Motors and Generators

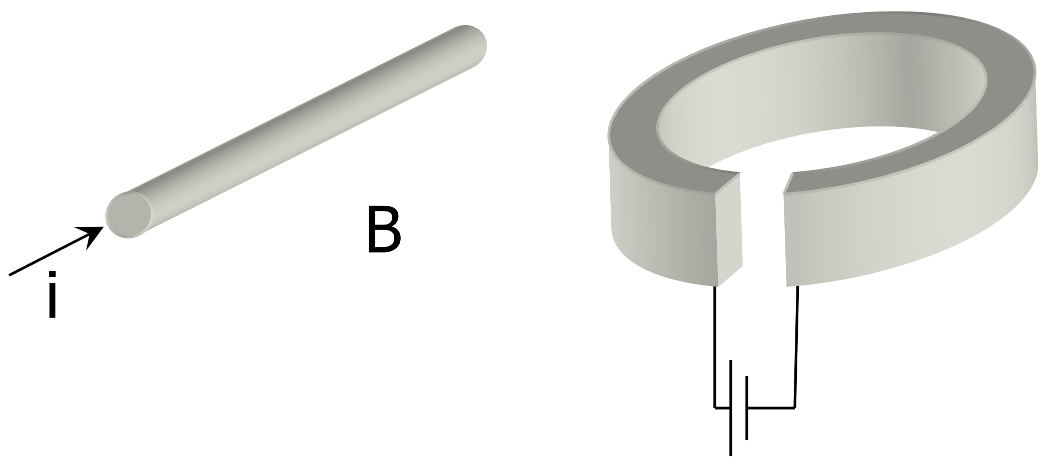
- Electro-mechanical devices: convert electrical energy to mechanical motion/work and vice versa
- Operate on the coupling between current-carrying conductors and magnetic fields
- Governed by a set of fundamental principles

Magnetism

- Magnets are composed of north and south pole pairs.
- B-field lines go from the north to the south poles.

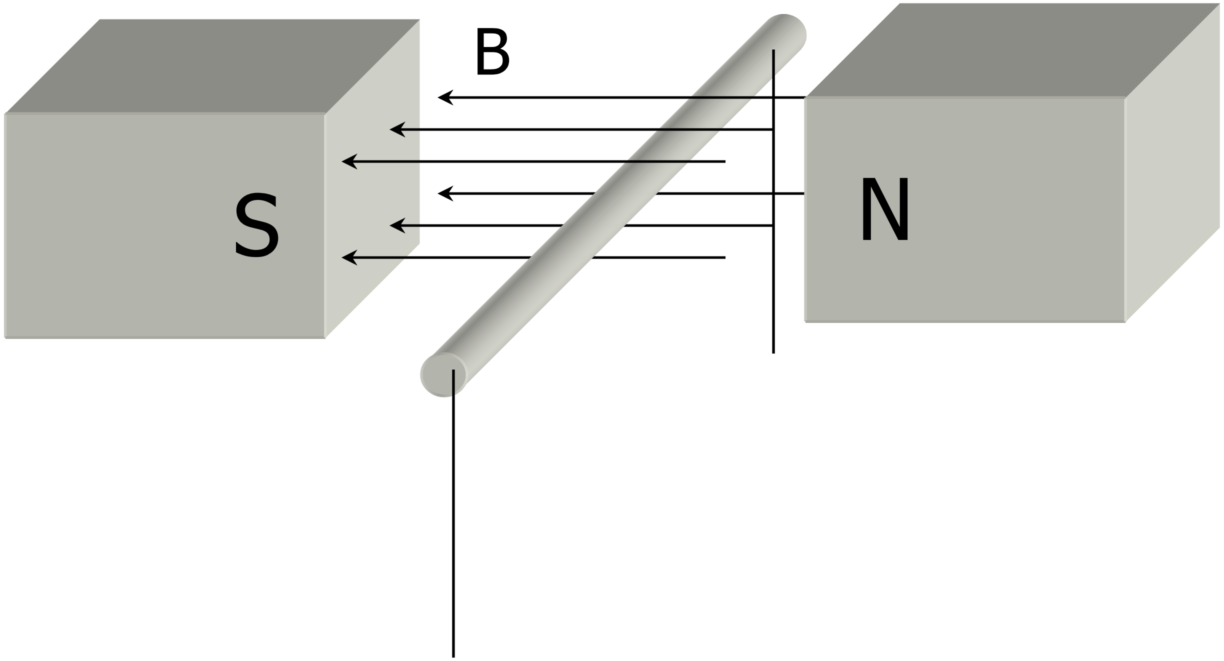
Principle #1

- Current in a conductor results in a magnetic field around the conductor. Use the right-hand rule to determine the field direction.



Principle #2

- Moving a conductor in a magnetic field induces a voltage across the conductor according to



Motion of a Coil in a B-Field

Commutation

Motion of a Coil in a B-Field

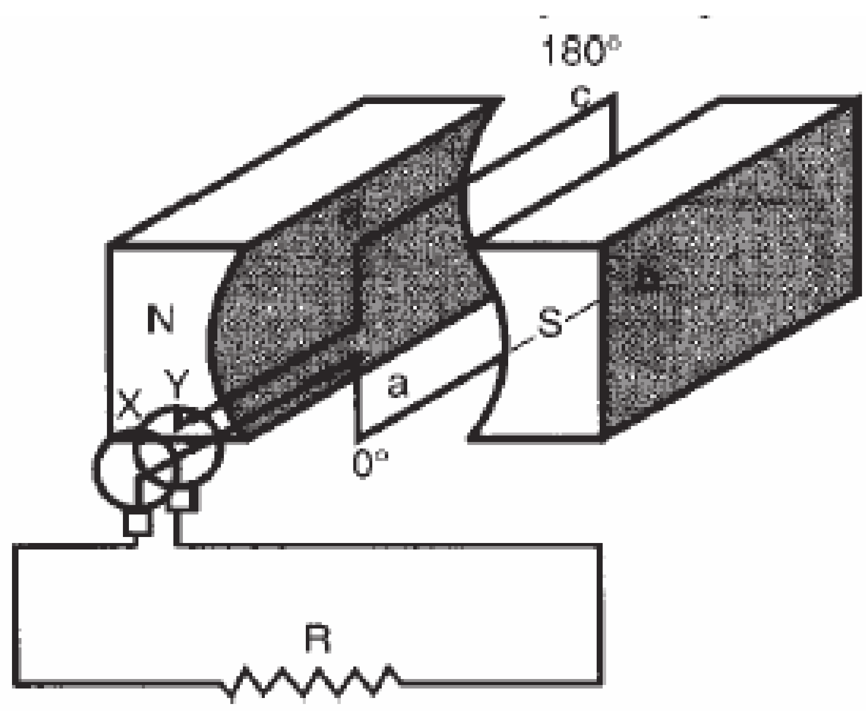


Fig. 1-23: Simple alternating current AC generator.

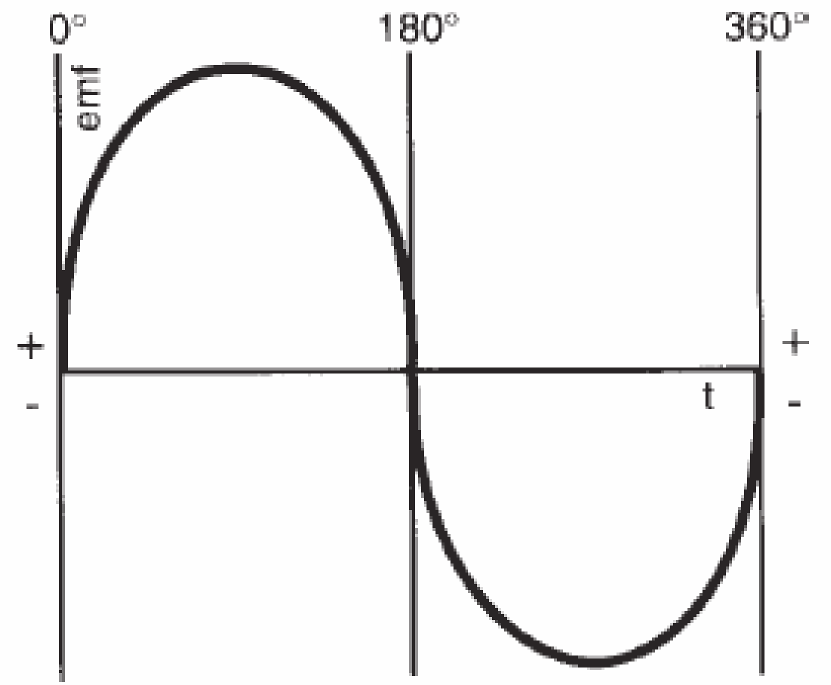
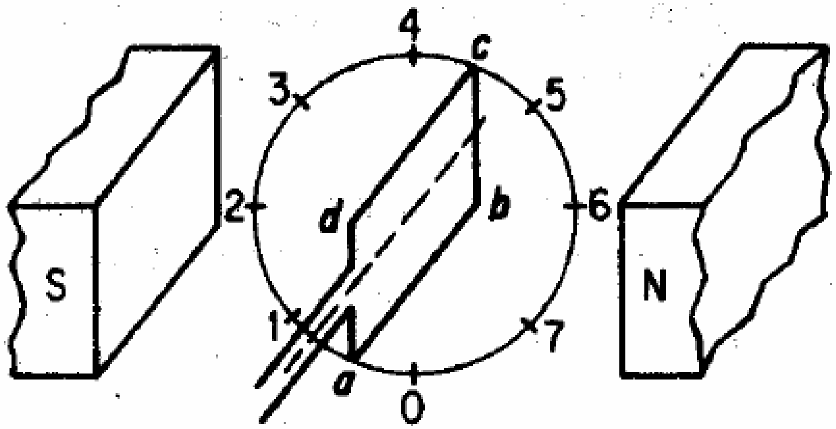
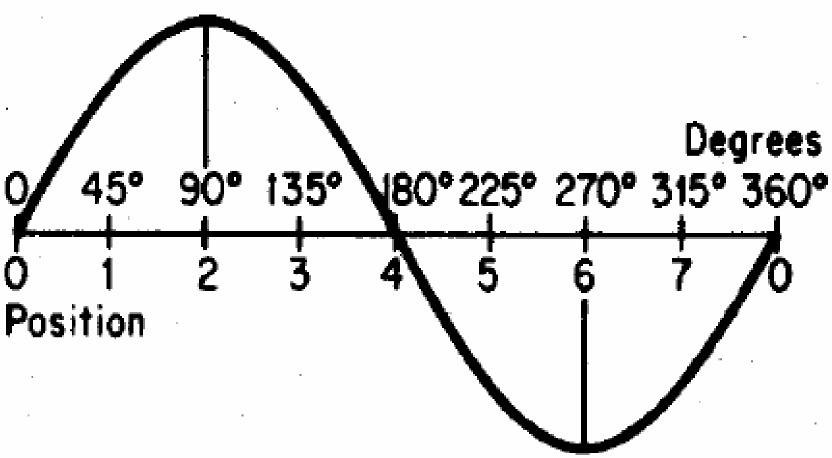


Fig. 1-24: Sine wave characteristic of AC current during one cycle (360°).

