

68

Commutation and Armature Construction in Real DC Machines

Comparison of Full-Pitch Coil and Fractional-Pitch Coil:



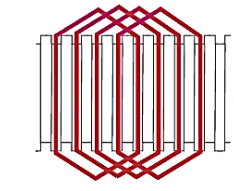
Full-Pitch Coil *Fractional-Pitch Coil*

69

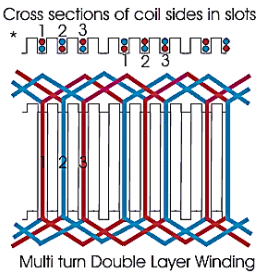
Commutation and Armature Construction in Real DC Machines

Multi-Winding Coil:

- Most rotor windings are **double-layer windings**.
- This means that sides from **two different coils** are inserted **into each slot**.
- One side of each coil will be at the **bottom of its slot**, and the other side will be at the **top of its slot**.
- In this fashion, all the windings are woven together, **increasing the mechanical strength and uniformity** of the final structure.



Multi turn Single Layer Winding



Multi turn Double Layer Winding

[*In Double layer winding, 1,2,3 are marked to only three coils among many]

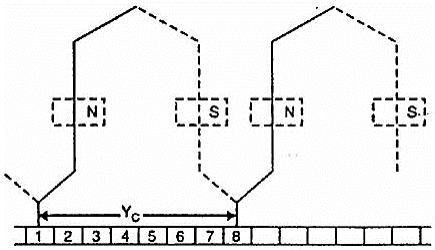
Source: https://electricalstudy.sarutech.com

70

Commutation and Armature Construction in Real DC Machines

Connections to the Commutator Segments:

- Once the **windings** are installed in the **rotor slots**, they must be connected to the **commutator segments**.
- There are a number of ways in which these connections can be made.
- There are also different winding arrangements which result have different advantages and disadvantages.
- The **distance** (***in number of segments***) between the commutator segments to which **the two ends of a coil** are connected is called "***commutator pitch, Yc***".



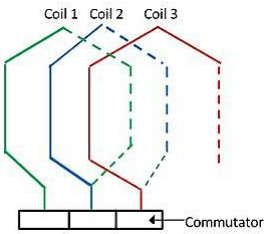
commutator pitch, Yc = 7

71

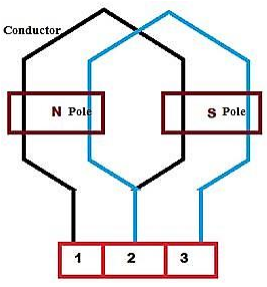
Commutation and Armature Construction in Real DC Machines

Progressive Winding:

- If the end of a coil is connected to a commutator segment **ahead** of the one its beginning is connected to, the winding is called a "**progressive winding**".



Source: https://circuitglobe.com



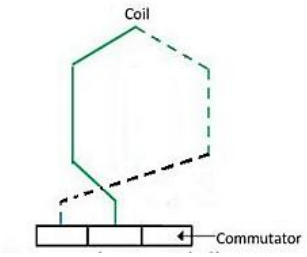
Source: http://electrialstandards.blogspot.com

72

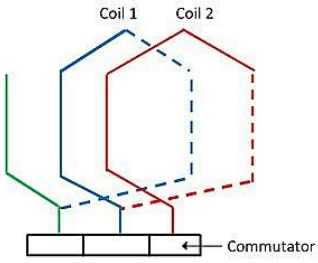
Commutation and Armature Construction in Real DC Machines

Retrogressive Winding:

- If the end of a coil is connected to a commutator segment **behind** the one its beginning is connected to, the winding is called a "**retrogressive winding**".



Source: https://circuitglobe.com



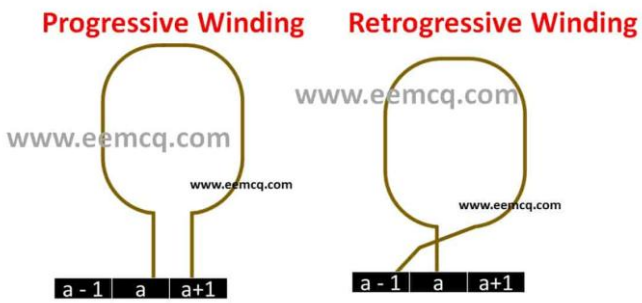
Source: https://circuitglobe.com

73

Commutation and Armature Construction in Real DC Machines

Comparison of Progressive and Retrogressive Windings:

- If everything else is identical, the direction of rotation of a **progressive-wound rotor** will be **opposite** to the direction of rotation of a **retrogressive-wound rotor**.

