EEE 321

Electromechanical Energy Conversion – I

By

Prof. Dr. A. Mete VURAL
mvural@gantep.edu.tr

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CHAPTER 3

DC MACHINERY FUNDAMENTALS

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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.

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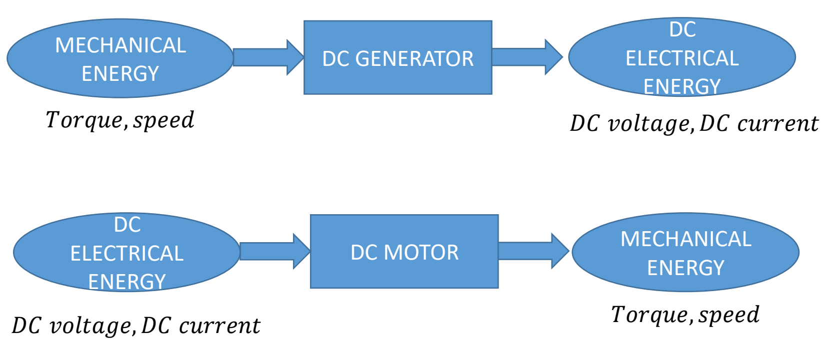
Introduction



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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

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What are applications of DC motors?

Drill

Spinning and Weaving machines (textile industry)

Crane

Lathe

Electric traction

Air compressor

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What are applications of DC motors?

Robotic applications

conveyors

tachogenerators

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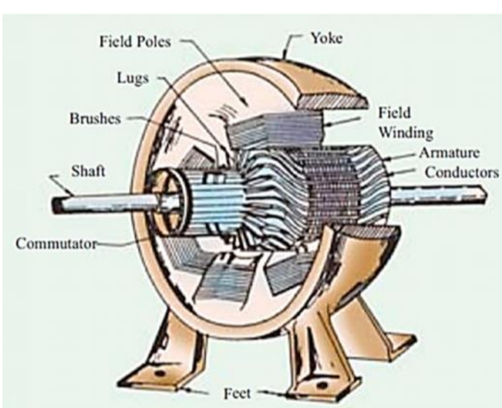
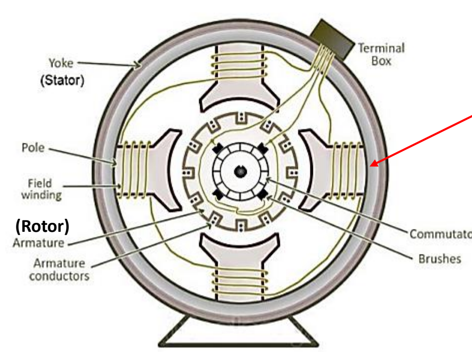
Construction of DC Machines





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

Basic components of a DC Machine

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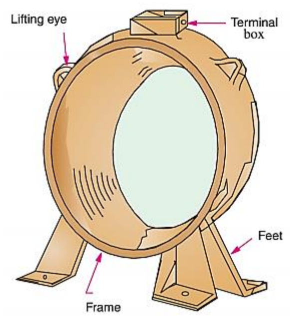
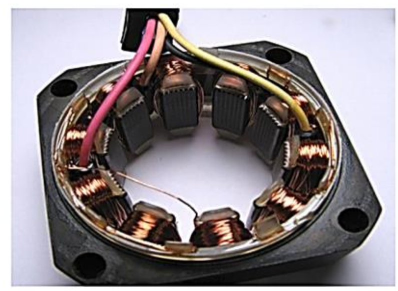
Construction of DC Machines

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

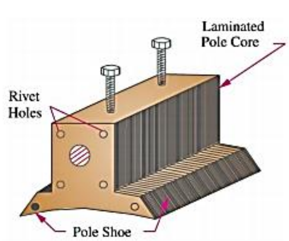
Construction of DC Machines

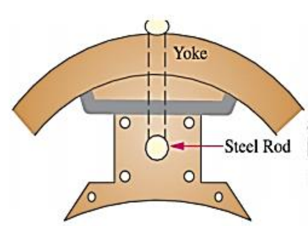
Pole-Cores and Pole-Shoes:

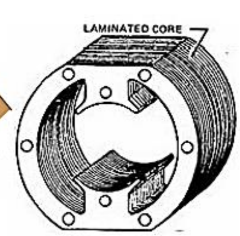
- The field magnets consist of pole cores and pole shoes as shown in the figure.

- 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.



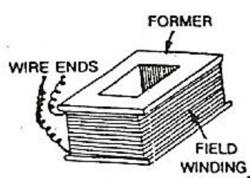


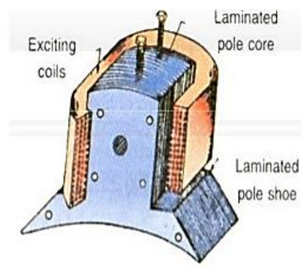


Construction of DC Machines

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.





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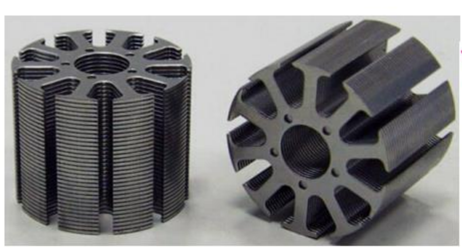
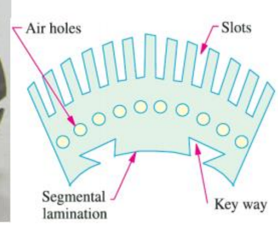
Construction of DC Machines

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.





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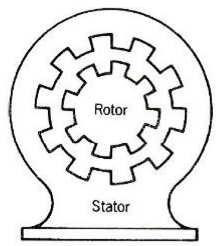
Construction of DC Machines

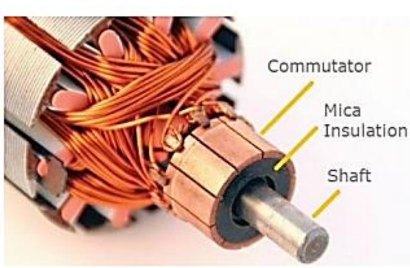
- Both **stator** and **rotor** are made of **ferromagnetic materials**.
- In most machines, slots are cut on the **inner periphery of the stator** and **outer periphery of the rotor** structure, as shown below.
- Copper conductors are placed in both of these slots.



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.



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.

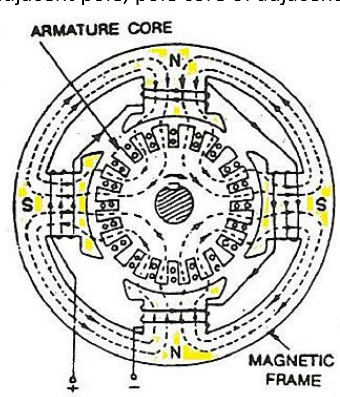
brushes

bearing

Construction of DC Machines

Magnetic circuit of DC Machines:

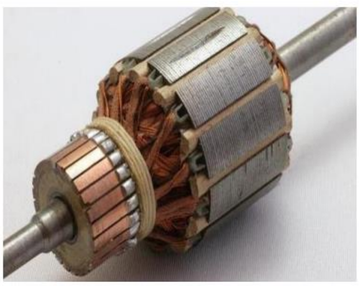
- In DC machines, there are as **many magnetic paths** as the **number of poles**.
- For example, there are **4 magnetic paths and 4 poles** of the DC machine as shown in the figure.
- Each complete path includes yoke, pole core, pole shoe, air gaps (*stator to rotor & rotor to stator*), armature teeth,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



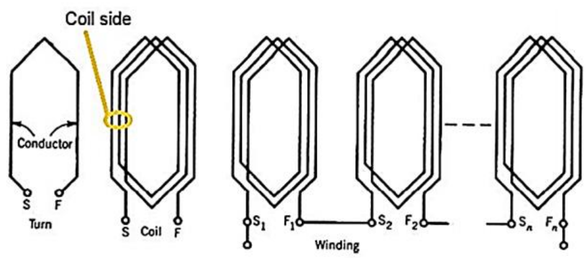
Construction of DC Machines

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



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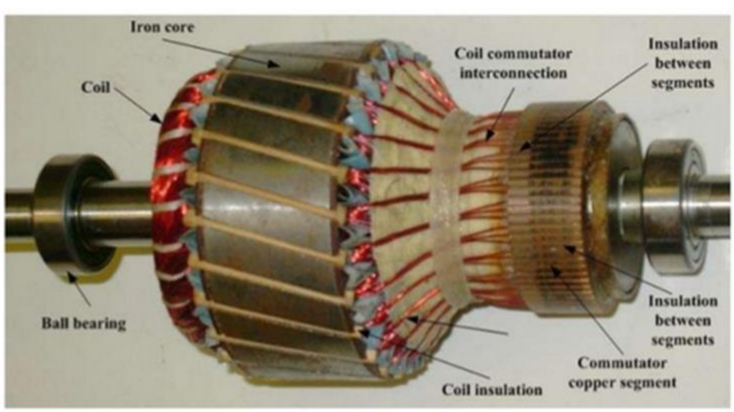
Construction of DC Machines

Armature of a DC machine:



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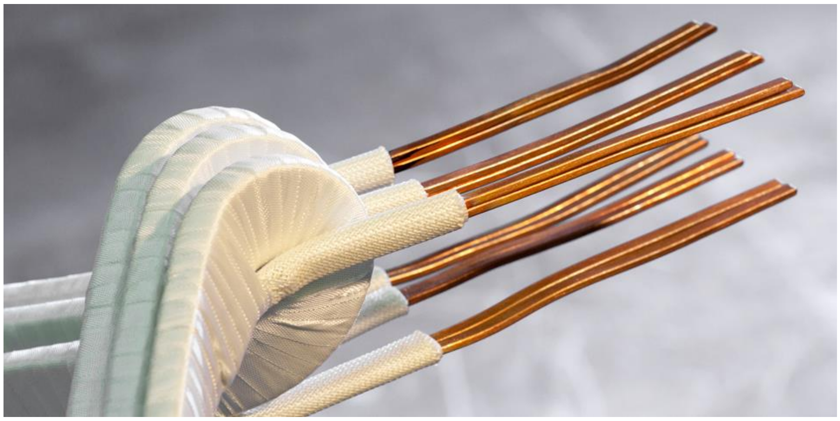
Construction of DC Machines

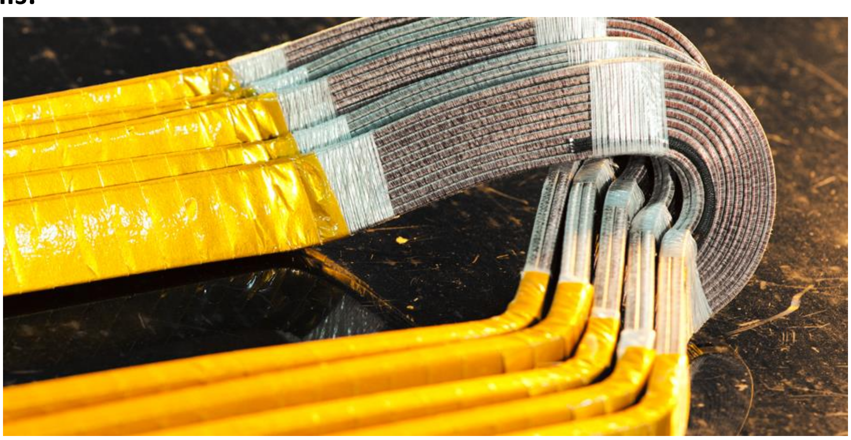
Rotor Coils:



Source: https://jayelectric.com

Construction of DC Machines

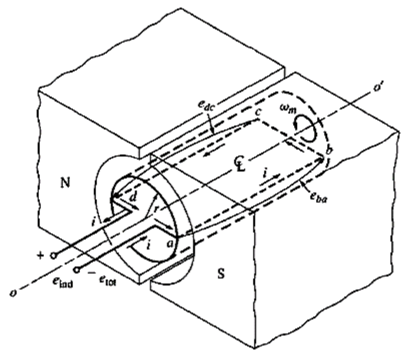
Rotor Coils:



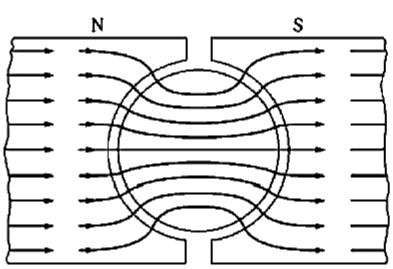
Source: https://jayelectric.com

Simple Rotating Loop Between Curved Pole Faces

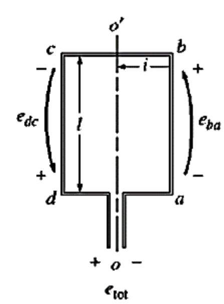
- The simplest possible rotating dc machine is shown in the figure.
- It consists of a single loop of wire rotating about a fixed axis.
- The **rotating part** of this machine is called the «**rotor**».
- The **stationary part** is called the «**stator**».
- The **magnetic field** for the machine is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



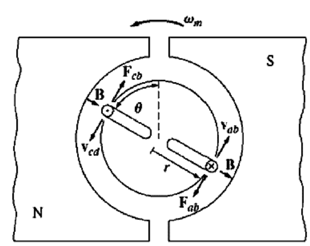
Simple Rotating Loop Between Curved Pole Faces



view of field lines.



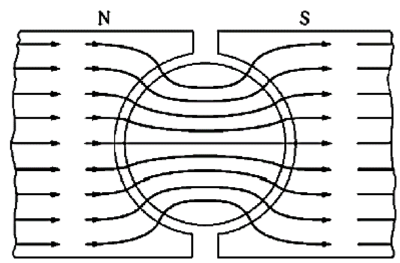
top view.



front view.

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**.



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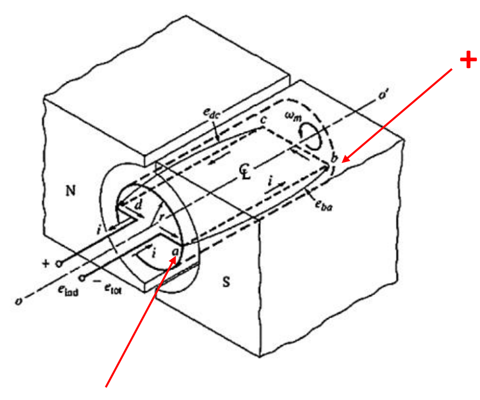
The Voltage Induced in a Rotating Loop

Segment ab:

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

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



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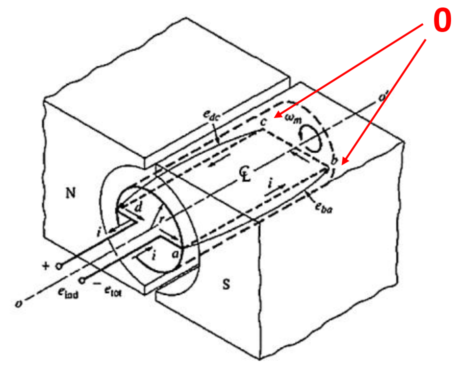
The Voltage Induced in a Rotating Loop

Segment bc:

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

$$e_{cb} = 0$$

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

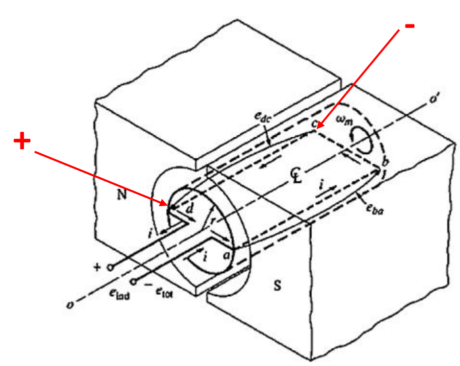


The Voltage Induced in a Rotating Loop

Segment cd:

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

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



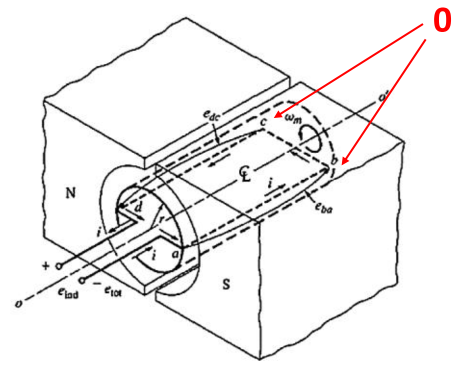
The Voltage Induced in a Rotating Loop

Segment da:

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

$$e_{ad} = 0$$

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

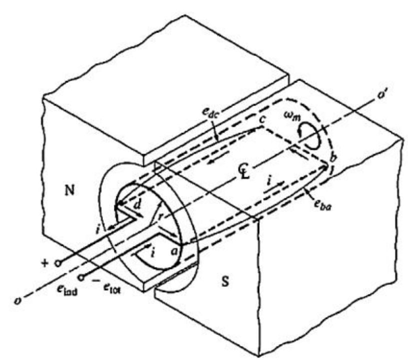


The Voltage Induced in a Rotating Loop

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

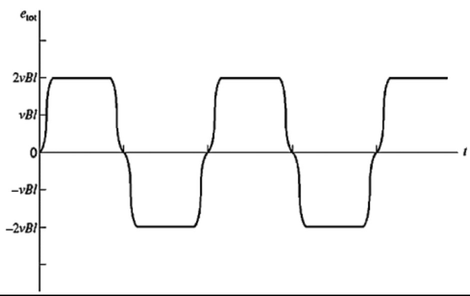
$$e_{ind} = e_{ba} + e_{cb} + e_{dc} + e_{ad}$$

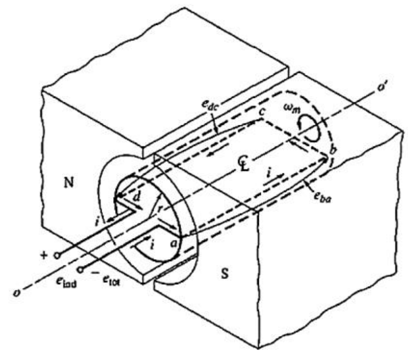
$$\boxed{e_{ind} = \begin{cases} 2vBl & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}}$$



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.





The Voltage Induced in a Rotating Loop

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

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

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

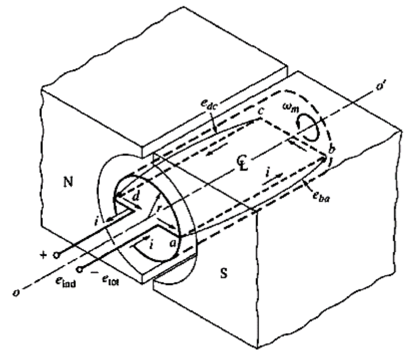
Since;

$v = r\omega$

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

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,



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

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

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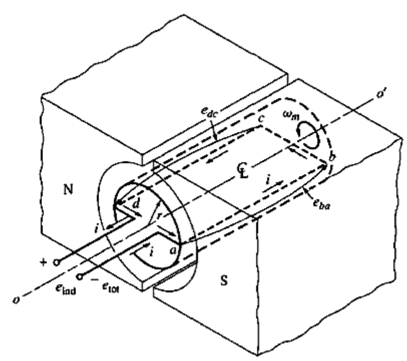
The Voltage Induced in a Rotating Loop

- The **flux density B** is **<u>constant</u>** 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:



$$\phi = A_P B$$

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

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

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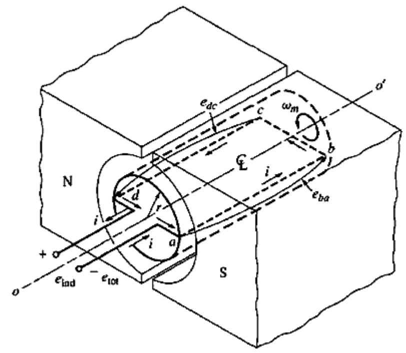
The Voltage Induced in a Rotating Loop

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

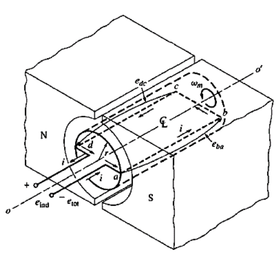


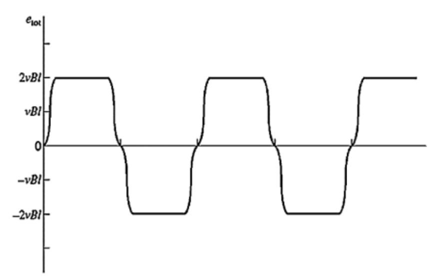
- The voltage generated in the machine is equal to the product of the **flux** inside the machine and the **speed of rotation** of the machine, multiplied by a **constant** representing the mechanical construction of the machine.

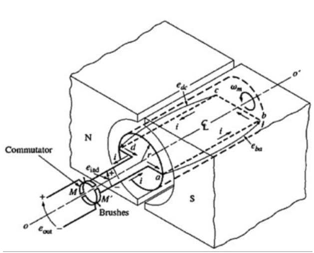
- In general, the voltage in any real machine will depend on the **three factors**:

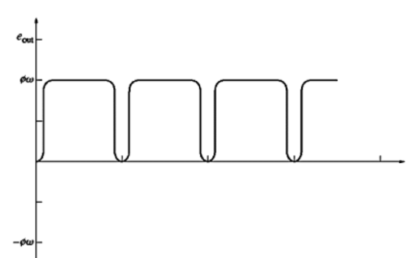
1) The flux in the machine
2) The speed of rotation
3) A constant representing the construction of the machine

Getting DC Voltage out of the Rotating Loop



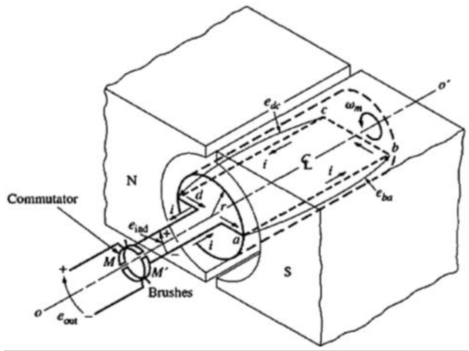






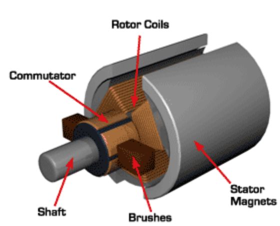
Getting DC Voltage out of the Rotating Loop

- 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.