Motion of a Coil (cont.)



a. Instantaneous positions of rotation at constant speed



b. EMF at respective positions

Figure 1–7 EMF generated by a coil moving in a uniform magnetic field

Commutation

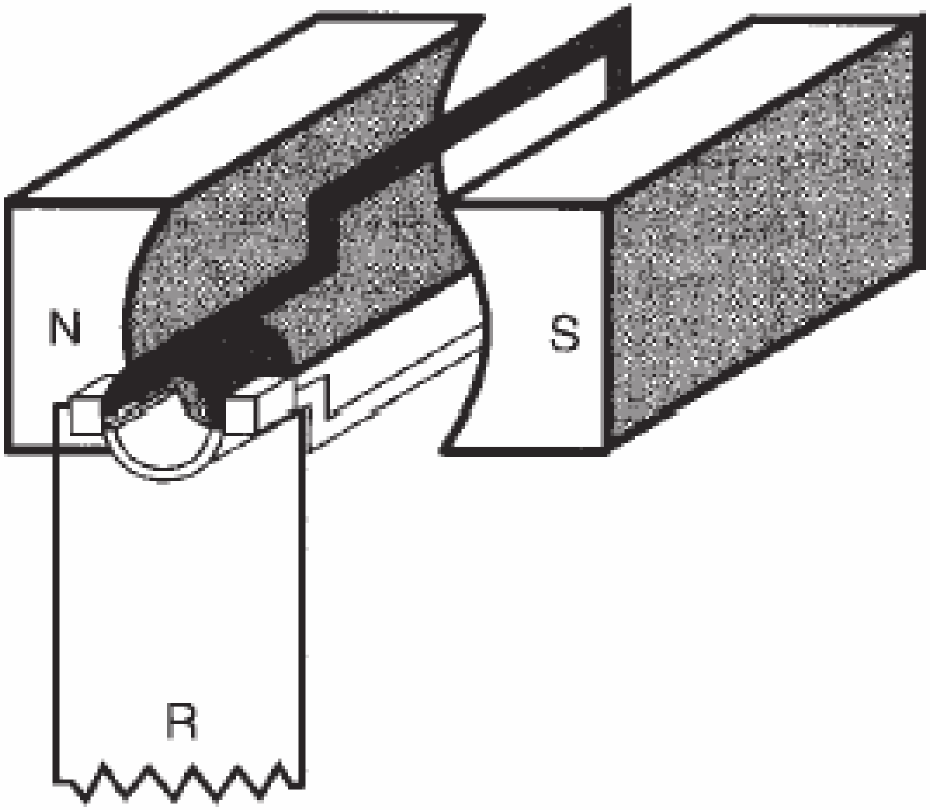


Fig. 1-25: Simple DC generator.

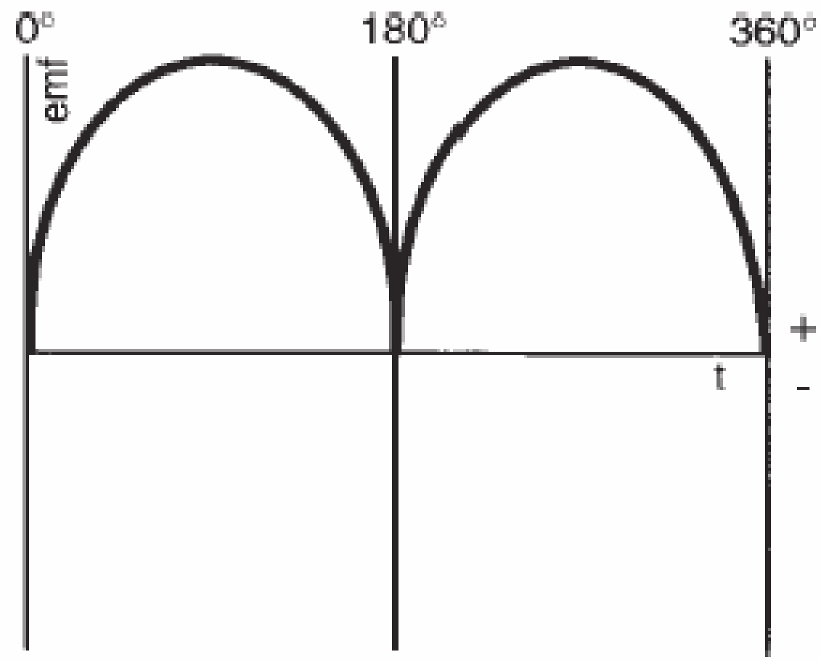
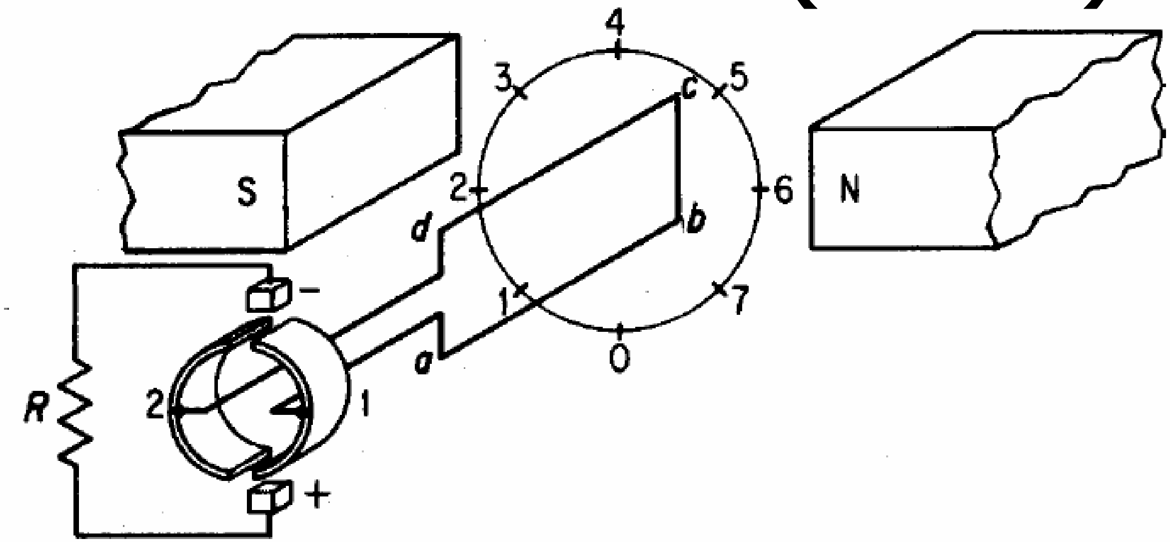
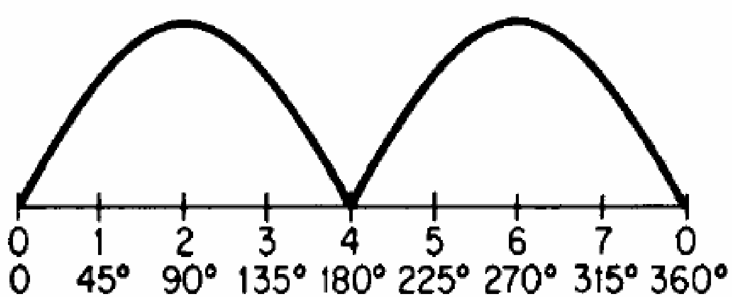


Fig. 1-26: Induced emf from the simple DC generator.

Commutation (cont.)



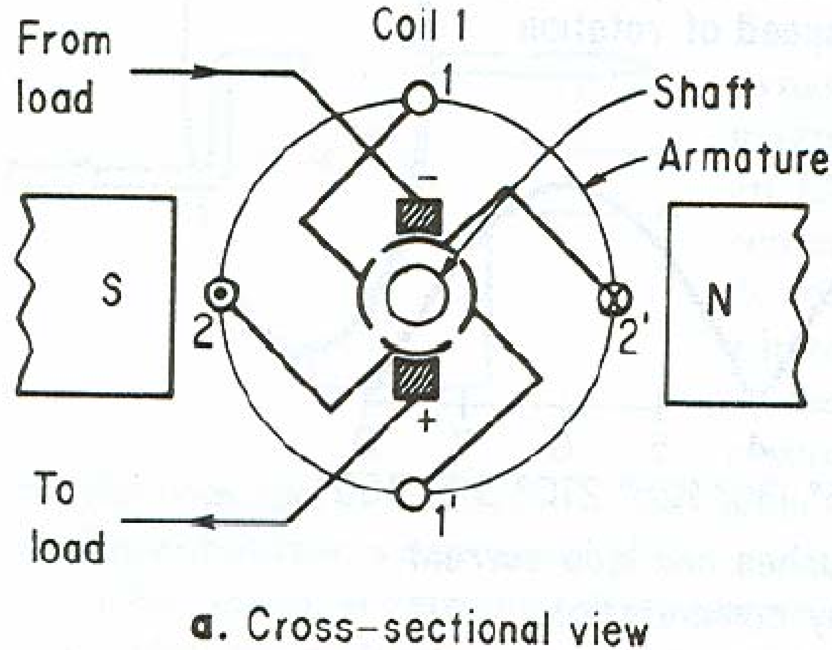
a. Instantaneous coil positions at constant speed of rotation



b. EMF at brushes and load current produced by commutation

Figure 1–8 Bipolar generator with two-segment commutator

Commutation: Multiple Coils



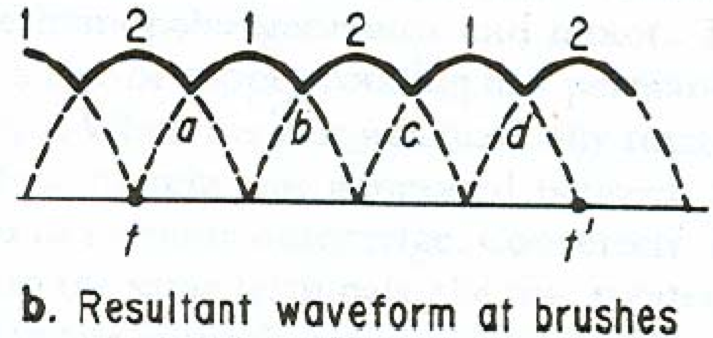
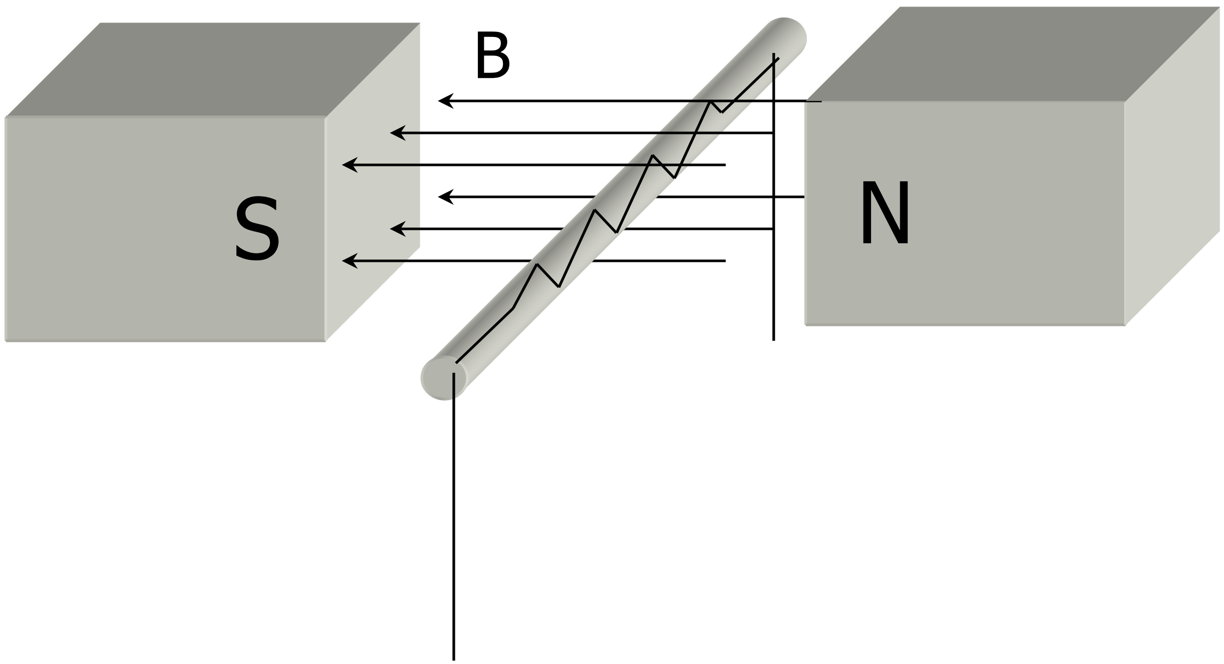
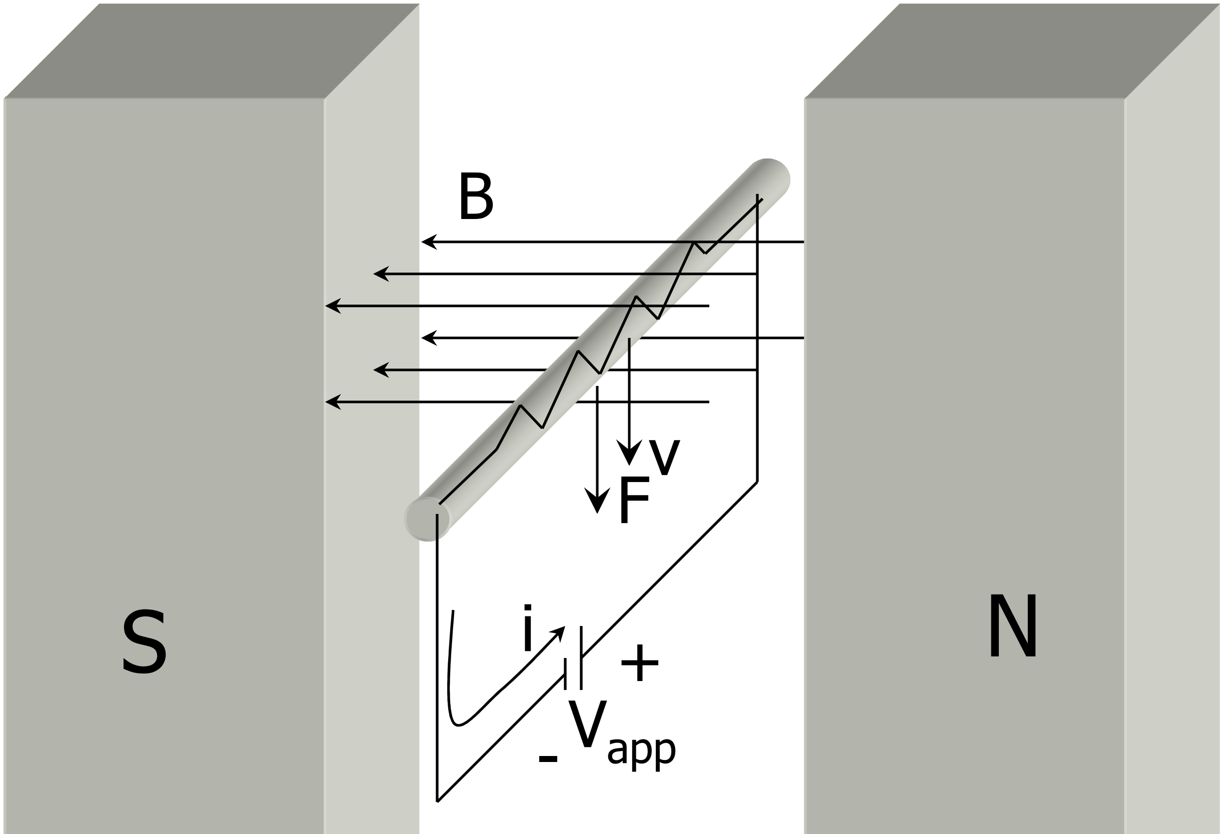