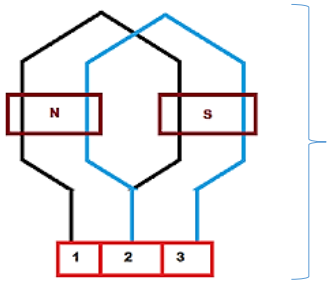


Source: www.eemcq.com

74

Commutation and Armature Construction in Real DC Machines

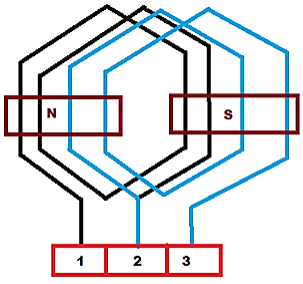
- **Rotor (*armature*) windings** are further classified according to the **plex** of their windings.
- A **simplex rotor winding** is a single, complete, closed winding wound on a rotor.
- A **duplex rotor winding** is a rotor with two complete and independent sets of rotor windings.
- A **triplex rotor winding** will have three complete and independent sets of rotor windings.
- Collectively, all armatures with **more than one set of windings** are said to have "***multiplex windings***".



Progressive Winding

Simplex lap winding

Source: https://www.electrical4u.com



Progressive Winding

Duplex lap winding

Source: https://www.electrical4u.com

75

Commutation and Armature Construction in Real DC Machines

Lap Winding and Wave Winding:

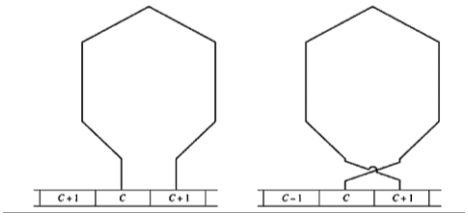
- **Armature windings** are also classified according to the **sequence of their connections** to the **commutator segments**.
- There are **two basic sequences** of armature winding connections: **"Lap Winding"** and **"Wave Winding"**.
- In addition, there is a **third type of winding**, called a **"Frog-leg winding"**, which combines **lap winding** and **wave winding** on a single rotor.
- Each one has its own **advantages** and **disadvantages**.

76

Commutation and Armature Construction in Real DC Machines

Lap Winding:

- The simplest type of winding construction used in modem dc machines is the **simplex series** or **lap winding**.
- A **simplex lap winding** is a rotor winding consisting of coils containing one or more turns of wire **with the two ends of each coil coming out at adjacent commutator segments**.
- If the end of the coil is connected to the segment **after the segment** that the beginning of the coil is connected to, the winding is a **progressive lap winding**.
- If the end of the coil is connected to the segment **before the segment** that the beginning of the coil is connected to, the winding is a **retrogressive lap winding**.



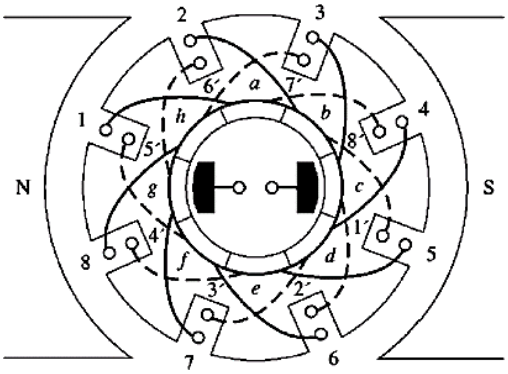
progressive *lap winding commutator pitch,* ***Yc = 1***

retrogressive *lap winding commutator pitch,* ***Yc = -1***

77

Commutation and Armature Construction in Real DC Machines

Lap Winding Example:



A simple two-pole lap-wound dc machine

Lap wound rotor
Pole number = 2
Slot number = 8
Pitch factor = 100%
Commutator segment number = 8
Brush number = 2
Coil number = 8
Conductor number = 2x8 = 16

78

Commutation and Armature Construction in Real DC Machines

Lap Winding:

- An interesting feature of **simplex lap windings** is that there are as **many parallel current paths** through the machine as there are **poles on the machine**.

The number of parallel current paths on the armature = the number of poles

- If **C** is the ***number of coils*** and ***commutator segments*** present in the rotor and **P** is the ***number of poles*** on the machine, then there will be **C/P *coils*** in each of the **P *parallel current paths*** through the machine.
- Also it is important to express that **P** current paths also requires that there be as **many brushes** on the machine as there are **poles** in order to tap all the current paths.

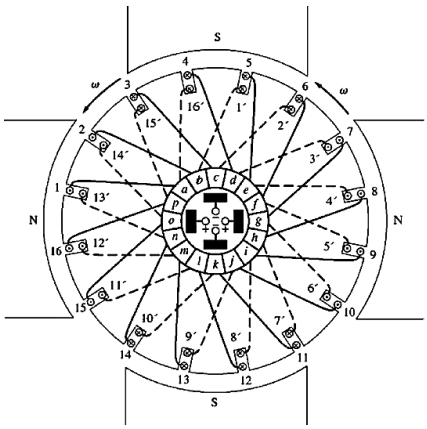
The number of brushes = the number of poles = the number of parallel current paths on the armature

79

Commutation and Armature Construction in Real DC Machines

Lap Winding:

- There are **four current paths** through the rotor, each having an equal voltage for the DC machine as shown in the figure.
- The fact that there are **many current paths** in a multi pole machine makes the lap winding an ideal choice for fairly **low-voltage, high-current DC machines**.
- Since the **required high currents can be split** among the **several different current paths**.