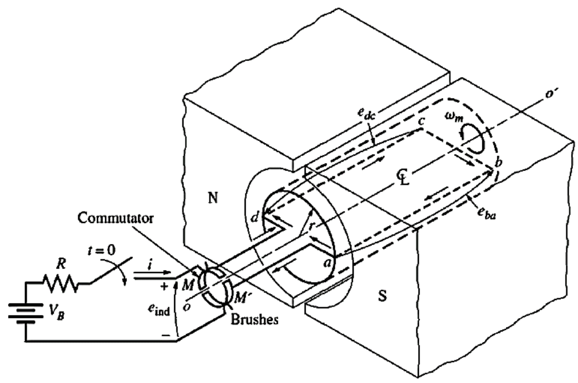
Getting DC Voltage out of the Rotating Loop



Source: electrical4u.com

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 ?

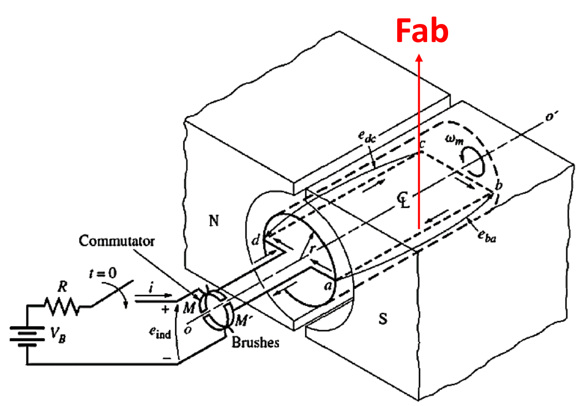


The Induced Torque in the Rotating Loop

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

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

The Induced Torque in the Rotating Loop

Segment bc:

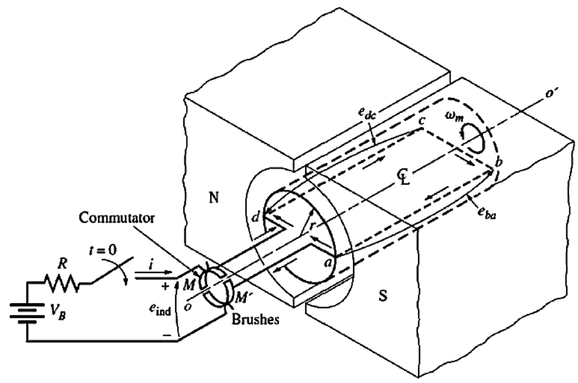
$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

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

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

Therefore,

$$\tau_{bc} = 0$$



The Induced Torque in the Rotating Loop

Segment cd:

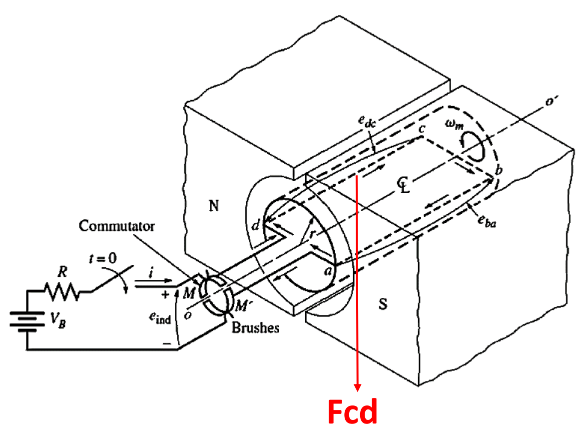
$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

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

(Direction is downside)

The torque on the rotor caused by this force is

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



The Induced Torque in the Rotating Loop

Segment da:

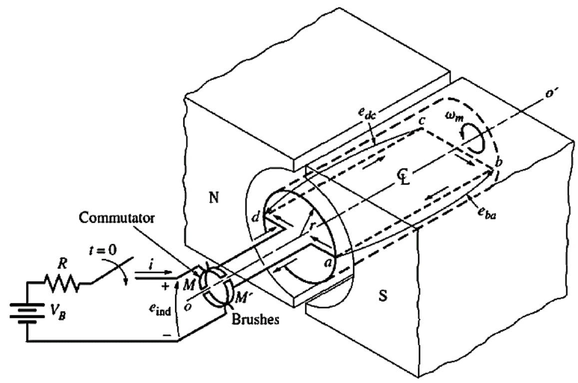
$$\mathbf{F} = i(\mathbf{l} \times \mathbf{B})$$

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

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

Therefore,

$$\tau_{da} = 0$$

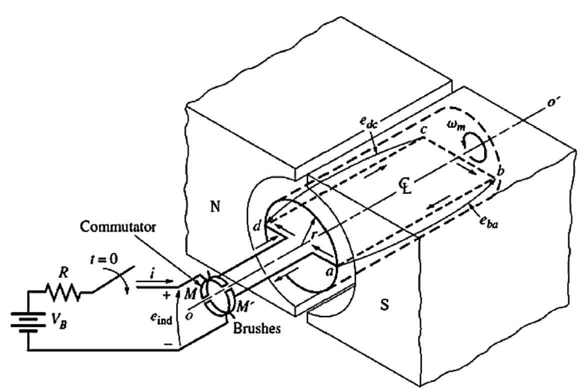


The Induced Torque in the Rotating Loop

The resulting total induced torque on the loop is given by

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

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



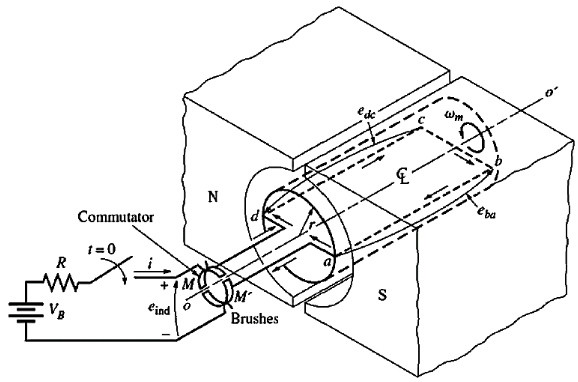
The Induced Torque in the Rotating Loop

- 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**

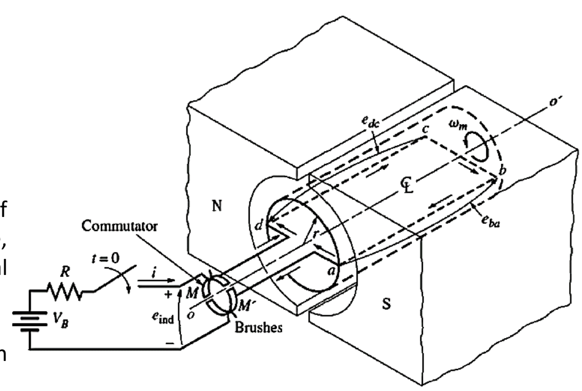
$$\tau_{\text{ind}} = \begin{cases} 2rilB & \text{under the pole faces} \\ 0 & \text{beyond the pole edges} \end{cases}$$

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



The Induced Torque in the Rotating Loop

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



- 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

Example

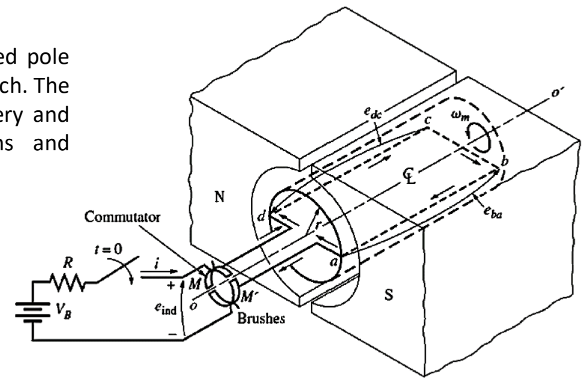
- The Figure shows a simple rotating loop between curved pole faces connected to a battery and a resistor through a switch. The resistor shown models the total resistance of the battery and the wire in the machine. The physical dimensions and characteristics of this machine are as follows:

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

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

$V_B = 120$ V

Answer the questions:



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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

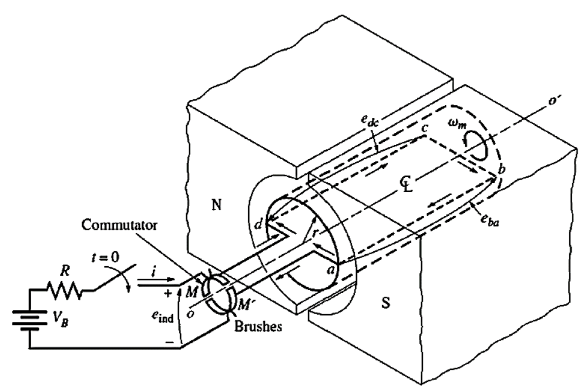
$$\tau_{\text{ind}} = \frac{2}{\pi}\phi i \qquad \text{CCW}$$

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 $V_B = e_{\text{ind}}$.

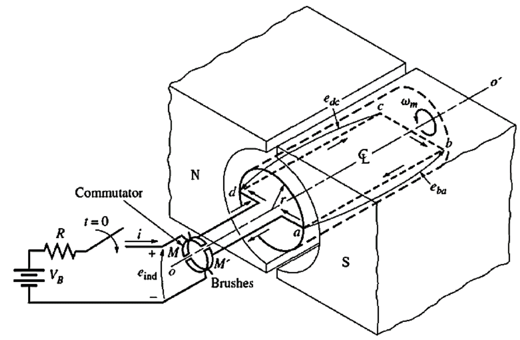
This is the same sort of starting behavior seen earlier in the linear dc machine.



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

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

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

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

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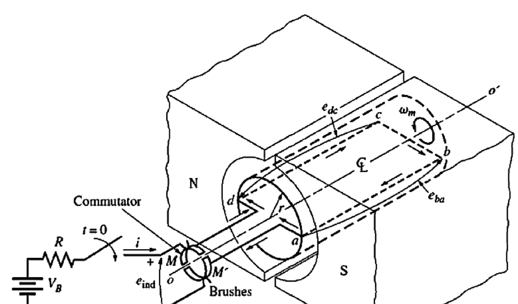
Example

(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, $e_{\text{ind}} = (2/\pi)\phi\omega\downarrow$ decreases and the rotor current increases $[i = (V_B - e_{\text{ind}}\downarrow)/R]$. 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,

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

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

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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

$$P = \tau\omega$$

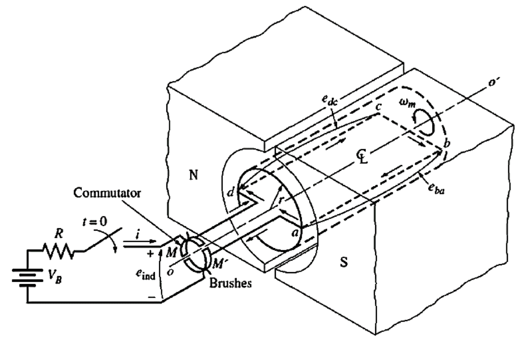
$$= (10\text{ N}\cdot\text{m})(432\text{ rad/s}) = 4320\text{ W}$$

The power out of the battery is

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

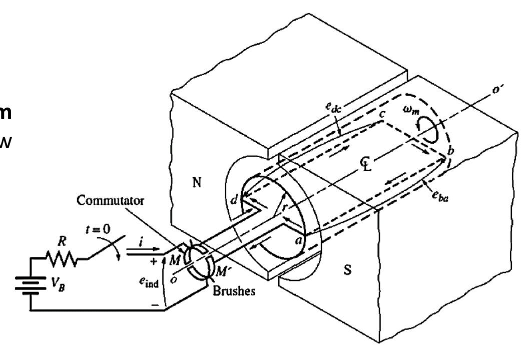
Why difference ?