Figure 1–10 Effect of four conductors and segments on output waveform of generator

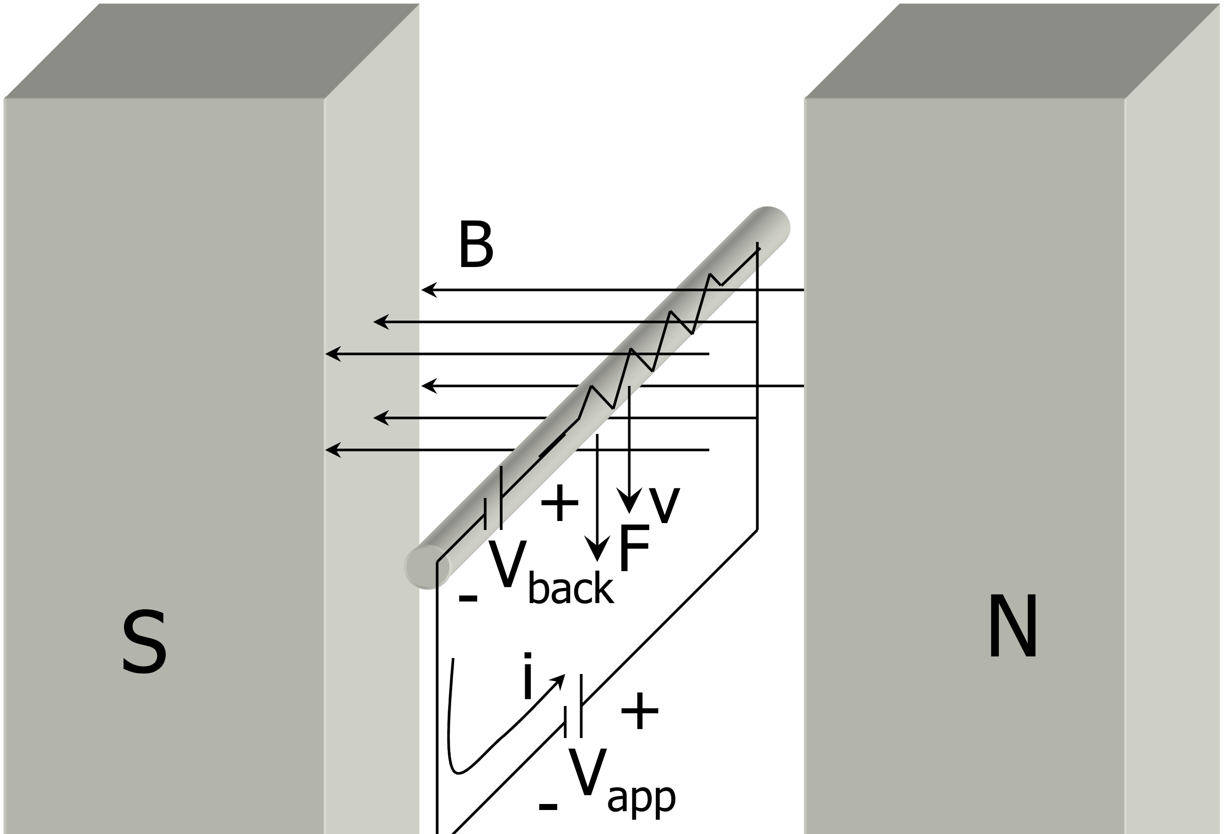
Principle #3

- Passing a current through a conductor in a magnetic field will result in a force acting on the conductor according to

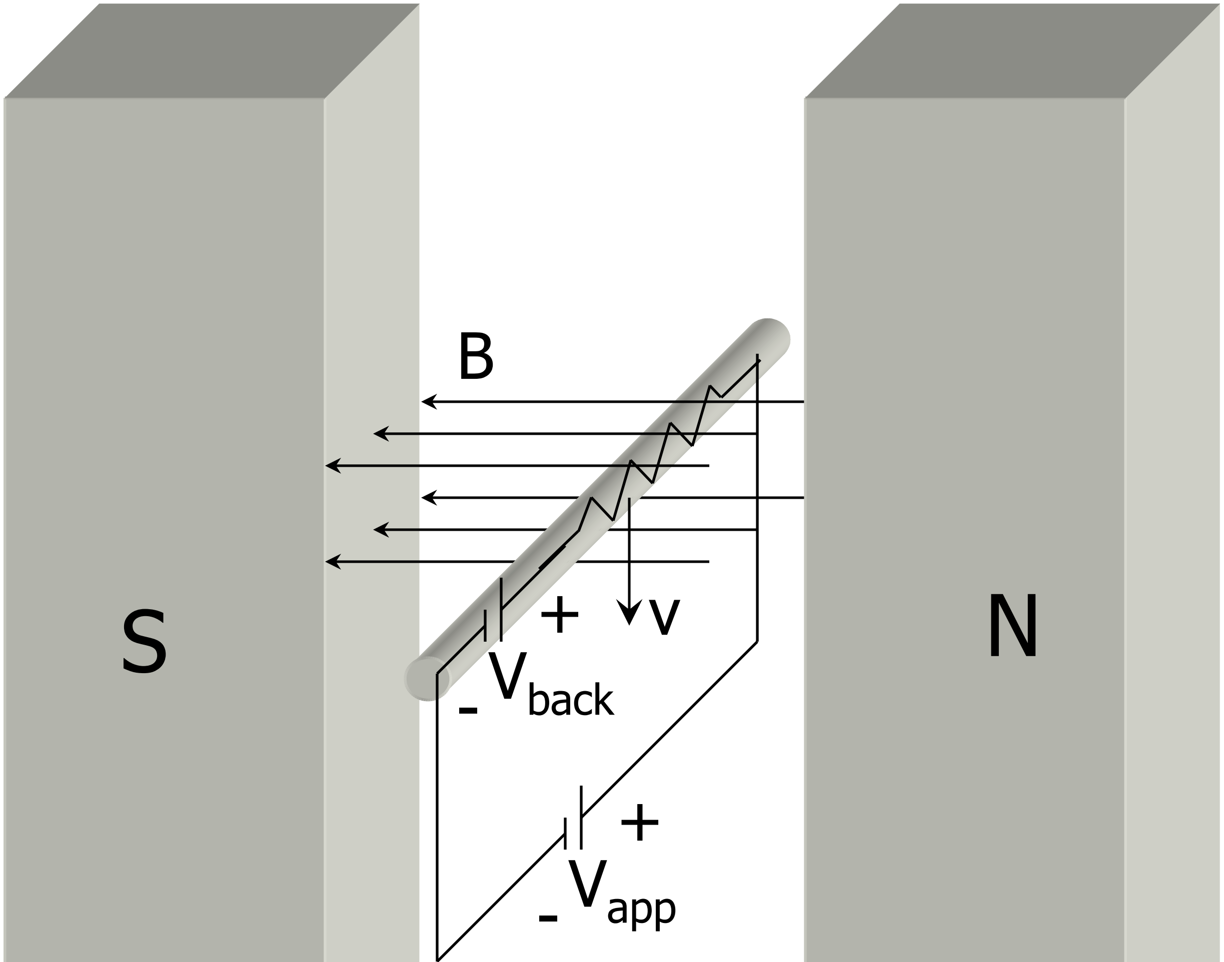




Step 1: Conductor initially at rest. Apply voltage; produces current; produces downward force; conductor accelerates downward; sees non-zero downward velocity.

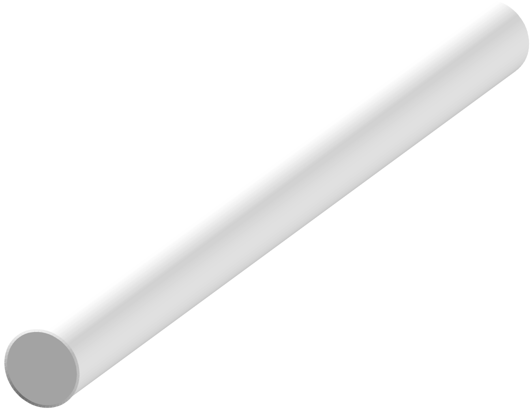


Step 2: Conductor moving downward; produces voltage in conductor; superimposes with applied voltage; reduces effective voltage; reduces current; force reduced, still accelerating.



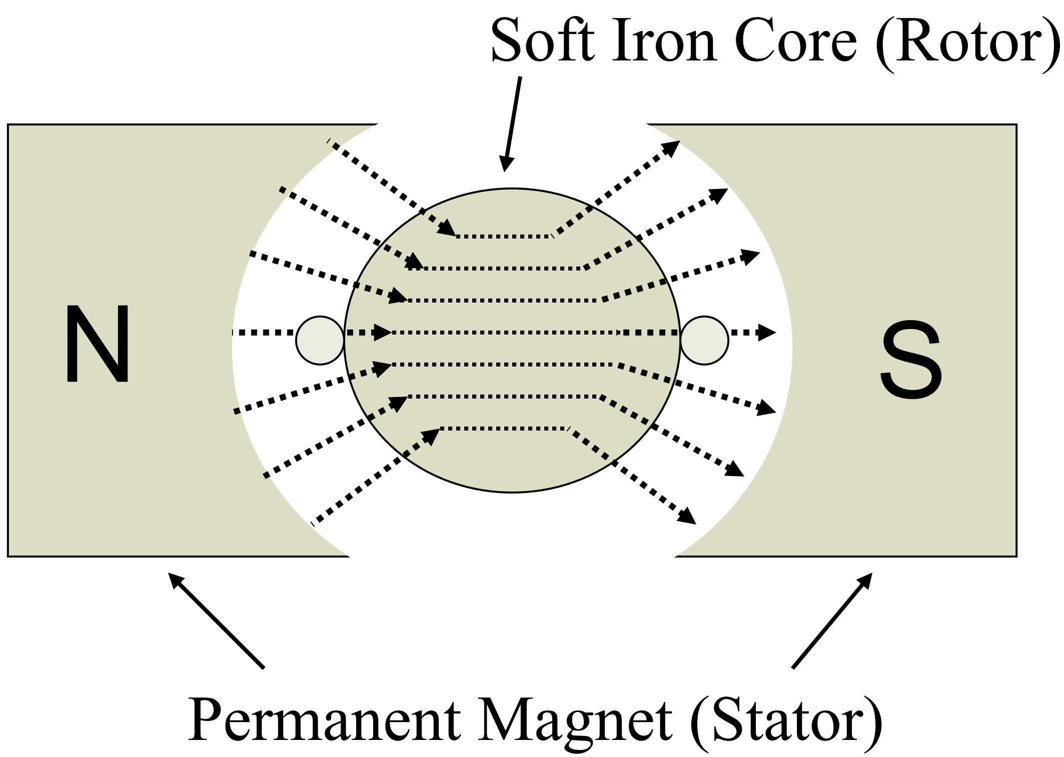
Step 3: Conductor downward velocity produces V_{back} equal to V_{app}; zero current flowing in conductor; zero force; *constant velocity*.