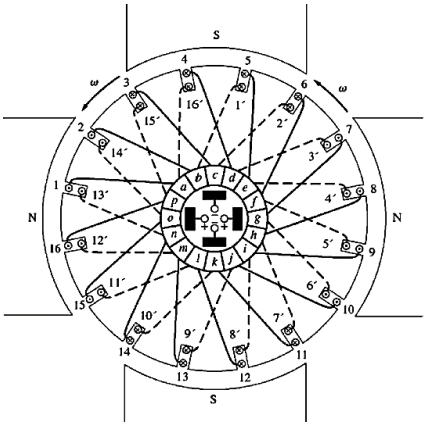


A simple four-pole lap-wound dc machine

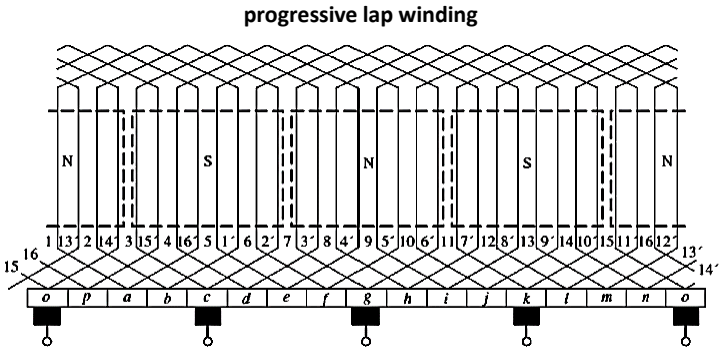
80

Commutation and Armature Construction in Real DC Machines

Lap Winding:



A simple four-pole lap-wound dc machine

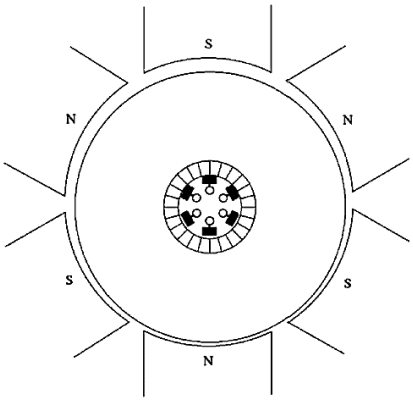


The rotor winding diagram of this machine

Commutation and Armature Construction in Real DC Machines

Possible Problem in Lap-Wound Machines:

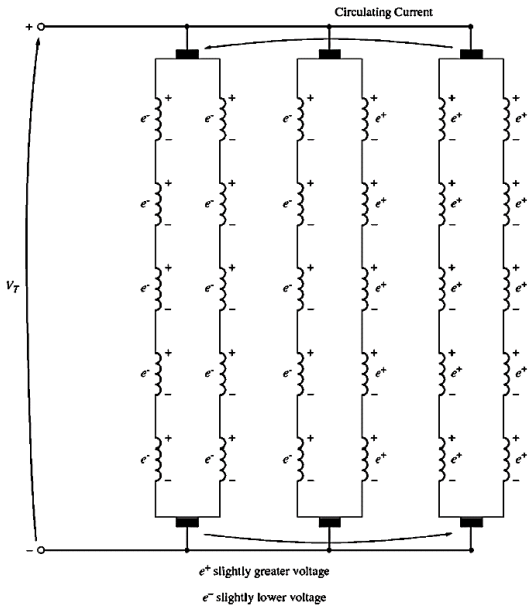
- Having **many parallel paths** in lap-wound machines can lead to a **serious problem**.
- As seen in the figure, **because of long usage**, there has been **slight wear on the bearings of this machine**, and the lower wires are closer to their pole faces than the upper wires are.
- As a result, there is a **larger voltage** in the current paths involving wires under the lower pole faces than in the paths involving wires under the upper pole faces.



A six-pole dc motor showing the effects of bearing wear. Notice that the rotor is slightly closer to the lower poles than it is to the upper poles.

Possible Problem in Lap-Wound Machines:

- Since **all the paths are connected in parallel**, the result will be a **circulating current** flowing out some of the brushes in the machine and back into others, as shown in the figure.
- **Circulating current** is **not good** for the machine.
- Since the winding resistance of a rotor circuit is so small, a very tiny imbalance among the voltages in the parallel paths will cause **large circulating currents through the brushes**.
- **Large circulating currents** will cause **serious heating problems** and **decrease the efficiency of the DC machine**.