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

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

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

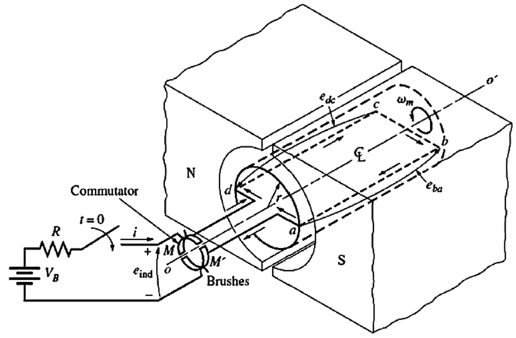
The induced voltage e_{ind} is

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

Finally, the speed of the shaft is

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

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



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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 ω = 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.

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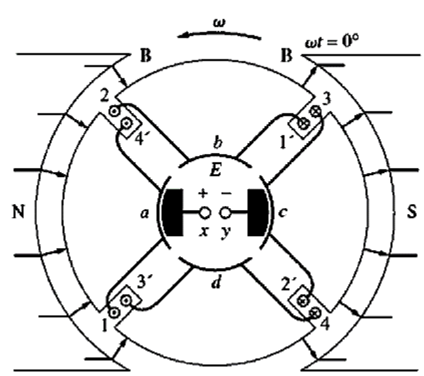
Commutation in a Simple Four-Loop DC Machine

- **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.

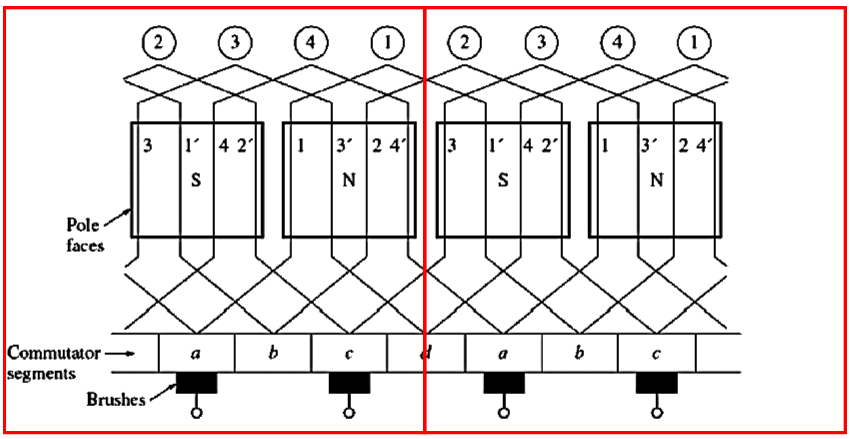
Commutation in a Simple Four-Loop DC Machine

- 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°

Commutation in a Simple Four-Loop DC Machine



First rotation

Second rotation

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

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

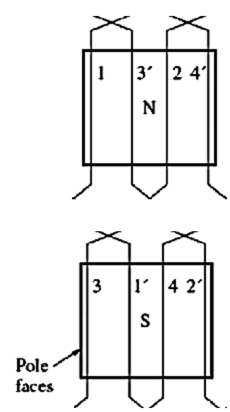
$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \qquad (1\text{–}45)$$

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

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

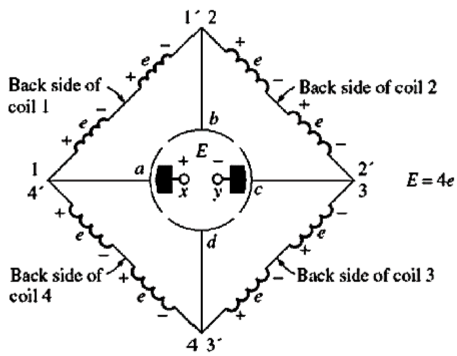
$$e_{ind} = (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{l} \qquad (1\text{–}45)$$

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



Check the polarities using slides 8 and 10 !

Commutation in a Simple Four-Loop DC Machine



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

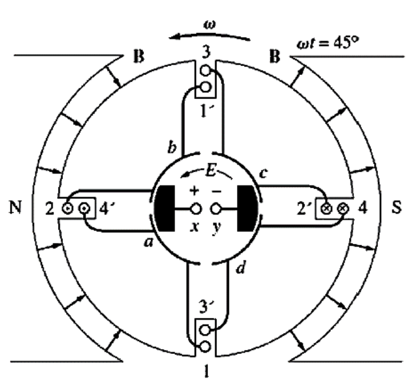
- Notice that there are **two parallel paths** for current in the armature.
- The existence of two or more parallel paths for rotor current is a common feature of all commutation schemes.

The total voltage at the brushes of the machine is

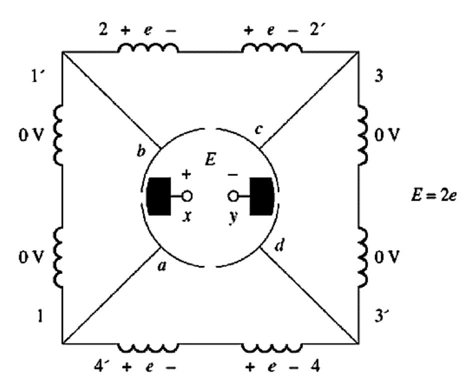
$$\boxed{E = 4e \qquad \omega t = 0^\circ}$$

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°



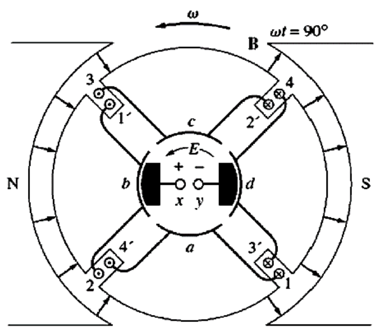
The voltages on the rotor conductors at wt=45°.

The total voltage at the brushes of the machine is

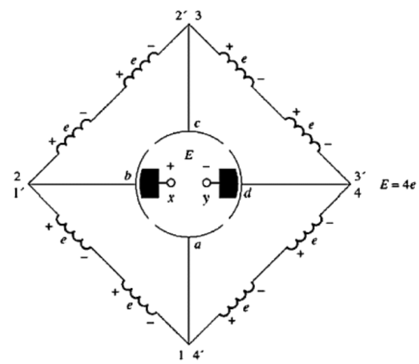
$$\boxed{E = 2e \qquad \omega t = 45^\circ}$$

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 $E = 4e \qquad \omega t = 90^\circ$

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

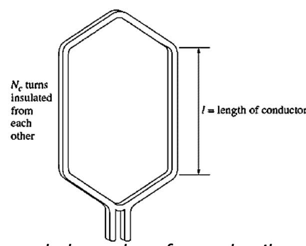
Commutation and Armature Construction in Real DC Machines

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

$$\boxed{Z = 2CN_C}$$

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



diamond-shaped preformed coils

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

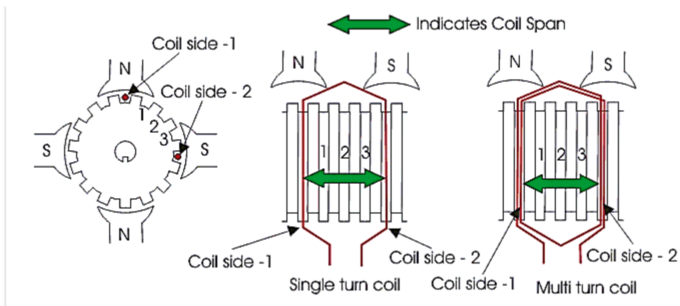
Rotor coils connected to commutator segments

Source: http://www.electricaledition.com

Commutation and Armature Construction in Real DC Machines

Rotor Coils:

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



Source: https://electricalstudy.sarutech.com

Commutation and Armature Construction in Real DC Machines

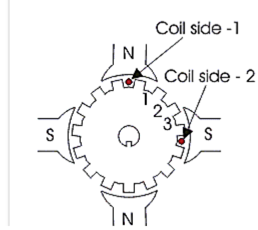
Rotor Coils:

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

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

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

Example:



Source: https://electricalstudy.sarutech.com

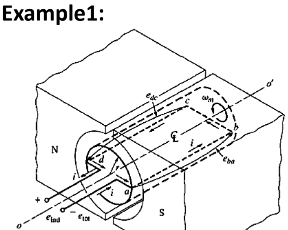
Pole number = 4
Electrical angle = 180°
Mechanical angle = 90°

Commutation and Armature Construction in Real DC Machines

Full-Pitch Coil:

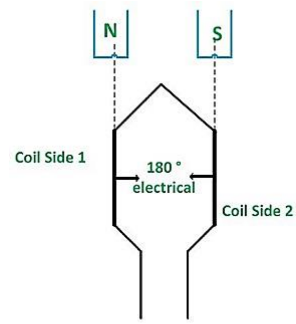
- If a coil spans **180 electrical degrees**, the voltages in the conductors on either side of the coil will be exactly the **same in magnitude** and **opposite in direction** at all times.
- Such a coil is called "***full-pitch coil***".

Example1:



Full-Pitch Coil

Example2:



Full-Pitch Coil

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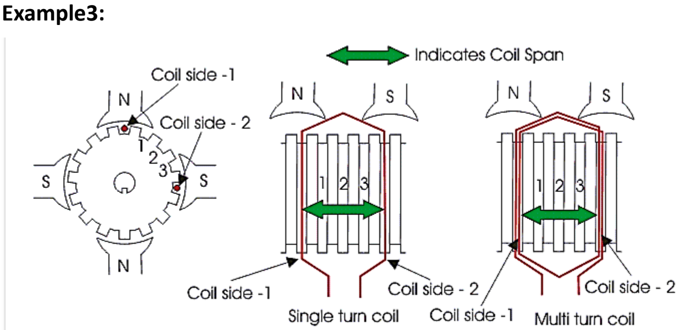
Commutation and Armature Construction in Real DC Machines

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

66

Source: https://electricalstudy.sarutech.com

Commutation and Armature Construction in Real DC Machines

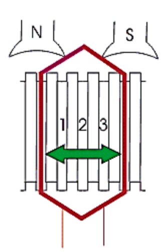
Fractional-Pitch Coil:

- 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**.