How does a DC Motor work?

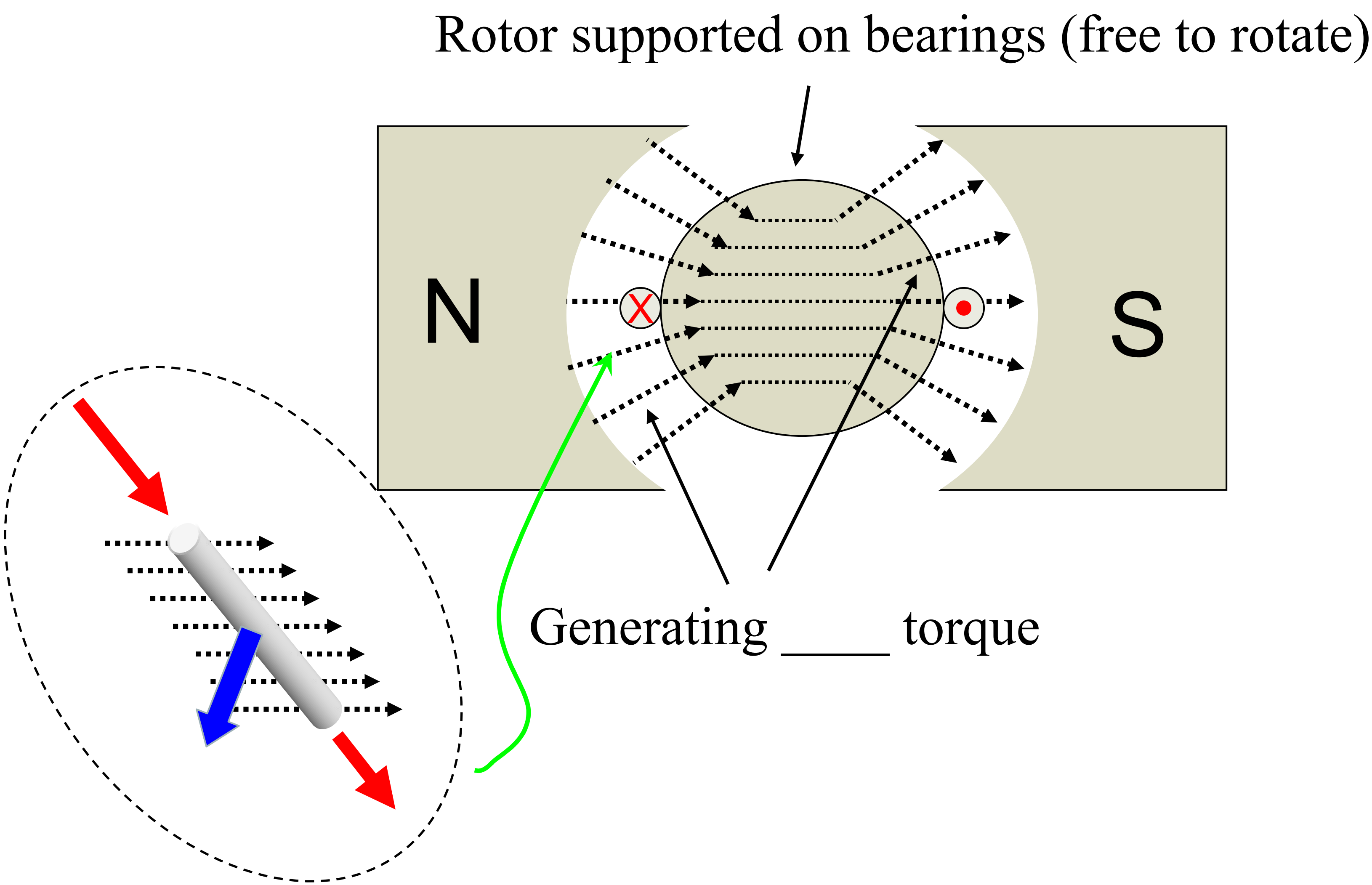


Wire length vector, d$\underline{L}$

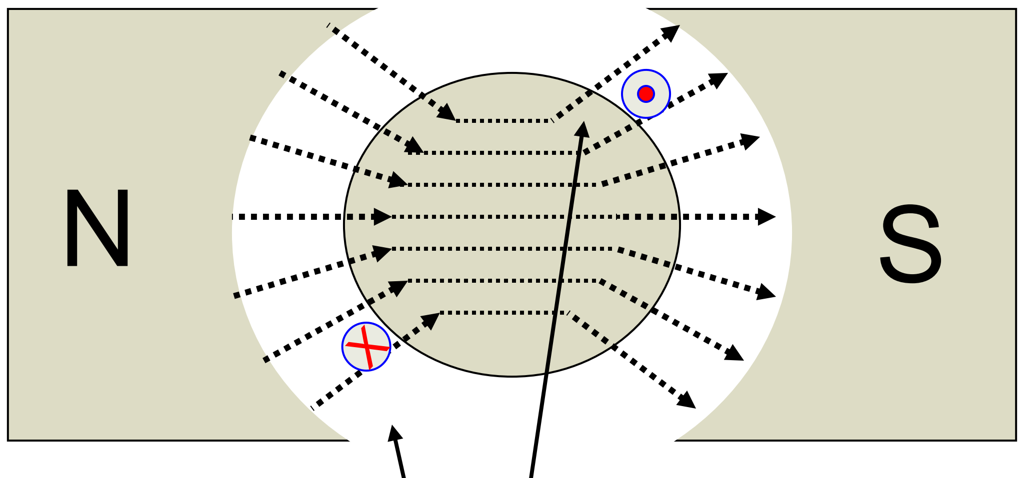
Cross-section of DC motor



Cross-section of DC motor



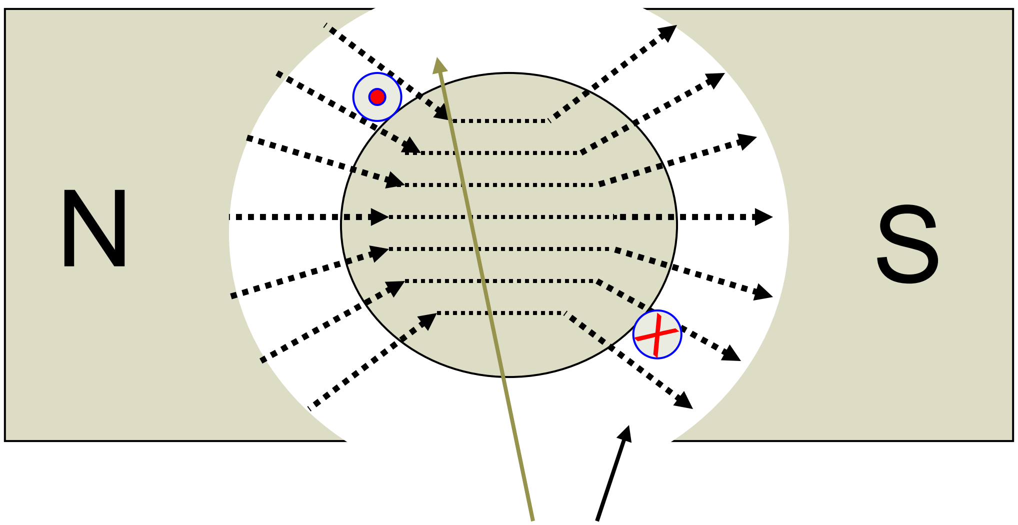
Cross-section of DC motor



Still generating _____ torque

Cross-section of DC motor

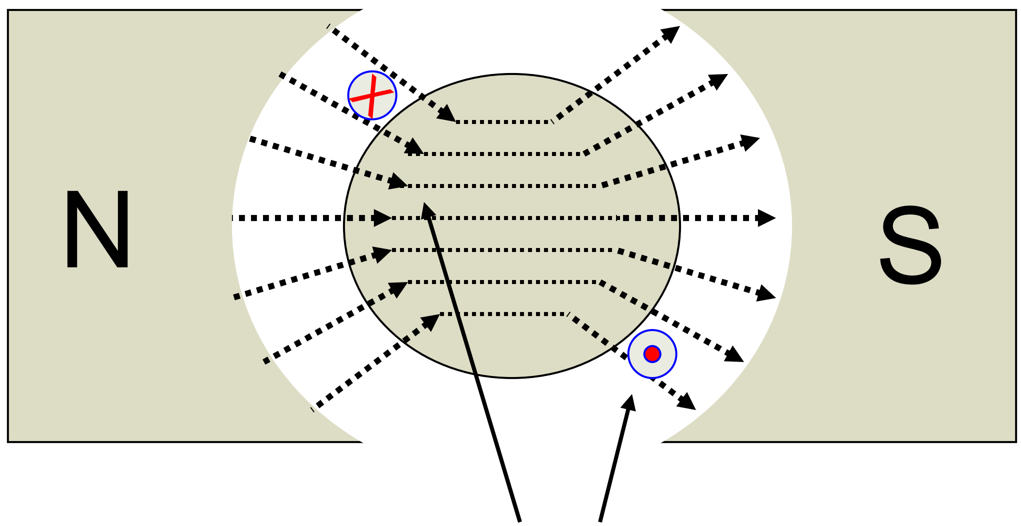
Rotation past 90 degrees:



Now generating ___ torque!

Cross-section of DC motor

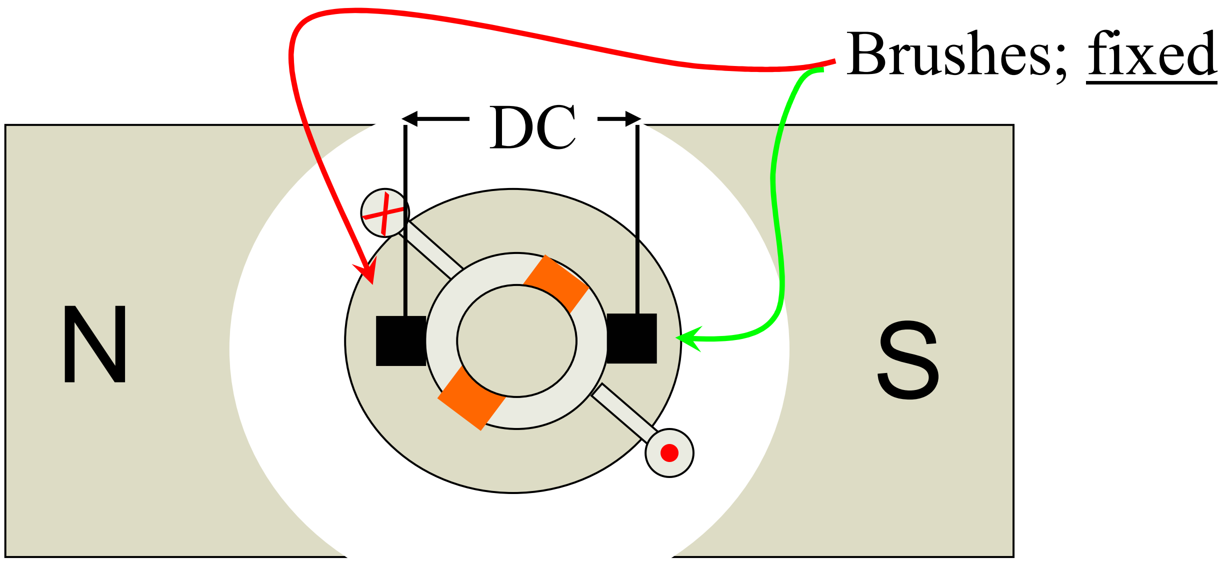
______________ of current flow after 90 degrees
(the current switching process is called ____________)