83

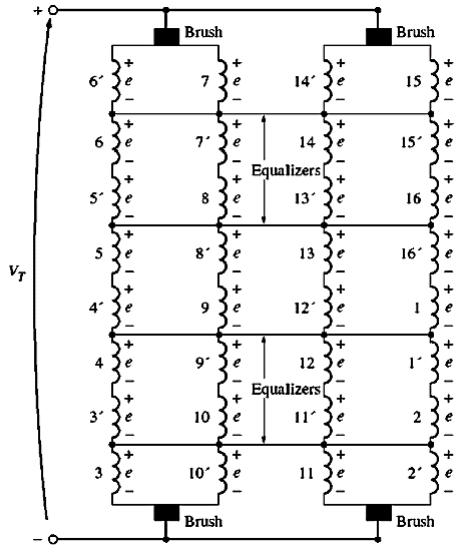
Commutation and Armature Construction in Real DC Machines

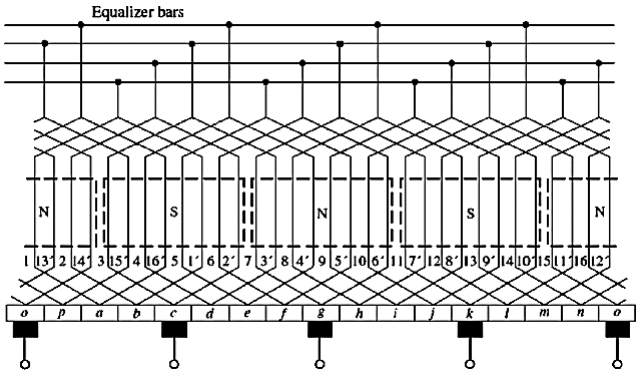
The Solution to Circulating Current Problem:

- The problem of circulating currents within the parallel paths of a machine **with four or more poles** can **never** be entirely resolved, but it **can be reduced** somewhat by ***equalizers* or *equalizing windings.***
- **Equalizers** are **bars** located **on the rotor** of a lap-wound dc machine that **short** together points at the **same voltage level** in the different parallel paths.
- The effect of this shorting is to cause any circulating currents that occur to now inside the small sections of windings thus shorted together and **to prevent** this circulating current from flowing through the brushes of the machine.

84

Equalizer Connection for the Four-Pole Machine:





85

Commutation and Armature Construction in Real DC Machines

Lap Winding:

- In general, for an ***m-plex*** **lap winding**, **the commutator pitch, yc** is

$$y_c = \pm m$$

+ for progressive winding
- for retrogressive winding

m=1 for simplex lap-winding
m=2 for dublex lap-winding
m=3 for triplex lap-winding

- T**he number of parallel current paths** for a ***P-pole*** **lap winding machine** is

$$a = mP$$

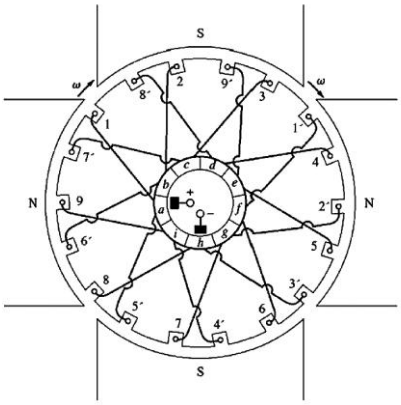
m=1 for simplex lap-winding
m=2 for dublex lap-winding
m=3 for triplex lap-winding
P is the pole number

86

Commutation and Armature Construction in Real DC Machines

Wave Winding:

- The **series** or **wave winding** is an alternative way to connect the rotor coils to the commutator segments.
- For the figure, (*simplex wave winding*), every *other* rotor coil connects back to a commutator segment adjacent to the beginning of the first coil.
- Therefore, there are **two coils in series** between the adjacent commutator segments.
- Furthermore, since each pair of coils between adjacent segments has a side under each pole face, all output voltages are the **sum** of the effects of every pole, and there can be **no voltage imbalances**.



A simplex four-pole wave-wound dc machine.

87

Commutation and Armature Construction in Real DC Machines

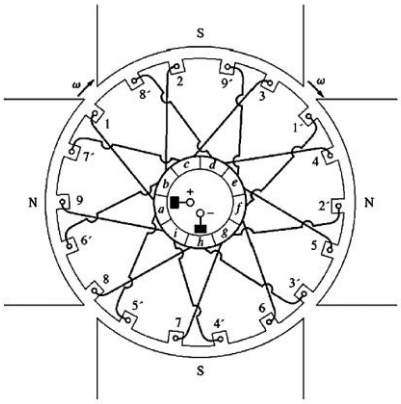
Wave Winding:

- The general expression for **commutator pitch** in any **simplex wave winding** is

$$y_c = \frac{2(C \pm 1)}{P} \qquad \text{simplex wave}$$

where

- **C** is the number of coils on the rotor.
- **P** is the number of poles on the machine.
- The **plus sign** is associated with **progressive windings**.
- The **minus sign** is associated with **retrogressive windings.**



A simplex four-pole wave-wound dc machine.