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

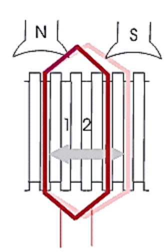
Commutation and Armature Construction in Real DC Machines

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



Full-Pitch Coil

$p = 100\%$

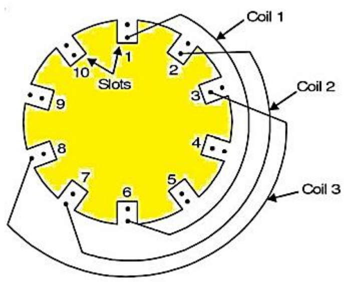


Fractional-Pitch Coil

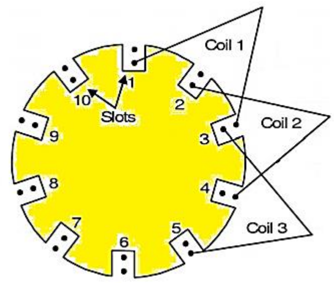
$p = 80\%$

Commutation and Armature Construction in Real DC Machines

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



Full-Pitch Coil

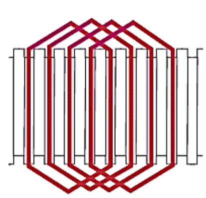


Fractional-Pitch Coil

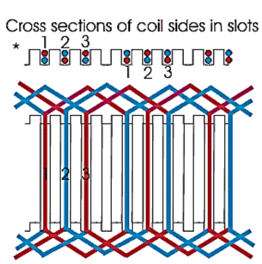
Commutation and Armature Construction in Real DC Machines

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

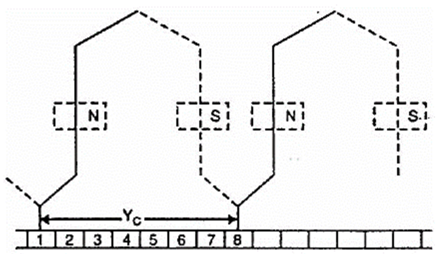
[*In Double layer winding, 1,2,3 are marked to only three coils among many]

Source: https://electricalstudy.sarutech.com

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***".

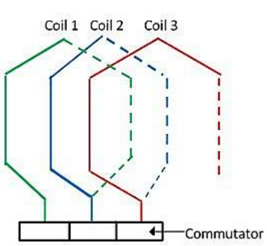


commutator pitch, Yc = 8

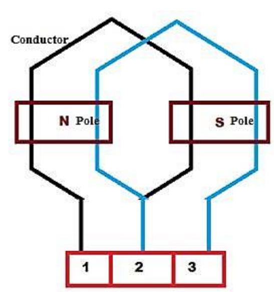
Commutation and Armature Construction in Real DC Machines

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

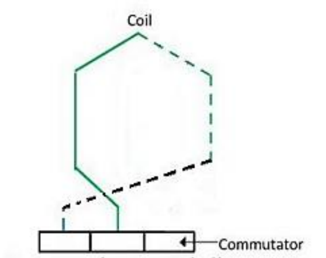


Source: http://electrialstandards.blogspot.com

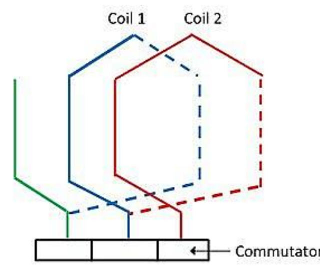
Commutation and Armature Construction in Real DC Machines

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

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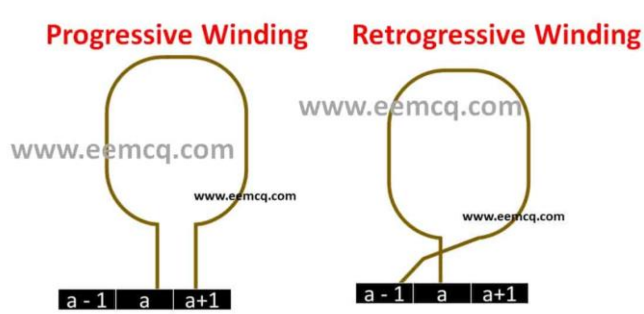
Commutation and Armature Construction in Real DC Machines

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

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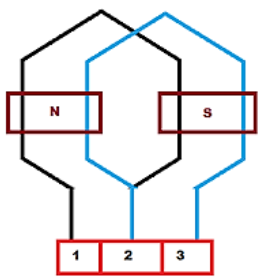
Commutation and Armature Construction in Real DC Machines

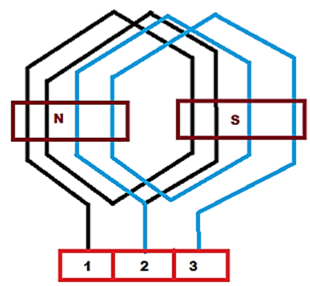
- **Rotor (*armature*) windings** are further classified according to the **plex** of their windings.
- A **simplex rotor winding** is a single, complete, closed winding wound on a rotor.
- A **duplex rotor winding** is a rotor with two complete and independent sets of rotor windings.
- A **triplex rotor 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***".



Simplex lap winding

Source: https://www.electrical4u.com

Progressive Winding



Duplex lap winding

Source: https://www.electrical4u.com

Progressive Winding

Commutation and Armature Construction in Real DC Machines

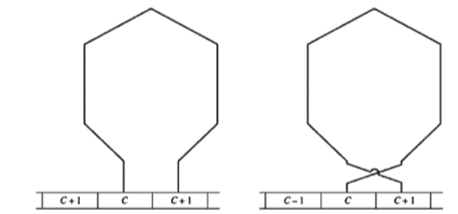
Lap Winding and Wave Winding:

- **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**.

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**.

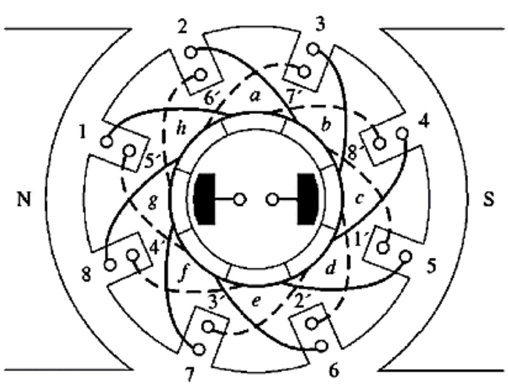


progressive *lap winding* ***retrogressive*** *lap winding*

commutator pitch, ***Yc = 1*** *commutator pitch,* ***Yc = -1***

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

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

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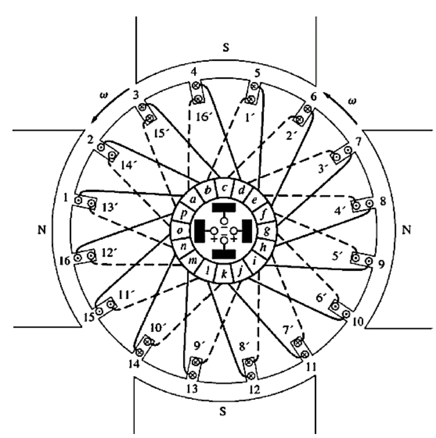
Commutation and Armature Construction in Real DC Machines

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

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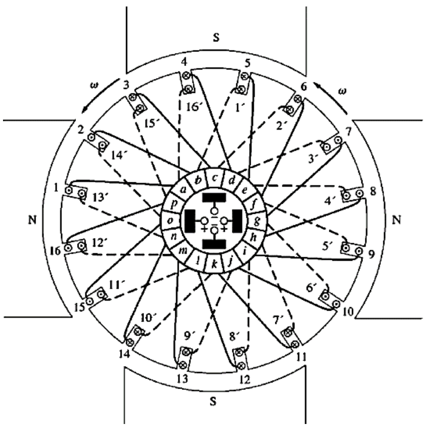
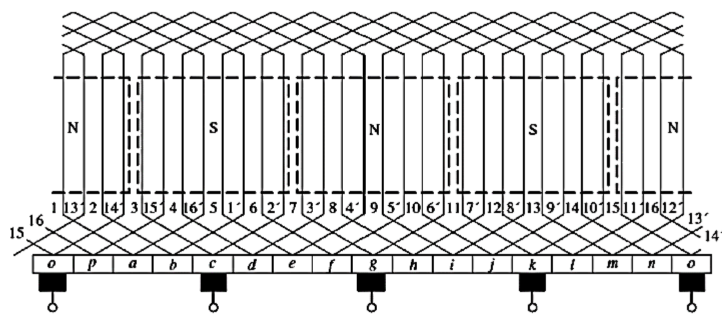
Commutation and Armature Construction in Real DC Machines

Lap Winding:



A simple four-pole lap-wound dc machine

progressive lap winding

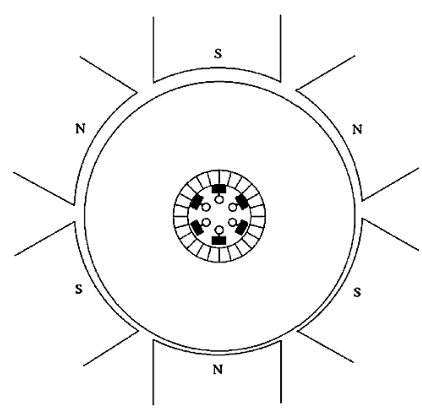


The rotor winding diagram of this machine

Commutation and Armature Construction in Real DC Machines

Possible Problem in Lap-Wound Machines:

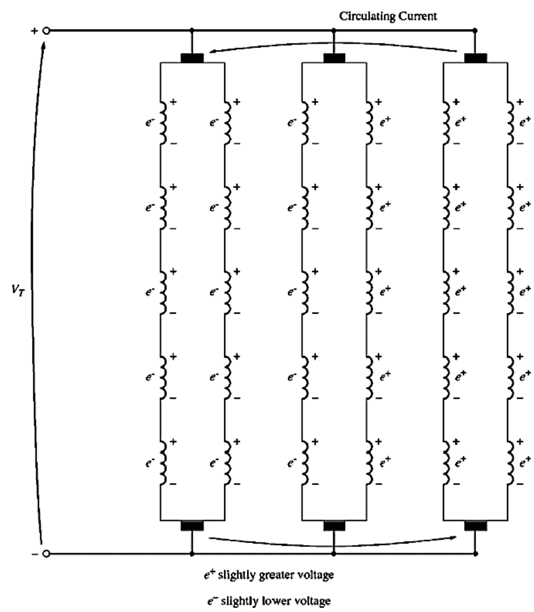
- Having **many parallel paths** in lap-wound machines can lead to a **serious problem**.
- As seen in the figure, **because of long usage**, there has been **slight wear on the bearings of this machine**, and the lower wires are closer to their pole faces than the upper wires are.
- As a result, there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

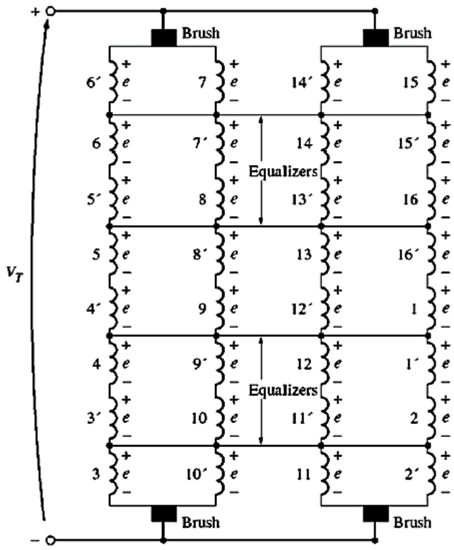


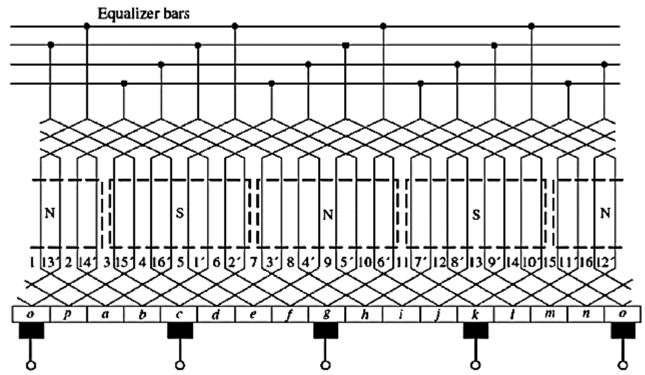
Commutation and Armature Construction in Real DC Machines

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.