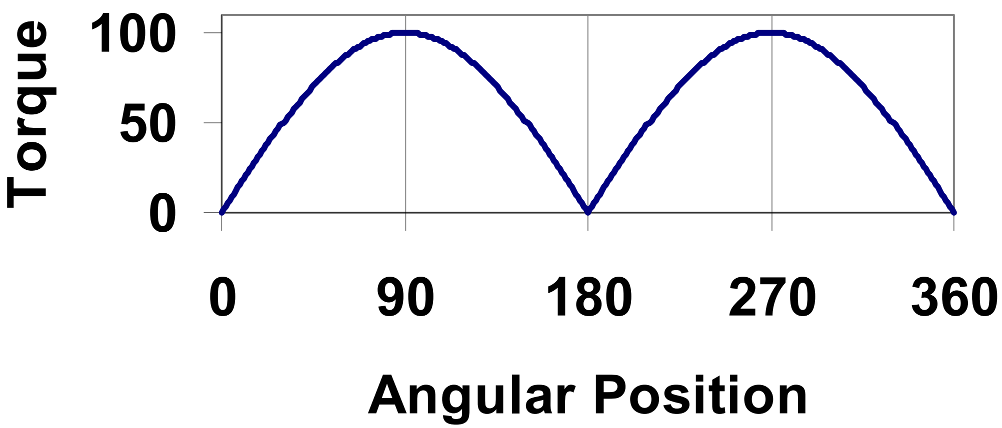
Now generating ____ torque!

2 Commutator Bars

Two segment commutation on rotor

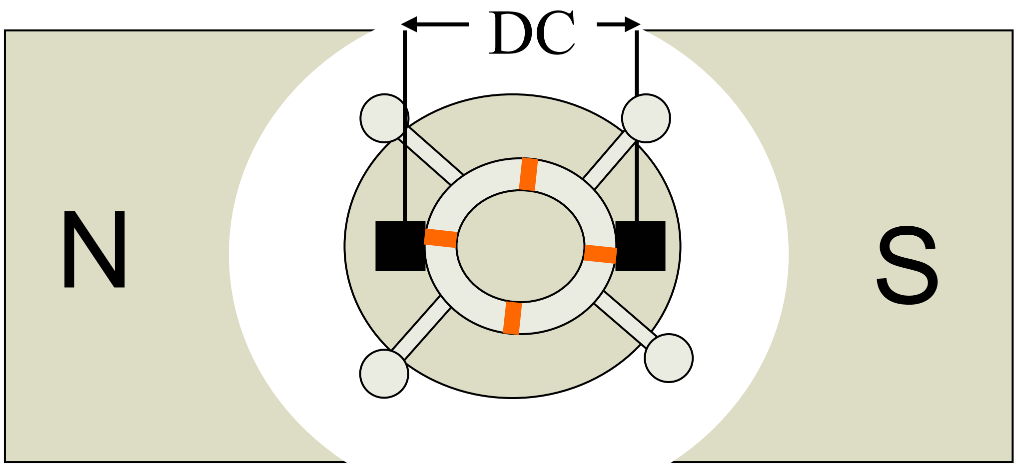


%Torque vs. Angular Position

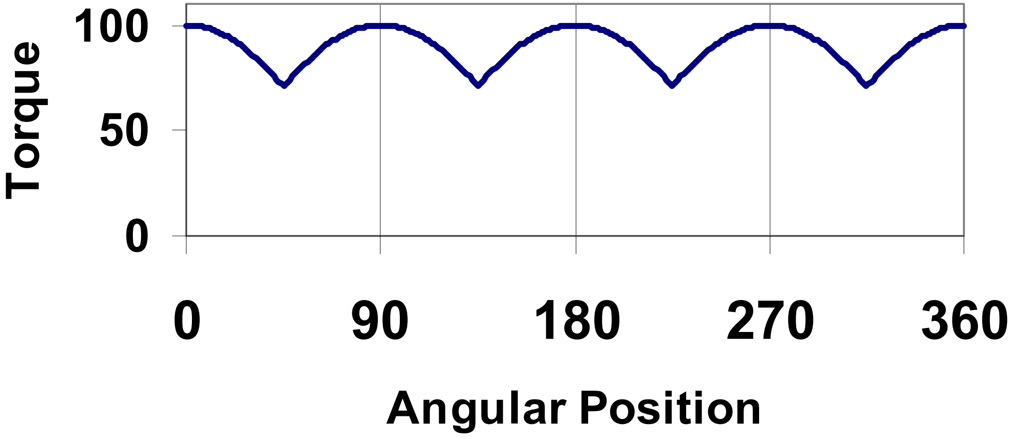


4 Commutator Bars

Four segment commutation on rotor

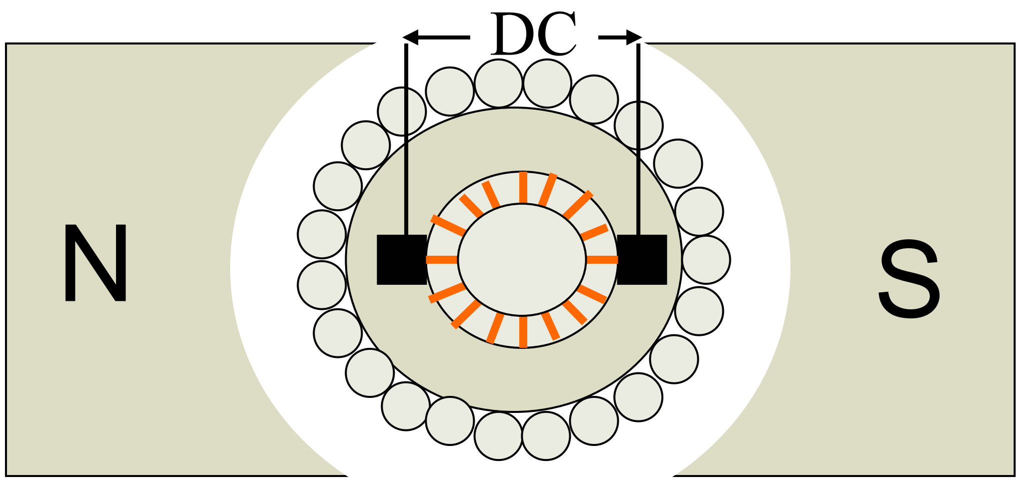


%Torque vs. Angular Position

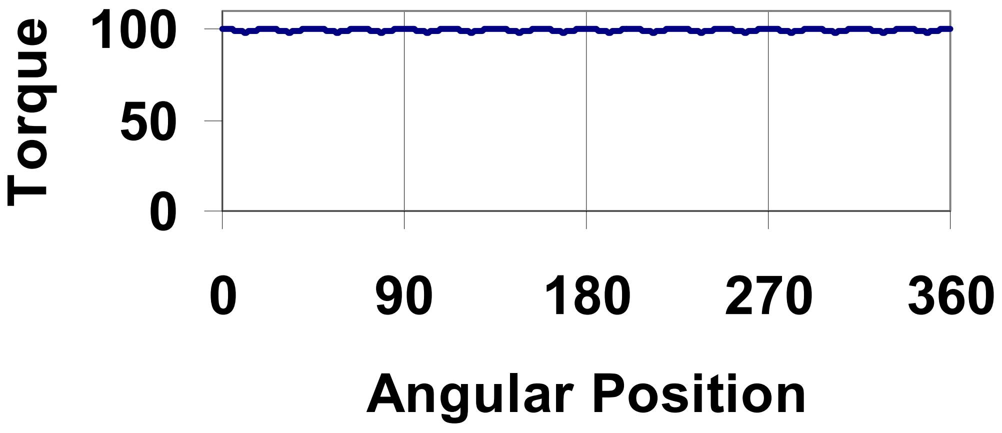


24 Commutator Bars

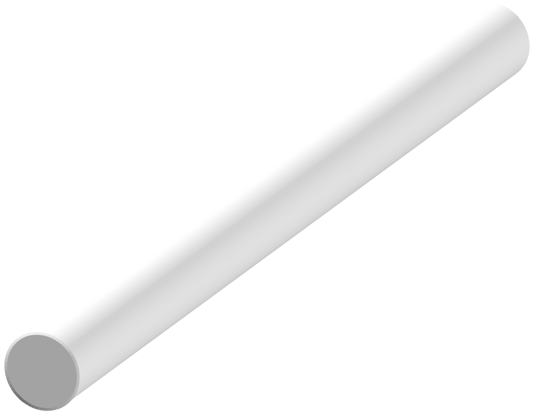
Sixteen segment commutation on rotor



%Torque vs. Angular Position



How does a DC Generator work?

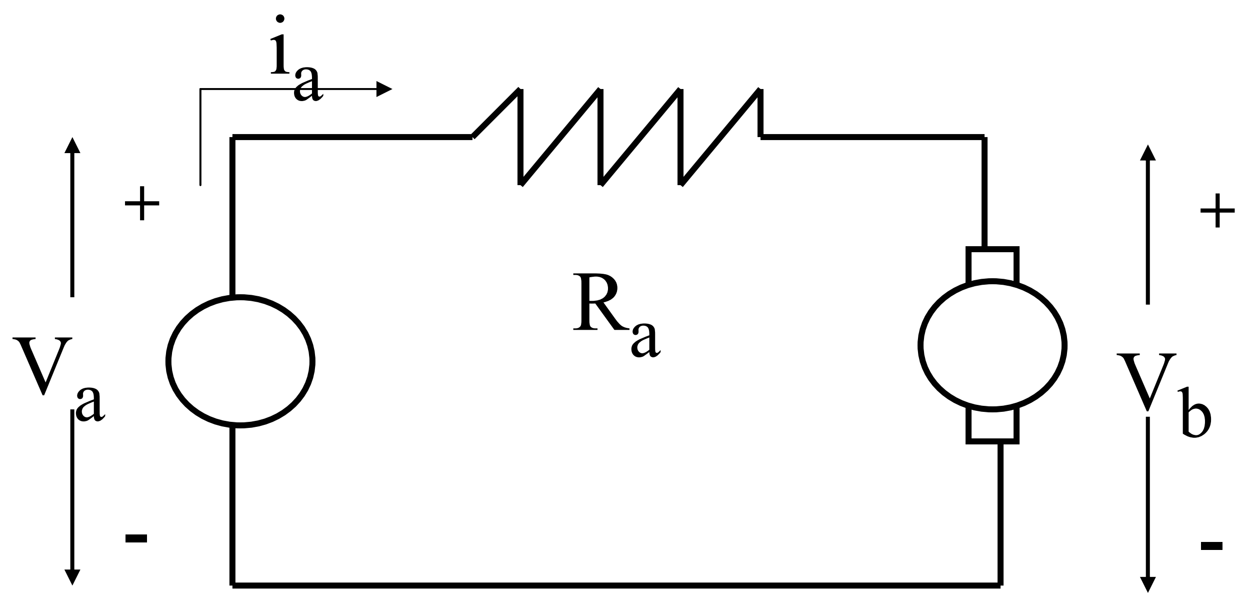


Wire length vector, d$\underline{L}$

DC Motors & Generator

- Note that a DC motor always begins to act like a generator once the rotor wires start to move through the magnetic field
  - the induced "back EMF" is ______________ to angular velocity
  - "back EMF" generates a current which _________ the applied current,
  - reduces the force (torque) output of the motor