88

Commutation and Armature Construction in Real DC Machines

Wave Winding:

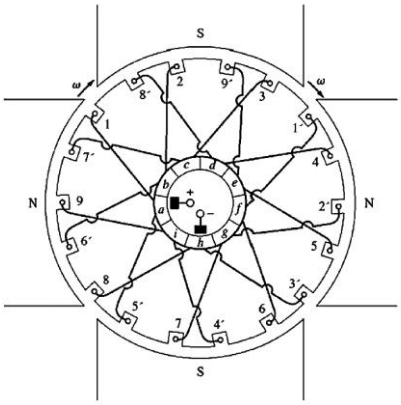
- The **number of current paths** on a **multiplex wave winding** is

$$\boxed{a = 2m} \qquad \text{multiplex wave}$$

where

- **m** is the **plex number**

  m=1 for **simplex** winding
  m=2 for **dublex** winding
  m=3 for **triplex** winding

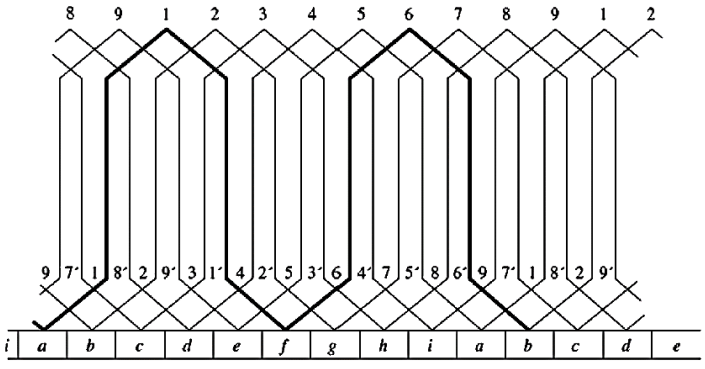


A simplex four-pole wave-wound dc machine.

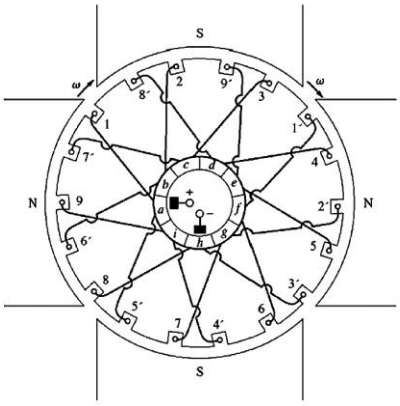
89

Commutation and Armature Construction in Real DC Machines

Wave Winding:



The rotor winding diagram

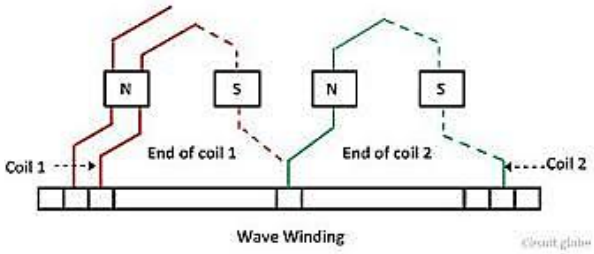


A simplex four-pole wave-wound dc machine

90

Commutation and Armature Construction in Real DC Machines

Wave Winding:

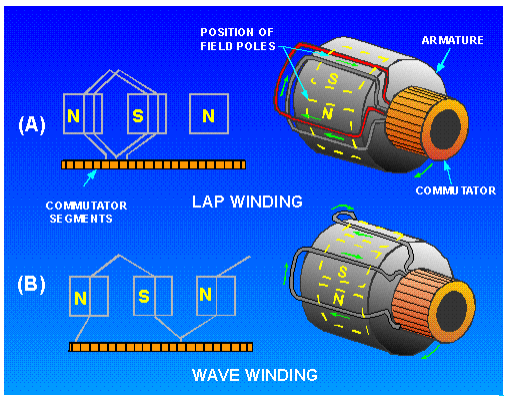


Source: https://circuitglobe.com

91

Commutation and Armature Construction in Real DC Machines

Comparison of Lap and Wave Winding:



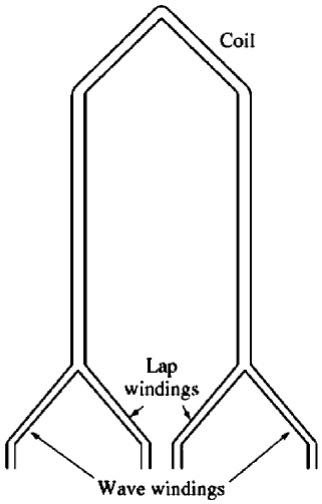
Source: https://www.quora.com

92

Commutation and Armature Construction in Real DC Machines

The Frog-Leg Winding:

- The frog-leg winding or self-equalizing winding gets its name from the shape of its coils, as shown in the Figure.
- It consists of a combination of a **lap winding** and a **wave winding**.
- **Wave windings** can function as ***equalizers*** for the lap winding.
- Since the ***equalizers*** in an **ordinary lap winding** are connected at points of equal voltage on the windings, **wave windings** reach between points of **essentially equal voltage** under successive pole faces of the same polarity, which are the same locations that equalizers tie together.