Equalizer Connection for the Four-Pole Machine:





Commutation and Armature Construction in Real DC Machines

Lap Winding:

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

$$\boxed{y_c = \pm m}$$

+ for progressive winding
\- for retrogressive winding

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

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

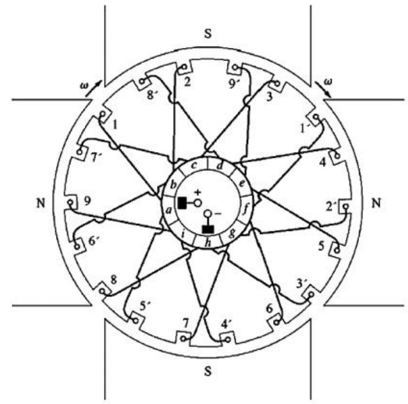
$$\boxed{a = mP}$$

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

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.

Commutation and Armature Construction in Real DC Machines

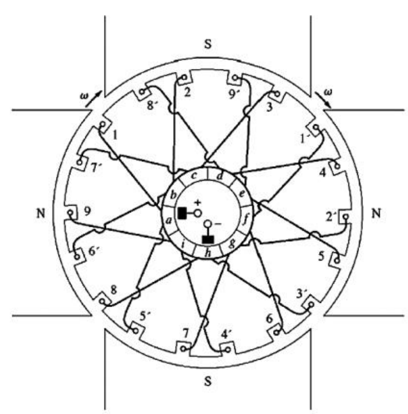
Wave Winding:

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

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

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.

Commutation and Armature Construction in Real DC Machines

Wave Winding:

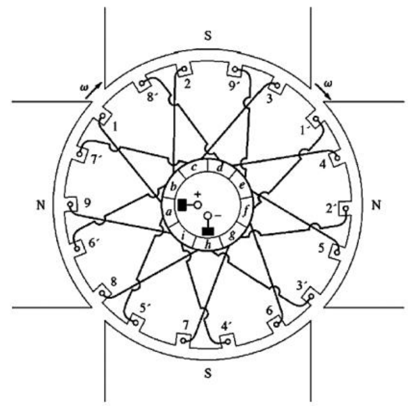
- The **number of current paths** on a **multiplex wave winding** is

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

where

❖ **m** is the **plex number**

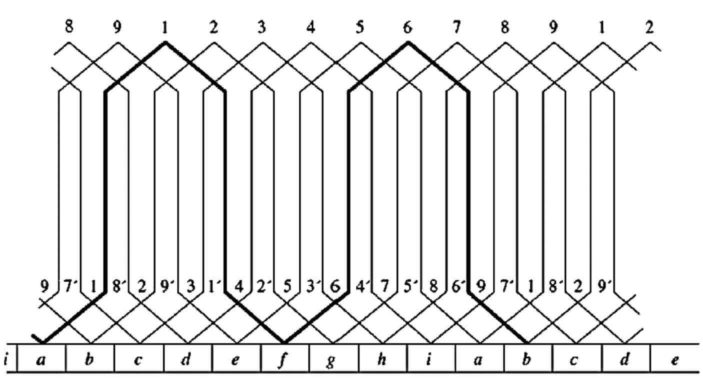
m=1 for **simplex** winding
m=2 for **dublex** winding
m=3 for **triplex** winding



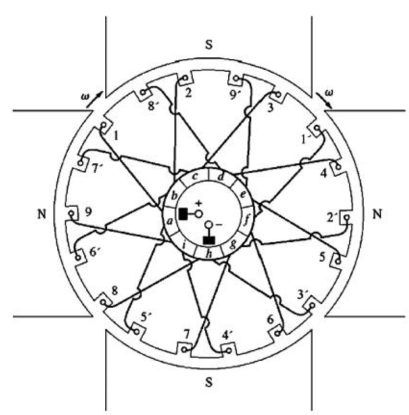
A simplex four-pole wave-wound dc machine.

Commutation and Armature Construction in Real DC Machines

Wave Winding:



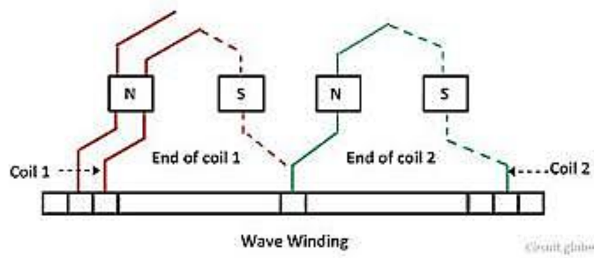
The rotor winding diagram



A simplex four-pole wave-wound dc machine

Commutation and Armature Construction in Real DC Machines

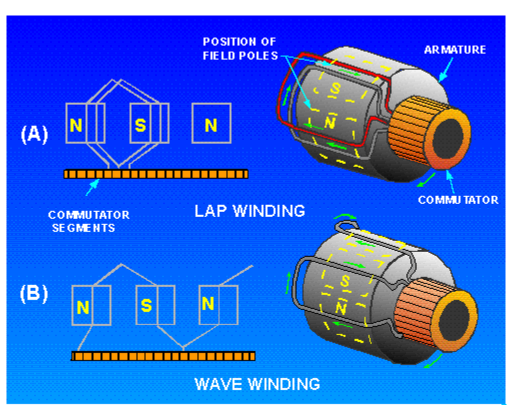
Wave Winding:



Source: https://circuitglobe.com

Commutation and Armature Construction in Real DC Machines

Comparison of Lap and Wave Winding:

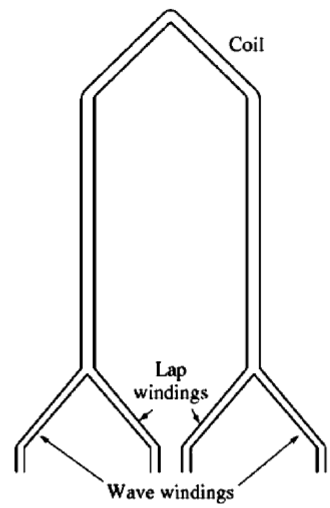


Source: https://www.quora.com

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.

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Commutation and Armature Construction in Real DC Machines

The Frog-Leg Winding:

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

$$\boxed{a = 2Pm_{lap}}$$

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

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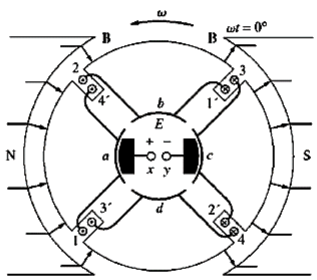
Commutation and Armature Construction in Real DC Machines

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**

Problems With Commutation in Real Machines

- The **commutation** process is not simple in practice.
- Because there are **two major effects** that occur in practice:
  - **Armature Reaction**
  - **L.di/dt Voltages**
- This section explores the **nature of these problems** and **the solutions** employed to mitigate their effects.

Problems With Commutation in Real Machines

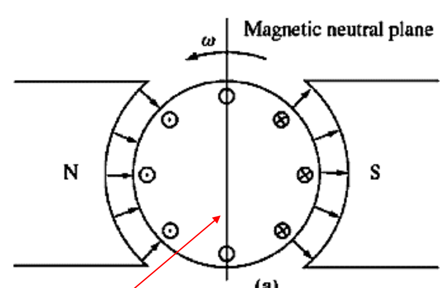
Definition of Armature Reaction:

- If the magnetic field windings (*on stator*) of a DC machine are connected to a power supply and the rotor of the machine is turned by an external source of mechanical power (*wind/water turbine, diesel motor, and etc…*) then a voltage will be induced in the rotor conductors.
- This voltage (*in AC form*) will be rectified into a DC output by the action of the machine's commutator.
- Now if we connect a load to the terminals of the machine, then a current will flow in its armature windings.
- This current flow will produce **its own magnetic field**, which will **distort** the original magnetic field from the machine 's poles (*on the stator*).
- This distortion of the flux in a machine as the load is increased is called "**Armature Reaction**".
- **Armature reaction** causes **two serious problems** in real DC machines.
  - ➢ **Neutral-Plane Shift**
  - ➢ **Flux Weakening**

Problems With Commutation in Real Machines

Neutral-Plane Shift:

- First we define the "**magnetic neutral plane**". It is defined as the plane within the machine where the velocity of the rotor wires is **exactly parallel** to the magnetic flux lines, so that induced voltage in the conductors in the plane is exactly zero.
- In the figure, the flux is distributed uniformly under the pole faces.
- The rotor windings have voltages built up **out of the page** for wires **under the north pole face** and **into the page** for wires **under the south pole face**.
- The **magnetic neutral plane** in this machine is **exactly vertical**.



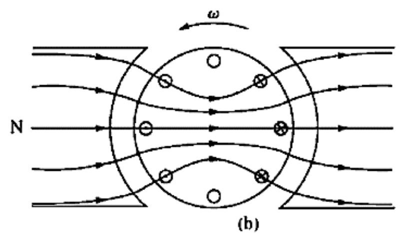
two-pole dc machine

The neutral plane in this machine is **exactly vertical**

Pole flux is **uniformly distributed**

Problems With Commutation in Real Machines

Neutral-Plane Shift:



Pole flux is **uniformly distributed**

Uniform pole flux distribution before load is connected
Effect of the airgap must be seen

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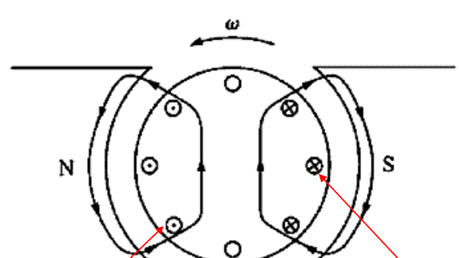
Problems With Commutation in Real Machines

Neutral-Plane Shift:

- Now suppose that **a load is connected** to this machine so that it acts as a **generator**.
- Current will now be out of the positive terminal of the generator, so current will be flowing **out of the page** for wires under the **north pole face** and **into the page** for wires under the **south pole face** as shown in the figure.
- This current flow produces a **magnetic field** in the rotor windings, as shown in the figure.



two-pole dc machine

Armature current **out of page**

Armature current **into the page**

The armature magnetic field when a load is connected to the machine.