Circuit Model for Permanent Magnet DC Motor



V_a= applied armature voltage

R_a= armature resistance

V_b= back EMF

i_a= armature current

PMDC Motor Steady-State Equations

from circuit

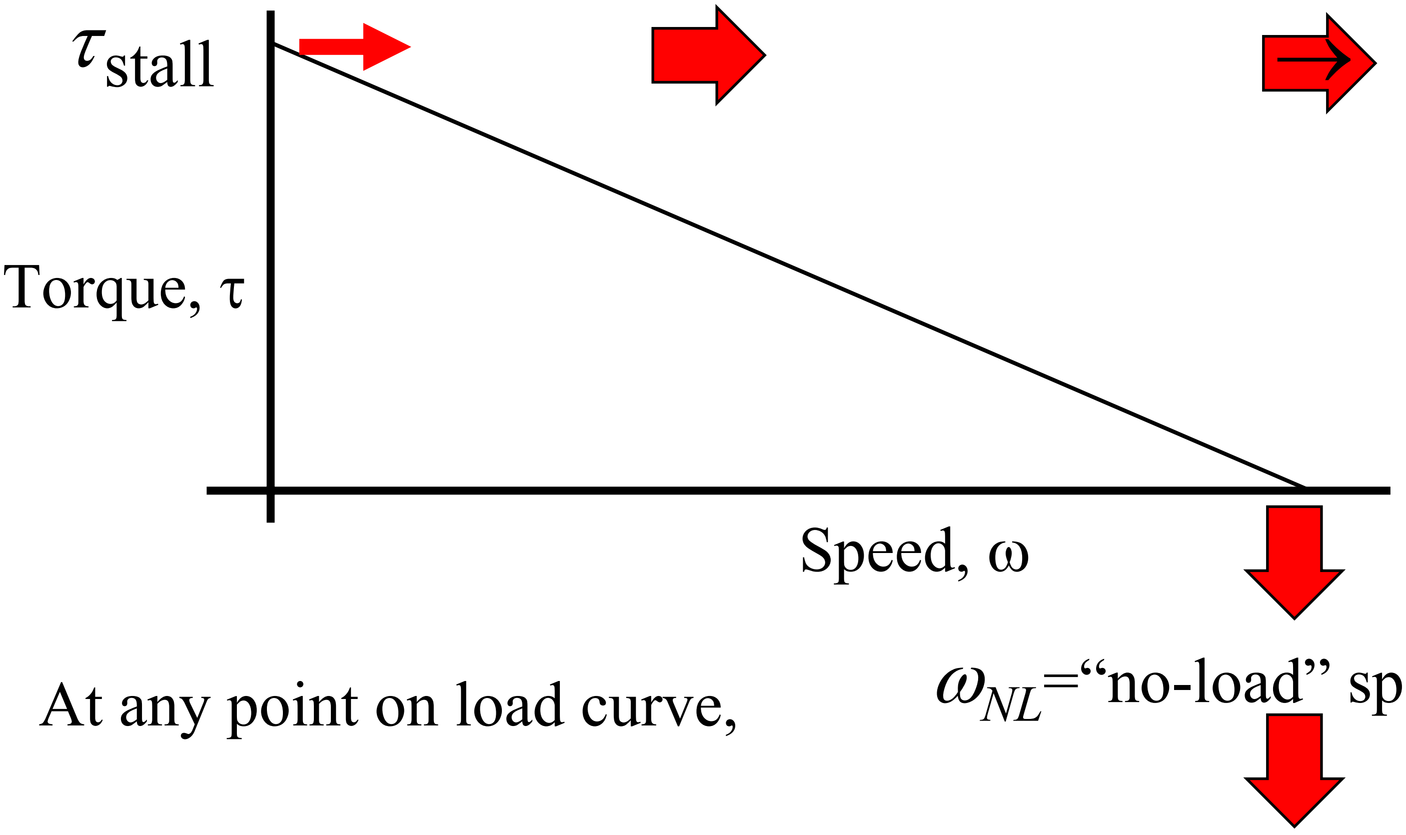
from $dV = B\,v\,dL$ and $v = r\omega$

from $df = i_a\,d\underline{L} \times \underline{B}$ and $\tau = rf$

PMDC Motor Steady-State Equations

- For a given motor, R_a, K_a, and K_b are constants
- Armature voltage V_a, speed ω, and output torque τ are related by the 3 equations
- ______________________________

PMDC Motor Equation Part #3



ω_{NL}=“no-load” speed (i_a=0)

At any point on load curve,

Number Assignments - Exercise #1

Student Group	Speed (RPM)	Speed (rad/sec)	Student Group	Speed (RPM)	Speed (rad/sec)
#1	250	26	#5	1250	131
#2	500	52	#6	1500	157
#3	750	79	#7	1750	183
#4	1000	105	#8	2000	209

In-Class Exercise #1

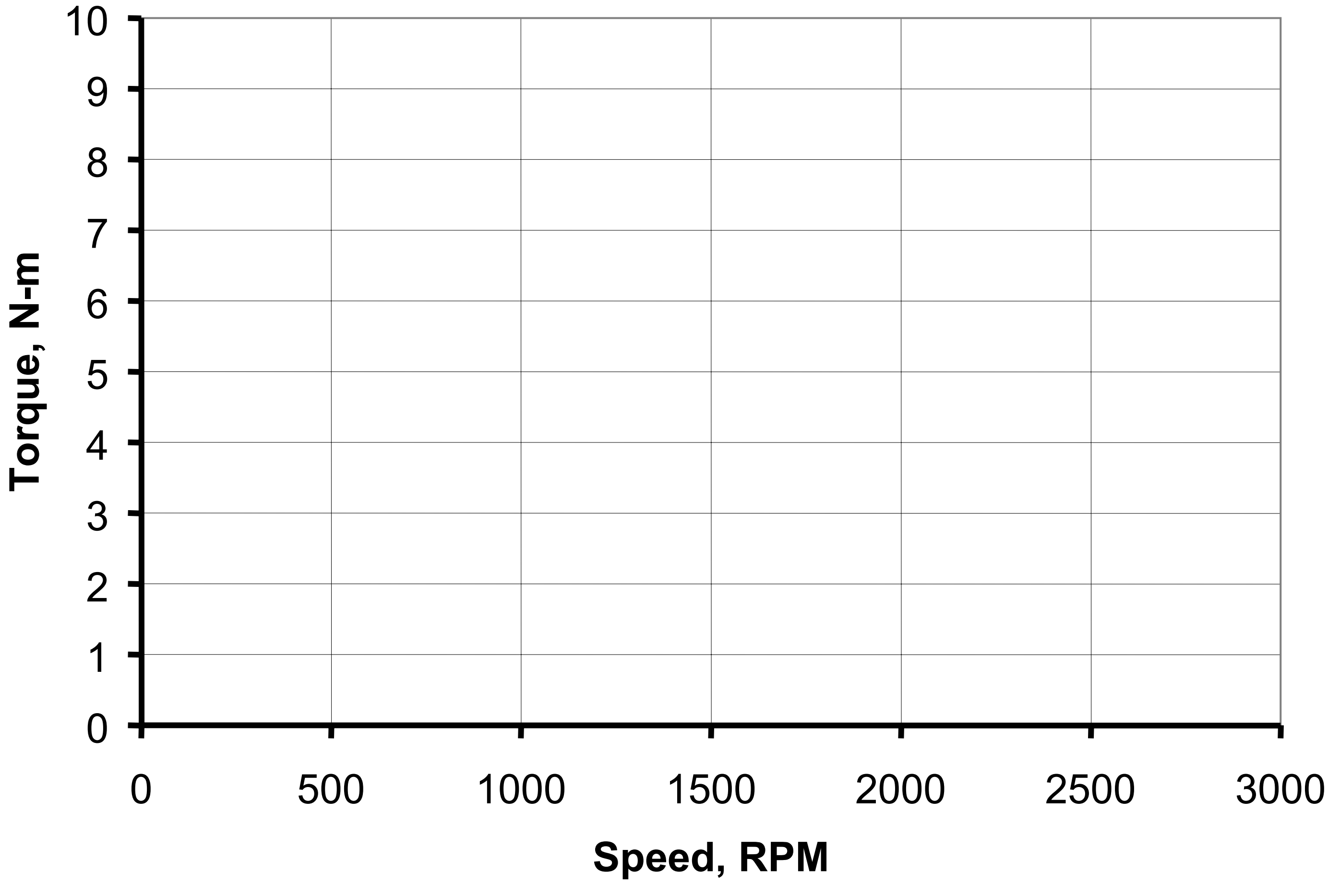
A small DC motor has these parameter constants

V_a	=	48	volts
K_a	=	0.17	N-m/amp
K_b	=	0.17	volt/rad/s
R_a	=	0.9	ohms

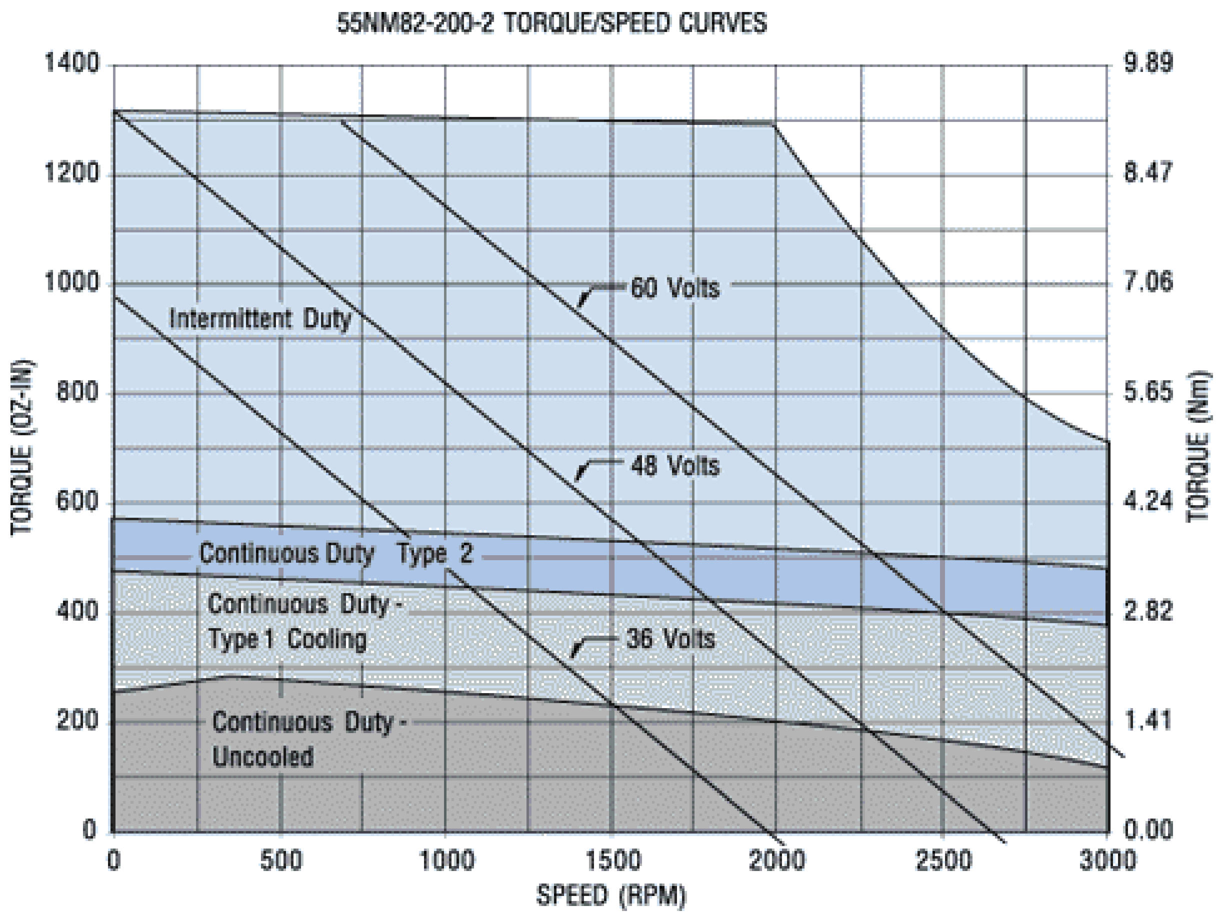
Determine the output torque, τ_a, for the speed assigned to your group

1) find back-EMF, V_b for your speed
2) find current, i_a for your speed
3) find torque, τ_a for your speed

Plot for In-Class Exercise #1



Manufacturer's Data



2nd In-Class Exercise

A small DC motor has these parameter constants

V_a	=	?	volts
K_a	=	3.60	oz-in/amp
K_b	=	2.67	volt/KRPM
R_a	=	50	ohms

On a single graph, we will plot the torque vs. speed relationship for different input voltages -