A frog-leg or self-equalizing winding coil.

93

Commutation and Armature Construction in Real DC Machines

The Frog-Leg Winding:

- The number of **current paths** present in a **frog-leg winding** is

$$a = 2Pm_{lap}$$

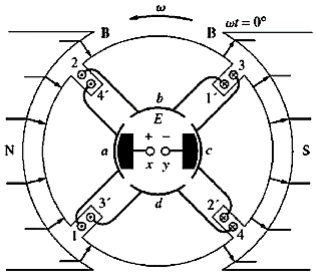
where **P** is the **number of poles** on the machine, and
$\mathbf{m_{lap}}$ is the **plex** of the lap winding.

94

Commutation and Armature Construction in Real DC Machines

Example:

Describe the rotor (*armature*) winding arrangement of the DC machine shown below.



Answer:

- The armature has 4 coils (1-1′,2-2′,3-3′,4-4′)
- Each coil has 1 turn
- There are a total of 8 conductors (4x2)
- There are 2 brushes (x,y)
- There are 4 commutator segments (a,b,c,d)
- There are 4 slots (1,2,3,4)
- The armature has **progressive lap winding**

95

Internal Generated Voltage of Real DC Machines

The **induced voltage** in any DC machine depends on **three factors:**

1) The flux in the machine
2) The speed of the rotor
3) A constant depending on the construction of the machine

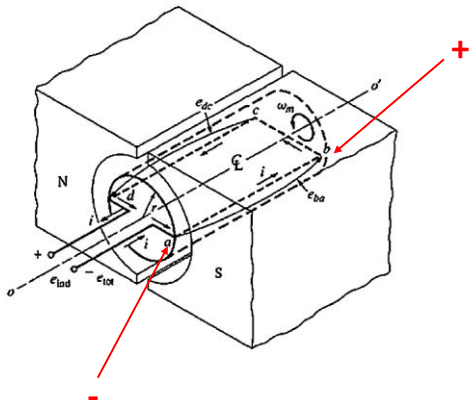
The voltage **in a single conductor** (***segment ab***) under the pole faces was previously shown to be

Segment ab:

$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$e_{ba} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l}$$

$$= \begin{cases} vBl & \text{under the pole face} \\ 0 & \text{beyond the pole edges} \end{cases}$$



96

Internal Generated Voltage of Real DC Machines

- The voltage out of the **armature** of a real machine is given as

$$E_A = \frac{ZvBl}{a}$$

where
Z is the **total number of conductors** in the armature
a is the **number of (*parallel*) current paths** in the armature

- Since ***v = w.r***

$$E_A = \frac{Zr\omega Bl}{a}$$

where
r is the **radius of the rotor (*armature*)**

97

Internal Generated Voltage of Real DC Machines

- Since the **flux of a pole** is equal to the **flux density** under the pole times **the pole's area**:

$$\phi = BA_P$$

where A_p is the pole area given by

$$A_P = \frac{A}{P} = \frac{2\pi rl}{P}$$

- The total flux per pole in the machine is thus

$$\phi = BA_P = \frac{B(2\pi rl)}{P} = \frac{2\pi rlB}{P}$$

- Therefore, the **internal generated voltage** in the armature can be expressed as

$$E_A = \frac{Zr\omega Bl}{a}$$
$$= \left(\frac{ZP}{2\pi a}\right)\left(\frac{2\pi rlB}{P}\right)\omega$$
$$\boxed{E_A = \frac{ZP}{2\pi a}\phi\omega}$$

Finally,

$$\boxed{E_A = K\phi\omega}$$

where

$$\boxed{K = \frac{ZP}{2\pi a}}$$

Since the conversion from revolutions per minute to radians per second is

$$\omega = \frac{2\pi}{60}n$$

$$\boxed{E_A = K'\phi n}$$
$$\boxed{K' = \frac{ZP}{60a}}$$

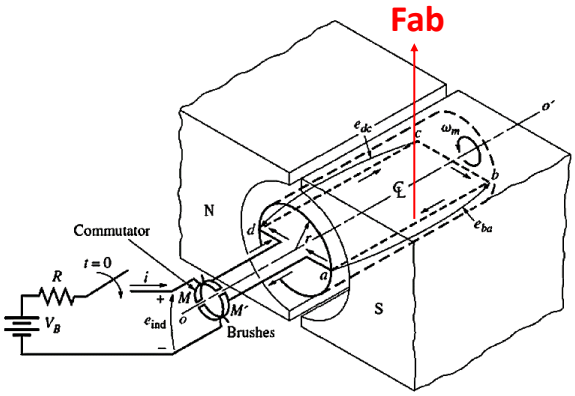
98

Induced Torque Equations Of Real DC Machines

The **induced torque** in any DC machine depends on **three factors:**

1) The flux in the machine
2) The armature (*rotor*) current in the machine
3) A constant depending on the construction of the machine