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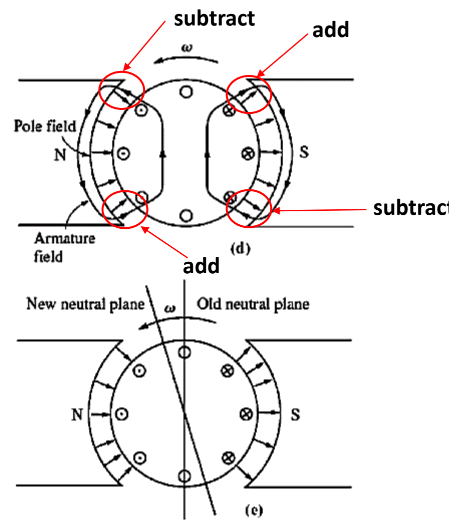
Problems With Commutation in Real Machines

Neutral-Plane Shift:

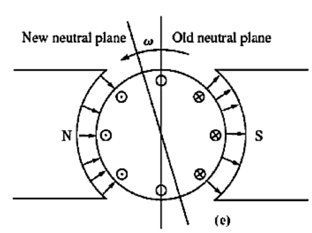
- This rotor magnetic field (*armature field*) affects the original magnetic field that was produced in the stator (*pole field*).
- In some places **under the pole surfaces**, it **subtracts** from the **pole flux**, and in other places it **adds** to the **pole flux**.
- The overall result is that the **magnetic flux in the air gap** of the machine is **skewed** as shown in the Figure.
- Notice that the place on the rotor where the induced voltage in a conductor would be zero (*the neutral plane*) has **shifted**.



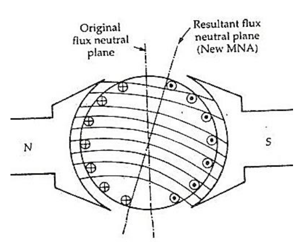
Problems With Commutation in Real Machines

Neutral-Plane Shift:

- As shown in the figure, the **magnetic neutral plane** is shifted **in the direction of rotation** for the **DC generator**.
- But, if this machine were a **DC motor**, the **current** in the rotor would be **reversed** and the **rotor flux directions** would be **just opposite** of the generator action.
- As a result, for **DC motor operation**, the **magnetic neutral plane** would shift **in the other way**.
- In general, the **magnetic neutral plane shifts** in the **direction of motion** for a **generator** and **opposite to the direction of motion** for a **motor**.
- Furthermore, the **amount of the shift** depends on the **amount of rotor current** and hence on the **load** of the machine.



Neutral plane shift for DC generator



Neutral plane shift for DC motor

Problems With Commutation in Real Machines

So what's the big deal about neutral-plane shift?

- The commutator must **short out** commutator segments just at the moment when the **voltage** across them is equal to **zero**.
- If the brushes are set to **short out** conductors **in the vertical plane**, then the voltage between segments is indeed **zero**.
- But when the machine is **loaded**, the **neutral plane shifts**, and the brushes **short out** commutator segments with **some voltage across them**.
- The result is that a **current circulates** between the shorted segments and **large sparks** at the brushes occur when the brush leaves a segment.
- The result is **arcing** and **sparking** at the brushes.
- This is a very **serious problem**, since it leads to drastically reduce the **brush life**, **pitting of the commutator segments**, and **greatly increase maintenance costs**.
- Notice that this problem **cannot be fixed** even by placing the brushes over the full-load neutral plane, because then they would spark at no load condition.

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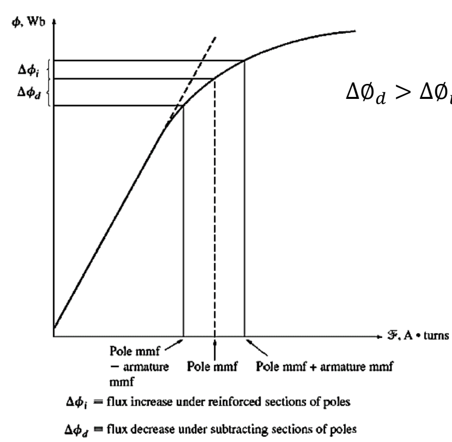
Problems With Commutation in Real Machines

Flux Weakening :

- The second major problem caused by armature reaction is called "**flux weakening**".
- To understand flux weakening, refer to the magnetization curve shown in the figure.
- Most machines operate at flux densities near the saturation point.
- Therefore, at locations on the pole surfaces where **the rotor magnetomotive force adds to the pole magnetomotive force**, **only a small increase in flux occurs.**
- But at locations on the pole surfaces where **the rotor magnetomotive force subtracts from the pole magnetomotive force**, **there is a larger decrease in flux**.
- The net result is that **the total average flux under the entire pole face** is **decreased**.



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Problems With Commutation in Real Machines

The Effect of Flux Weakening :

- **Flux weakening** causes problems in both generators and motors.
- In generators, the effect of flux weakening is simply **to reduce the voltage supplied by the generator** for any given load.
- In motors, **the effect can be more serious**. When the **flux in a motor** is <u>**decreased**</u>, its **speed** <u>**increases**</u>. (*refer to the example in slide no:52*)
- But **increasing the speed of a motor** can **increase its load**, <u>**resulting in more flux weakening**</u>.
- It is possible for some **shunt DC motors** to reach a **runaway** condition **as a result flux weakening**, where the speed of the motor just keeps increasing until the machine is ***disconnected from the power line*** or ***until it destroys itself.***

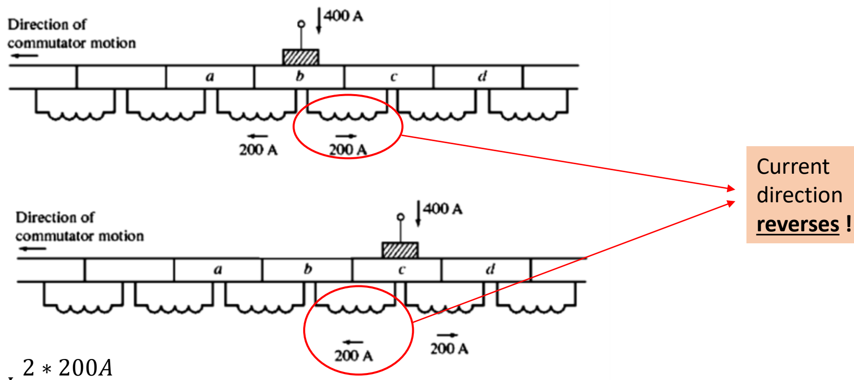
Problems With Commutation in Real Machines

L.di/dt Voltages:

- The **second major problem about commutation** is the **L.di/dt voltages** that occurs in commutator segments being shorted out by the brushes.
- This problem is also called as "**inductive kick**".
- Because of the **rotation** of the DC machine, there can be **fast change** in the **current of armature coils**.
- This is due to the fact that during rotation **two commutator segments** are being <u>**shorted out**</u> continuously by the **brush**.
- This **fast current change** in the armature coil together with the **coil inductance** will induce a **voltage**.
- In some cases, this **voltage** can be **high** and causes **natural sparking** and **arcing** at the **brushes** of the machine.
- This **sparking** and **arcing** problem is also observed in the neutral-plane shift problem.

Problems With Commutation in Real Machines

L.di/dt Voltages:



$$inductive\ kick\ voltage = L\frac{2 * 200A}{\Delta t}$$

L is the **coil inductance** between **commutator segments *b & c***
Δt *is the time passed for the fast current change in the coil*

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Self-study

- Study the numerical example about ***Ldi/dt problem*** at pages 505-506 in Chapman.

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Solutions to the Problems with Commutation

- There are in general **3 approaches** to *partially* or *completely* correct the problems of **armature reaction** and ***L.di/dt* voltages**:

    - **Brush Shifting**
    - **Commutating Poles (*or* Interpoles)**
    - **Compensating Windings**

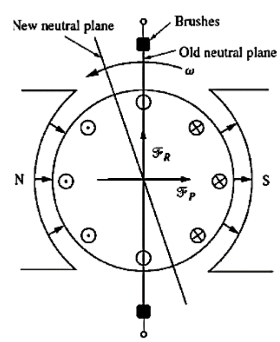
- Each of these techniques will be explained in the coming slides together with its advantages and disadvantages.

Solutions to the Problems with Commutation

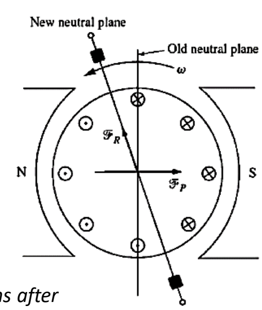
Brush Shifting:

- **Brush shifting** is a **very old** method to improve commutation in real DC machines.
- The solution is based on the shifting the brushes positions if the neutral plane of the machine shifts.
- It seems a good idea at first instant, but there are <u>**three problems**</u> with this solution:

    - A person must adjust the brush positions of the machine each time when the load changes.
    - The neutral plane shift direction reverses when the machine goes from motor operation to generator operation.
    - Brush shifting <u>**increases**</u> flux weakening problem.



Brush positions before neutral plane shift

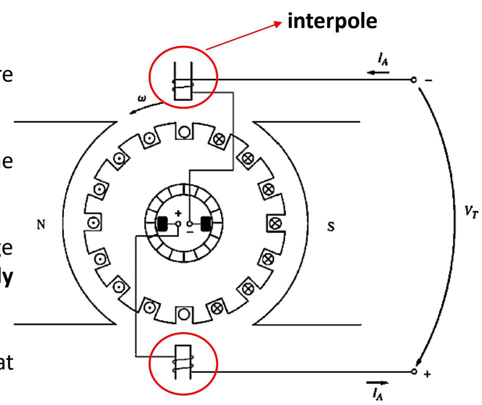


New brush positions after neutral plane shift

Solutions to the Problems with Commutation

Commutating Poles (*or* Interpoles)

- Small poles, called "***commutating poles***" or "***interpoles***", are placed midway between the main poles.
- These commutating poles are located **directly over** the **conductors** being commutated.
- By providing a flux from the commutating poles, the voltage in the coils undergoing commutation **can be exactly canceled.**
- If the **cancellation is exact**, then **there will be no sparking** at the **brushes**.
- In this method, **flux weakening problem** is still **continuing**, since **interpoles** are **far away** from the **main poles**.



A DC machine with interpoles

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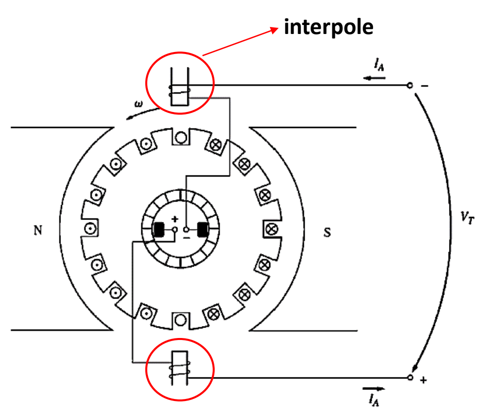
Solutions to the Problems with Commutation

Commutating Poles (*or* Interpoles)

- The **cancellation of voltage** in the **commutator segments** can be accomplished **for all values of load**.
- This is done by simply connecting the ***interpole windings* in series** with the rotor windings, as shown in the figure.
- As the **load increases**, the **rotor current increases too**, and the **interpoles** generate **stronger flux** to cope with the **increasing voltage problem** in the **commutator segments** that must be cancelled.
- The **interpoles** can work for both **motor** and **generator** operation **without making any physical change on the machine**.
- This method is **very common** for **medium-size DC machines** (*1hp or more*), since it is a **cheap method**.