24, 18, 12, 6 VDC

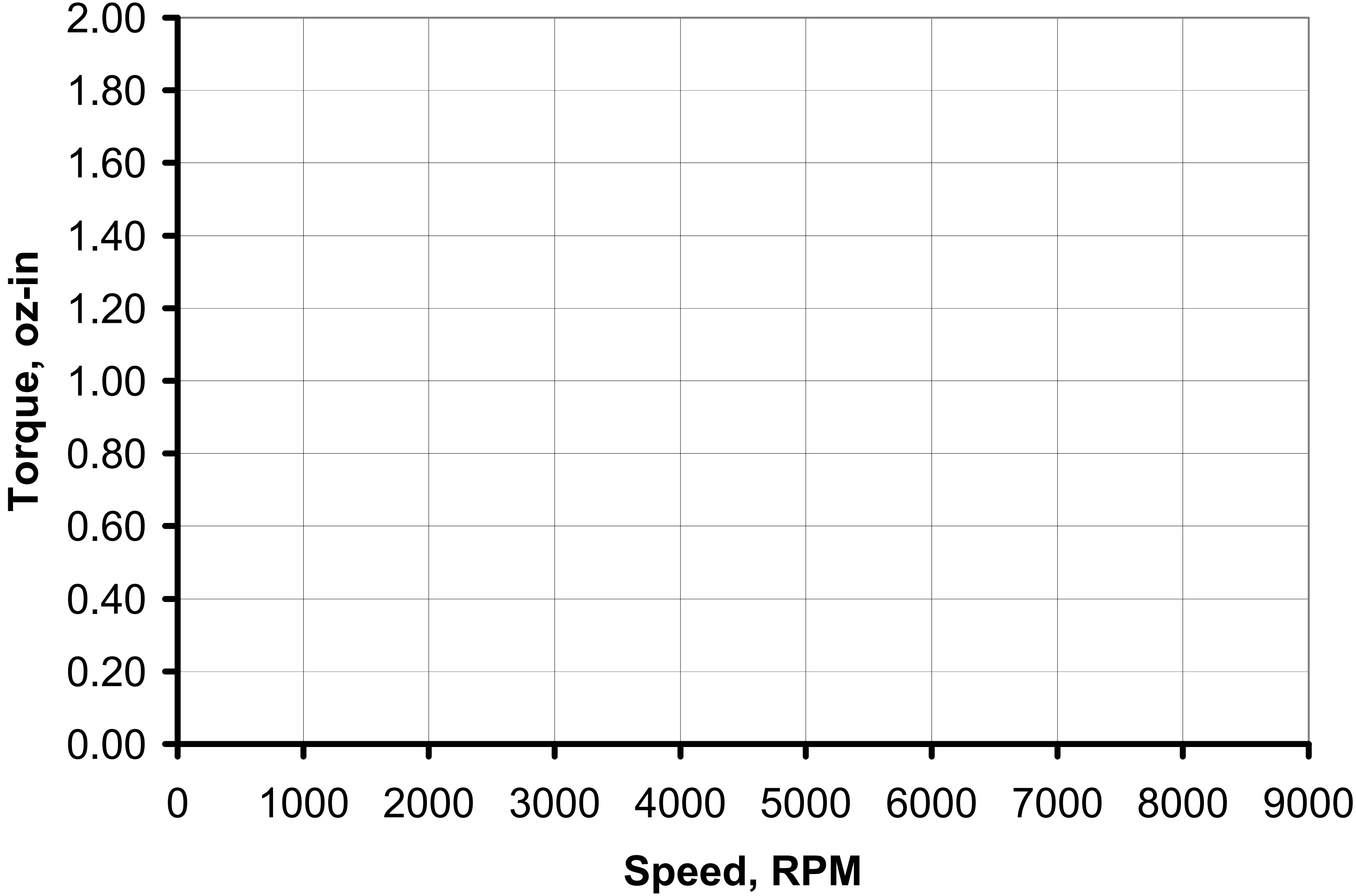
Number Assignments - Exercise #2

Both 1000 and 3000 RPM

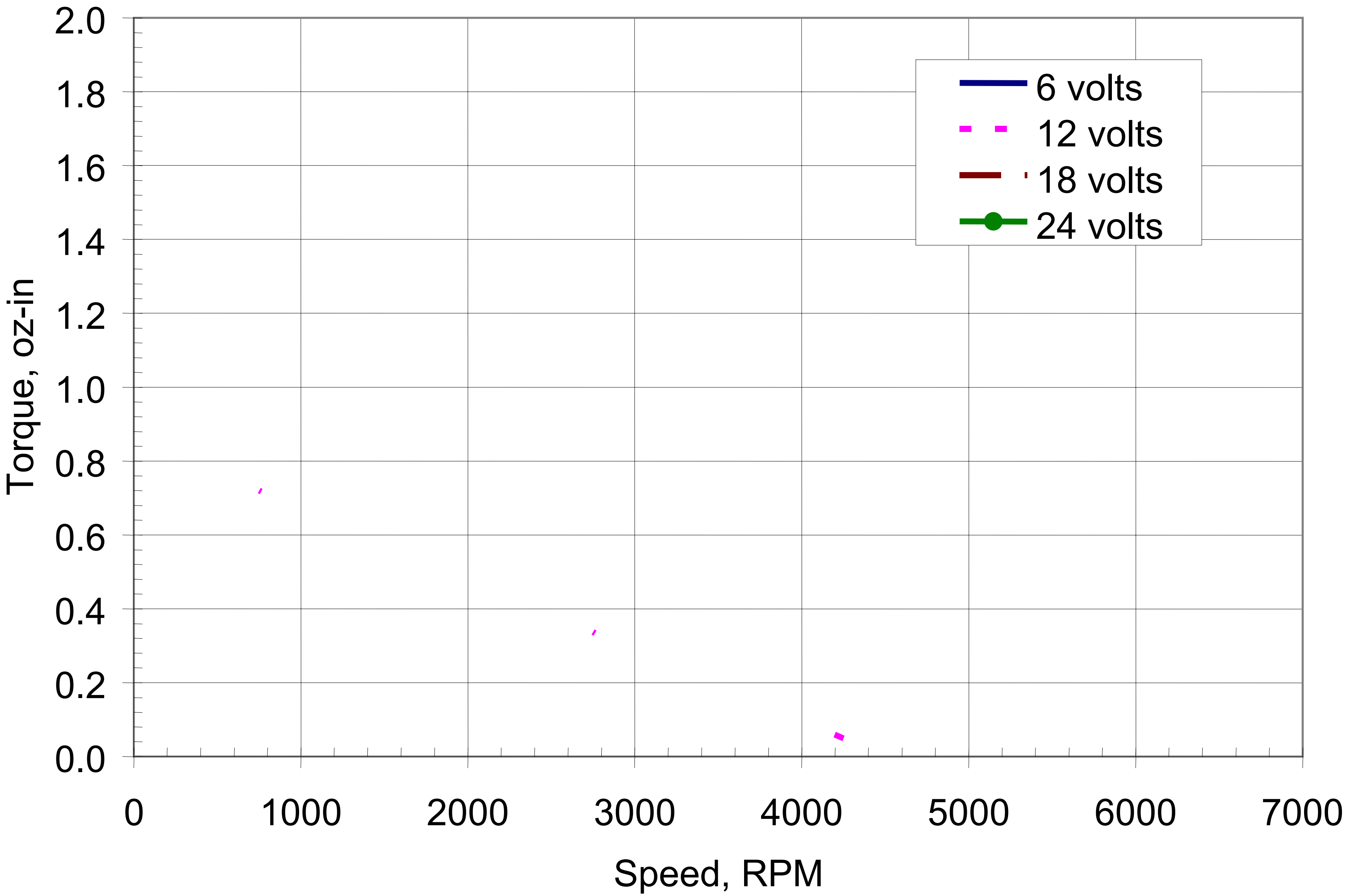
Group	V_a, volts	Group
#1	24 VDC	#5
#2	18 VDC	#6
#3	12 VDC	#7
#4	6 VDC	#8