The **torque <u>in a single conductor</u>** (***segment ab***) under the pole faces was previously shown to be



Segment ab:

$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

$$\mathbf{F}_{ab} = i(\mathbf{l} \times \mathbf{B}) = ilB$$

The torque on the rotor caused by this force is

$$\tau_{ab} = rF \sin\theta = r(ilB) \sin 90^\circ = rilB \quad \text{CCW}$$

99

Induced Torque Equations Of Real DC Machines

- If there are "***a***" current paths in the machine, then the total armature current (I_A) is split among the current paths, and the **current <u>in a single conductor</u>** (I_{cond}) is given by

$$I_{cond} = \frac{I_A}{a}$$

- and the torque in a single conductor on the motor may be expressed as

$$\tau_{cond} = \frac{rI_A lB}{a}$$

- Since there are ***Z* conductors** in the armature, the **total induced torque on rotor** is

$$\tau_{ind} = \frac{ZrlBI_A}{a}$$

- And the total flux per pole in the machine was previously shown to be

$$\phi = BA_P = \frac{B(2\pi rl)}{P} = \frac{2\pi rlB}{P}$$

100

Induced Torque Equations Of Real DC Machines

- Therefore, the **total induced torque** on the rotor can be expressed as

$$\tau_{ind} = \frac{ZP}{2\pi a}\phi I_A$$

Finally,

$$\boxed{\tau_{ind} = K\phi I_A}$$

where

$$\boxed{K = \frac{ZP}{2\pi a}}$$

101

Self-study

- Solve Example 8.3 at page 517 from Chapman
- Solve Example 8.4 at page 517 from Chapman

102

Losses in DC Machines

- **DC generators** take the **mechanical power** and produce **electrical power**.
- **DC motors** take the **electrical power** and produce **mechanical power**.
- In either case, **energy conversion** is **not perfectly realized** because of **losses in DC machines**.

- The **output power** of a DC machine is always **less** than its **input power,** because of the **losses**.

$$P_{out} < P_{in}$$

$$P_{in} = P_{out} + P_{losses}$$

- Because of this fact, the efficiency is of a DC machine is **always less** than 100% and defined as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \quad < 100\%$$

- The **losses of a DC machine** are due to the
  - **Copper losses on the stator and armature (*rotor*)**
  - **Core losses of the stator and armature (Hysteresis losses + Eddy current losses)**
  - **Brush Losses due to commutation process**
  - **Mechanical Losses**
  - **Stray Losses (*any kind of losses different from the listed ones above*)**

103

Losses in DC Machines

Copper Losses:

- **Copper losses** are the **electrical losses** that occur in the **armature windings (*on rotor*)** and **field windings (*on stator*)** of the machine.

- The **copper losses** for the **armature windings** and **field windings** are given by

Armature loss:	$P_A = I_A^2 R_A$
Field loss:	$P_F = I_F^2 R_F$

where P_A = armature loss
P_F = field circuit loss
I_A = armature current
I_F = field current
R_A = armature resistance
R_F = field resistance

The **resistance** used in these calculations is usually the winding resistance at normal operating temperature.

104

Losses in DC Machines

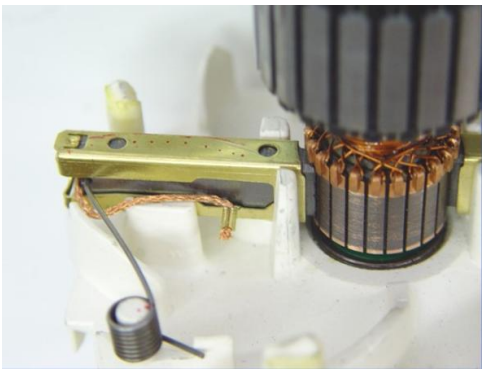
Brush Losses:

- The **brush loss** is the **power lost** across the contact potential at the brushes of the machine.
- **Brush loss** is given by the following equation:

$$P_{BD} = V_{BD} I_A$$

where P_{BD} = brush drop loss
V_{BD} = brush voltage drop
I_A = armature current

- Brush voltage drop (V_{BD}) is **approximately constant** over a large range of armature currents and about **2 V**.



105

Losses in DC Machines

Core Losses:

- The **core losses** are the sum of **hysteresis losses** and **eddy current losses** occurring in the metal of the motor (both in stator and armature).
- **Core losses** of DC machines are similar to the core losses occurring in the transformers.
- **Core losses** of DC machines is proportional to **the square of the flux density** (B^2)
- **Core losses** of DC machines is proportional to **the 1.5th power of the speed of rotation** ($n^{1.5}$)







106

Losses in DC Machines

Mechanical Losses:

- **Mechanical losses** in a DC machine are the losses associated with **mechanical effects**.
- There are two basic types of **mechanical losses**:
  - **Friction losses**
  - **Windage losses**
- **Friction losses** are caused by the **friction** of the **bearings** in the DC machine
- **Windage losses** are caused by the **friction** between the **moving parts** of the DC machine and the **air** inside the motor's casing.
- Both of these losses are proportional to the **cube of the speed of rotation of the machine (n^3)**.