A DC machine with interpoles

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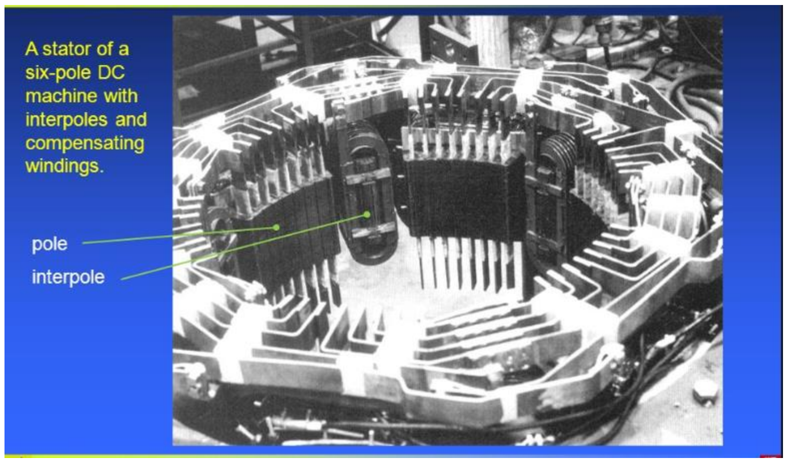
Solutions to the Problems with Commutation

Commutating Poles (*or* Interpoles)



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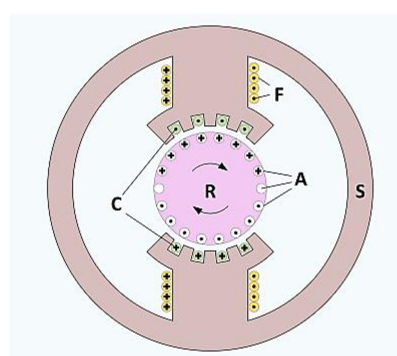
Solutions to the Problems with Commutation

Compensating Windings:

- This method is used to **completely cancel armature reaction** (*eliminating both neutral-plane shift and flux weakening*).
- The **compensating windings** are replaced **in slots carved in the faces of the poles parallel to the rotor conductors**, as shown in the figure.
- **Compensating windings** are **connected in series** with the **rotor windings**, so that whenever the **load changes**, the **current** in the compensating windings **changes**, too.



Cross section of DC motor with compensation windings. A = armature windings, ***C = compensation windings****, F = field windings, R = rotor (armature),*

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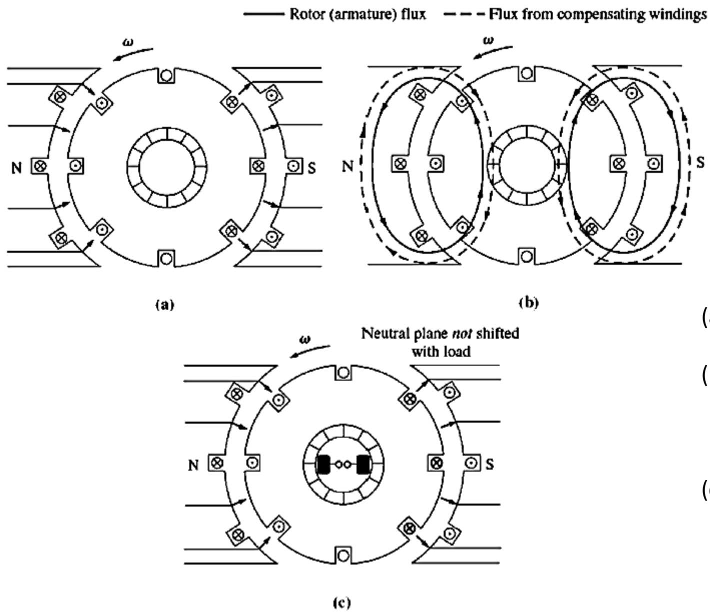
The Effects of Compensating Windings in a DC Machine:



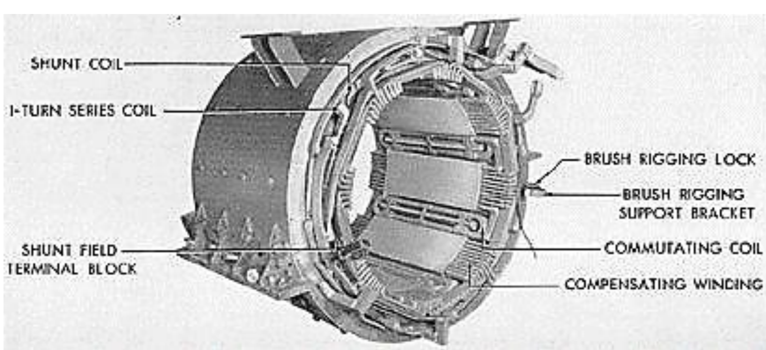
(a) The **pole flux** in the machine.

(b) The **armature flux** and **the flux of compensating windings**. Notice that they are **equal** and **opposite**.

(c) The **net flux** in the machine (*the sum of all three fluxes*). which is just the original pole flux.

Solutions to the Problems with Commutation

Compensating Windings:



Compensating windings on a real DC machine

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

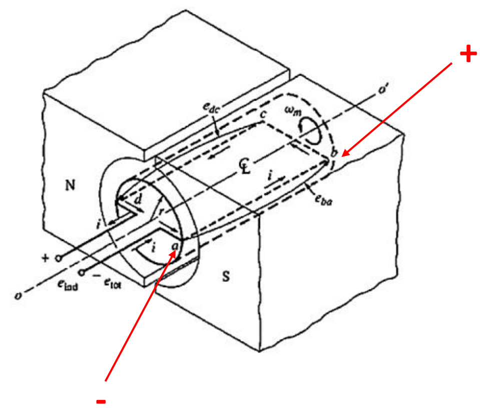
The voltage **in a single conductor** (***segment ab***) under the pole faces was previously shown to be

Segment ab:

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

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

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



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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*)**

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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

$$\omega = \frac{2\pi}{60}n \quad \Rightarrow \quad \boxed{E_A = K'\phi n} \qquad \boxed{K' = \frac{ZP}{60a}}$$

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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

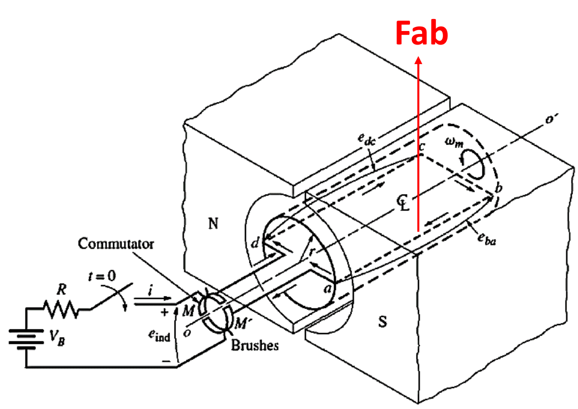
Segment ab:

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

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

The torque on the rotor caused by this force is

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



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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

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

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

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

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

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

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

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

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Induced Torque Equations Of Real DC Machines

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

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

Finally,

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

where

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

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Self-study

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

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:

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

- 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*)**

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

$$\boxed{\begin{array}{ll} \text{Armature loss:} & P_A = I_A^2 R_A \\ \text{Field loss:} & P_F = I_F^2 R_F \end{array}}$$

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.

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Losses in DC Machines

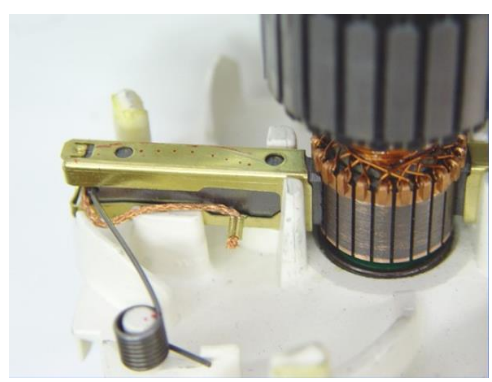
Brush Losses:

- 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:

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

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**.

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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** (***$n^{1.5}$***)



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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)**.

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Losses in DC Machines

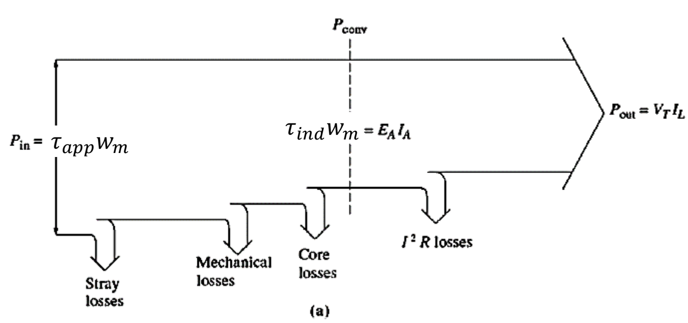
Stray Losses:

- **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 **<u>1 percent of full load (1%)</u>**.

The Power Flow Diagram

For DC Generator:

Input power is mechanical power



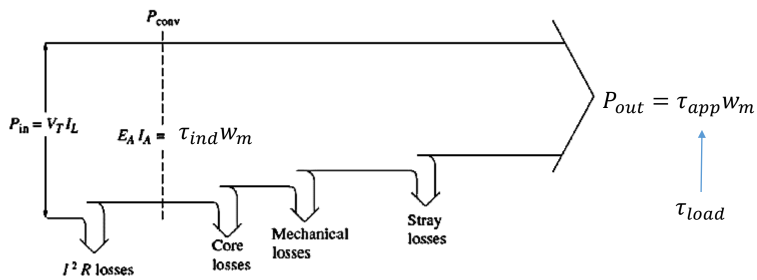
Output power is electrical power

Power-flow diagram for DC generator

The Power Flow Diagram

For DC Motor:

Input power is electrical power

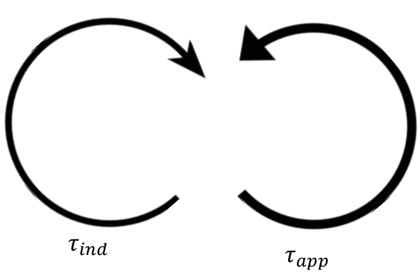


Output power is mechanical power

Power-flow diagram for DC motor

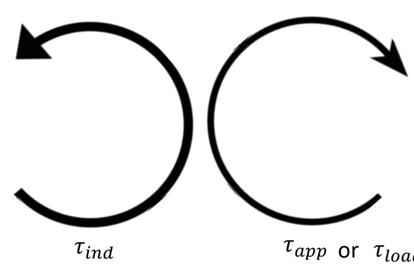
Comparison of Torques for DC Motors and Generators

For DC Generator:



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

For DC Motor:



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

Comparison of Armature Currents for DC Motors and Generators

For DC Generator:

I_A

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

For DC Motor:

I_A

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

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Self-study

- Solve **<u>all problems</u>** of Chapter 3 from Chapman

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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