107

Losses in DC Machines

Stray Losses:

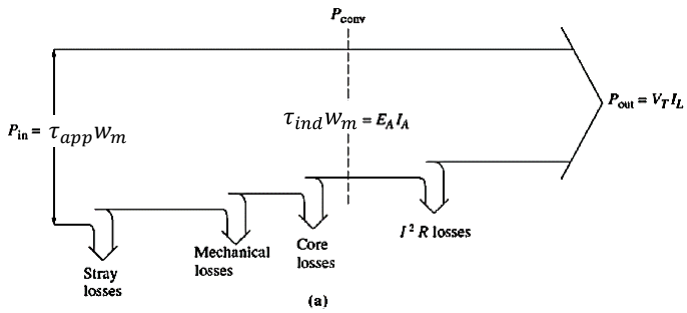
- **Stray losses** are *miscellaneous losses* that can occur in DC machines.
- **Stray losses** are losses that cannot be placed in one of the previous categories.
- No matter how carefully losses are accounted for, some always escape inclusion in one of the above categories.
- All such losses are lumped into stray losses.
- For most machines, **stray losses** are taken by convention usually to be **1 percent of full load (1%)**.

108

The Power Flow Diagram

For DC Generator:

Input power is mechanical power



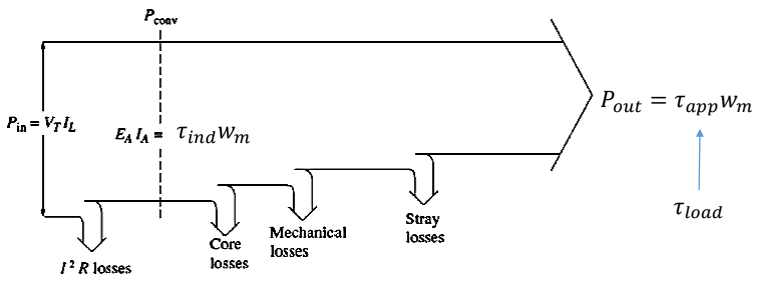
Output power is electrical power

Power-flow diagram for DC generator

The Power Flow Diagram

For DC Motor:

Input power is electrical power

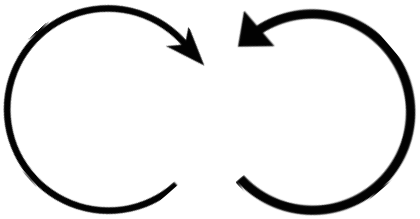


Output power is mechanical power

Power-flow diagram for DC motor

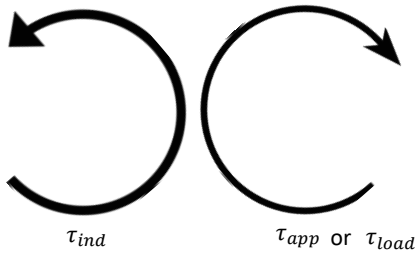
Comparison of Torques for DC Motors and Generators

For DC Generator:



$\tau_{ind} = K\phi I_A$

For DC Motor:



$\tau_{ind} = K\phi I_A$

111

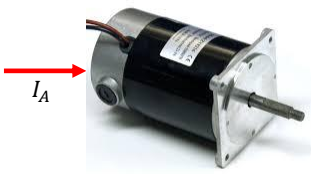
Comparison of Armature Currents for DC Motors and Generators

For DC Generator:



$E_A = K\phi\omega$

For DC Motor:



$E_A = K\phi\omega$

112

Self-study

- Solve **all problems** of Chapter 3 from Chapman

Review Questions

1) What is commutation? How can a commutator convert ac voltages on a machine's armature to dc voltages at its terminals?
2) Why does curving the pole faces in a dc machine contribute to a smoother dc output voltage from it?
3) What is the pitch factor of a coil?
4) Explain the concept of electrical degrees. How is the electrical angle of the voltage in a rotor conductor related to the mechanical angle of the machine's shaft?
5) What is commutator pitch?
6) What is the plex of an armature winding?
7) How do lap windings differ from wave windings?
8) What are equalizers? Why are they needed on a lap-wound machine but not on a wave-wound machine?
9) What is armature reaction? How does it affect the operation of a dc machine?
10) Explain the L di/dt voltage problem in conductors undergoing commutation.
11) How does brush shifting affect the sparking problem in dc machines?
12) What are commutating poles? How are they used?
13) What are compensating windings? What is their most serious disadvantage?
14) Why are laminated poles used in modem dc machine construction?
15) What is an insulation class?
16) What types of losses are present in a dc machine?

END OF CHAPTER 3

DC MACHINERY FUNDAMENTALS