Both 5000 and 7000 RPM

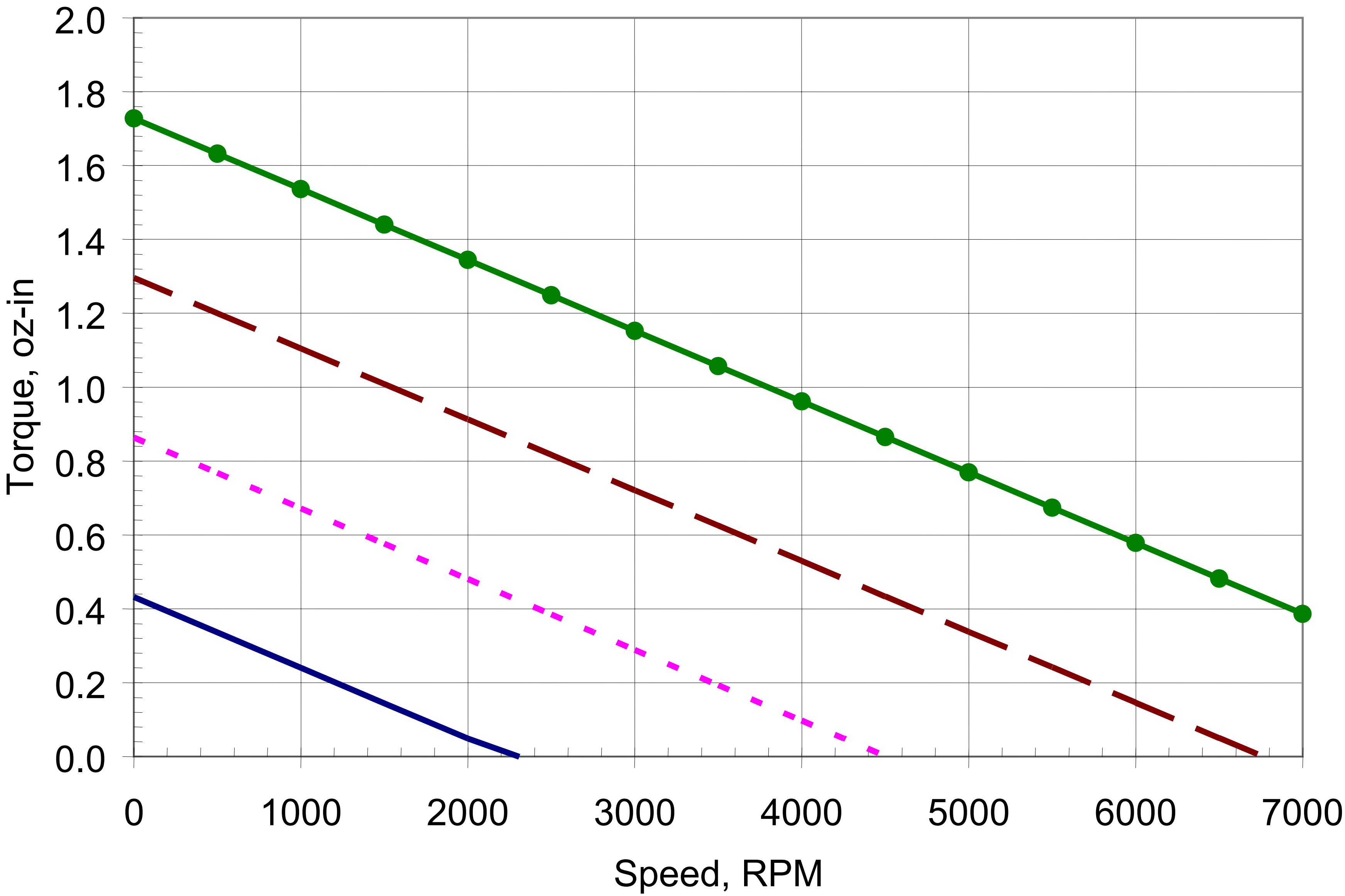
In-Class Exercise #2



In-Class Exercise - Solution



In-Class Exercise - Solution



PMDC Motor Equation Part #2

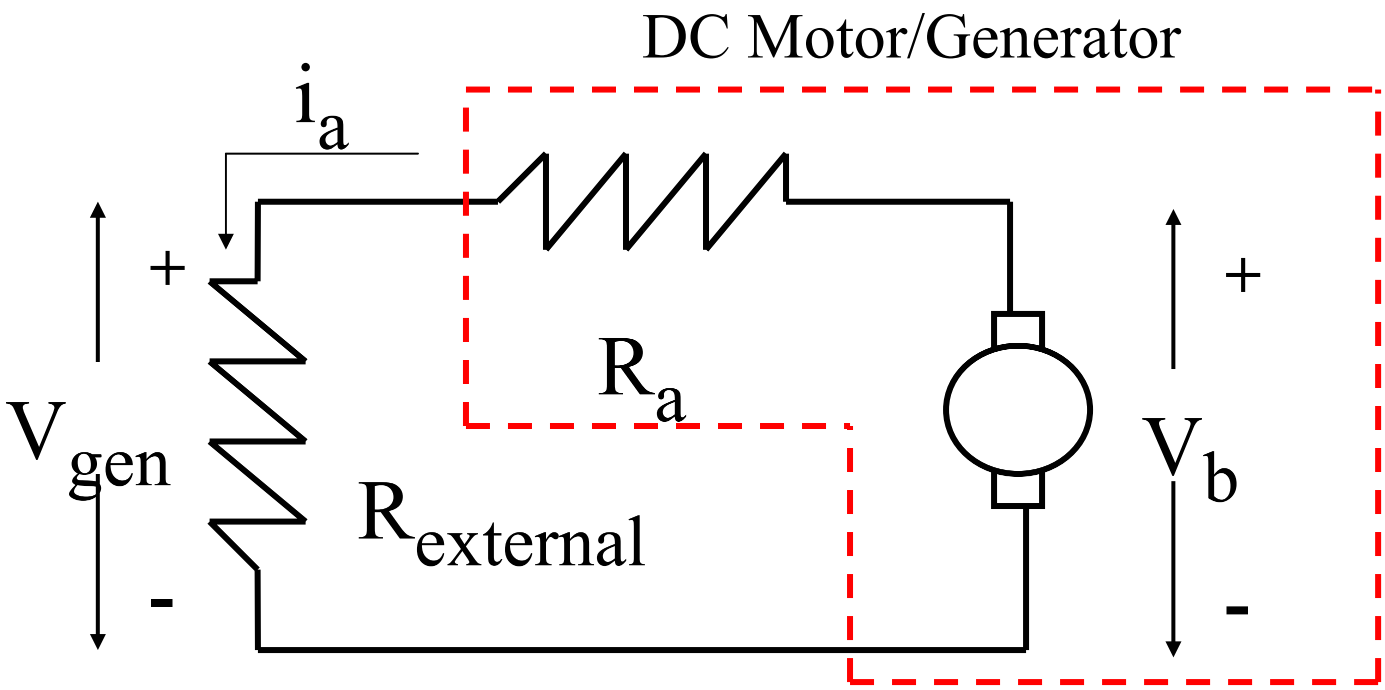
$V_a = R_a i_a + V_b$ $\quad V_b = k_b \omega$ $\quad \tau = k_a i_a$

PMDC Motor Equation Part #2b

$$V_a i_a = R_a i_a^2 + \tau\omega$$

Electrical Power	= Power Dissipated	+ Mechanical Power
(Input)	(as heat)	(useful output)

Circuit Model for Permanent Magnet DC Generator



V_{gen} = generated armature voltage

V_b = back EMF

R_a = armature resistance

i_a = armature current

PMDC Generator Equations

$$V_{gen} + R_a i_a = V_b \qquad V_b = k_b \omega \qquad \tau = k_a i_a$$

DC Motor Commutation

- DC motors require periodic switching of currents to maintain rotation (“commutation”)
  - conventional DC motors use brushes to provide commutation, but
  - "brushless" DC motors which use electronic commutation have been developed.

DC Brushed Motor Advantages

- Simplicity of operation, requiring only a voltage source, power op-amp, and analog control input for variable speed operation.
- Torque ripple can be easily minimized through design variations
- Dynamic braking capability without additional power input

DC Brushed Motor Disadvantages

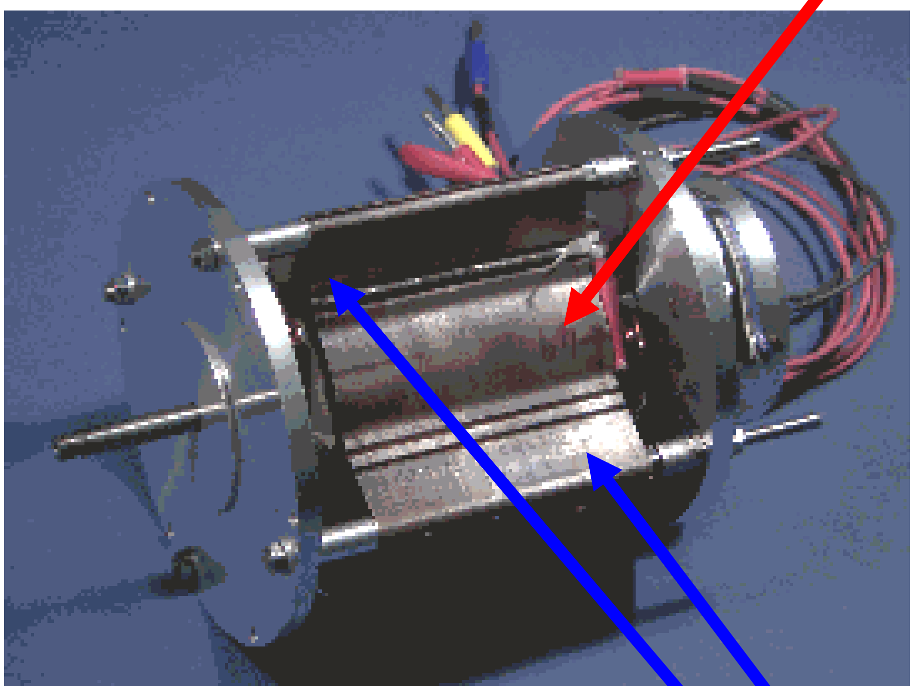
- The brushes wear, the wear producing small particles which can affect the cleanliness of surrounding operations.
- High current through the brushes can cause them to burn out rapidly
- Heat is generated in the rotor windings which is primarily conducted away through the rotor shaft
- Small sparks are generated at the brush/rotor interface

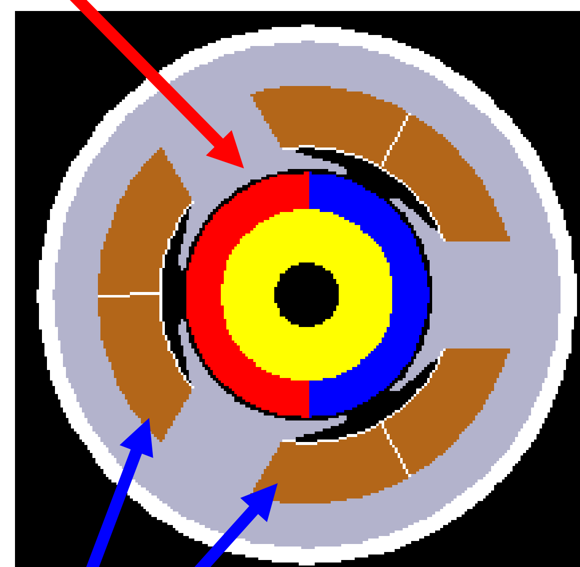
DC Brushless Motor

- The magnetic field in the rotor is provided by permanent magnets on the ______
- Hall effect sensors (or resolver output) are used to signal a motor driver when to switch the current in the _________________
- Motor driver depends on the controller to set desired torque output

DC Brushless Motor

Permanent Magnet Rotor





Wound Wire Stator

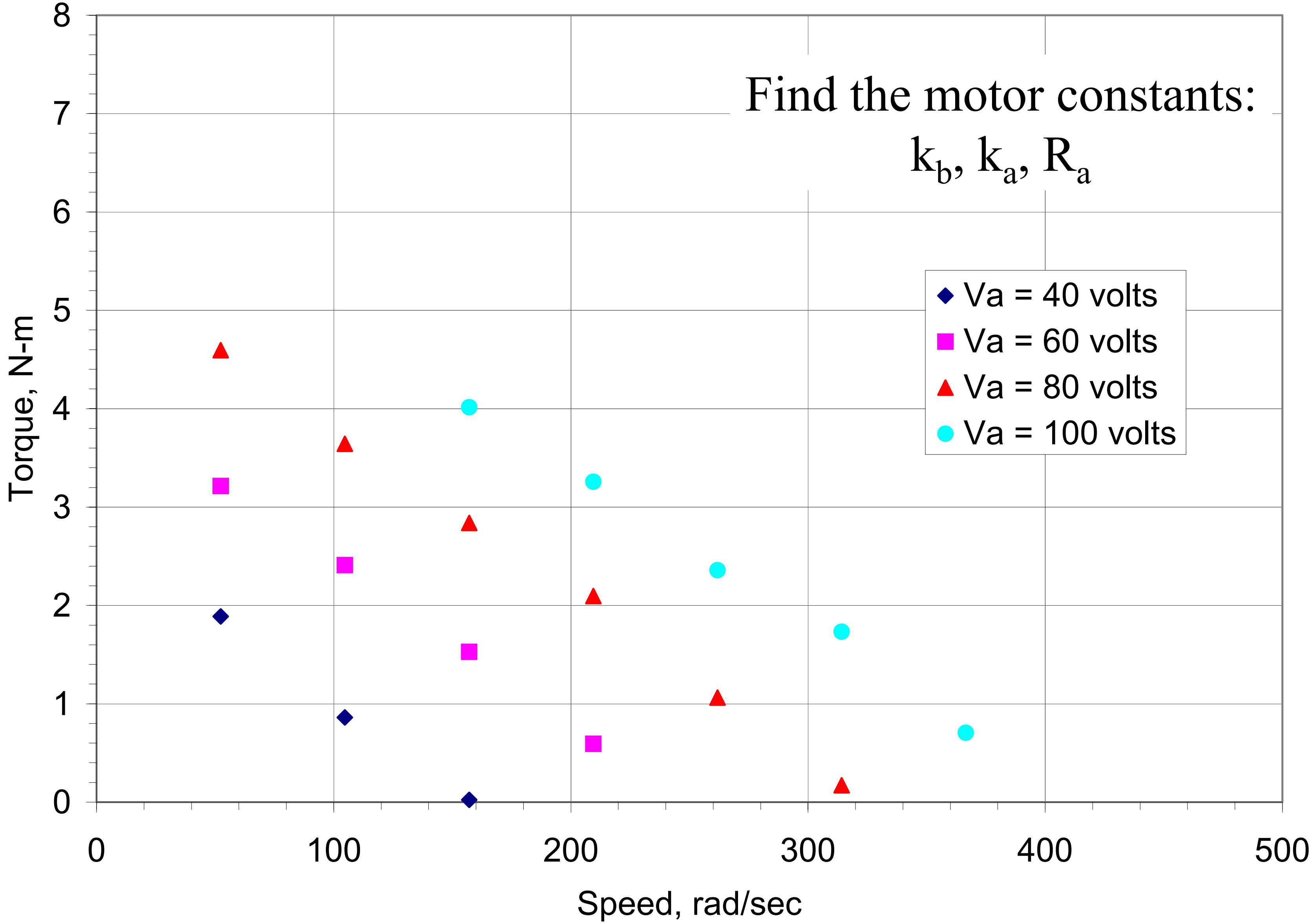
DC Brushless Motor Advantages

- No appreciable heat is generated in the rotor and hence the heat conducted to the shaft is minimized.
- Due to the lack of brushes, motors can be operated at high torque and zero rpm indefinitely as long as the winding temperature does not exceed the limit.
- No brushes to wear out or contaminate the surroundings

DC Brushless Motor Disadvantages

- Torque ripple is hard to minimize by design
- Motor operation requires the purchase of an electronic motor driver
- Rotor magnets can become demagnetized in high current or temperature environments
- Most motor drivers brake DC brushless motors by applying reverse current, in which almost as much power is expended to stop the motor as was required to start it moving

Experimental Results #1



DC Tachometer Equations

Mechanical construction of a DC tachometer is essentially identical to DC motor

$$i_a = \frac{1}{R_a}\left(V_a - V_b\right) = 0$$

High impedance load, No current

$$V_b = k_b \omega = V_a$$

Output voltage proportional to angular velocity, ω

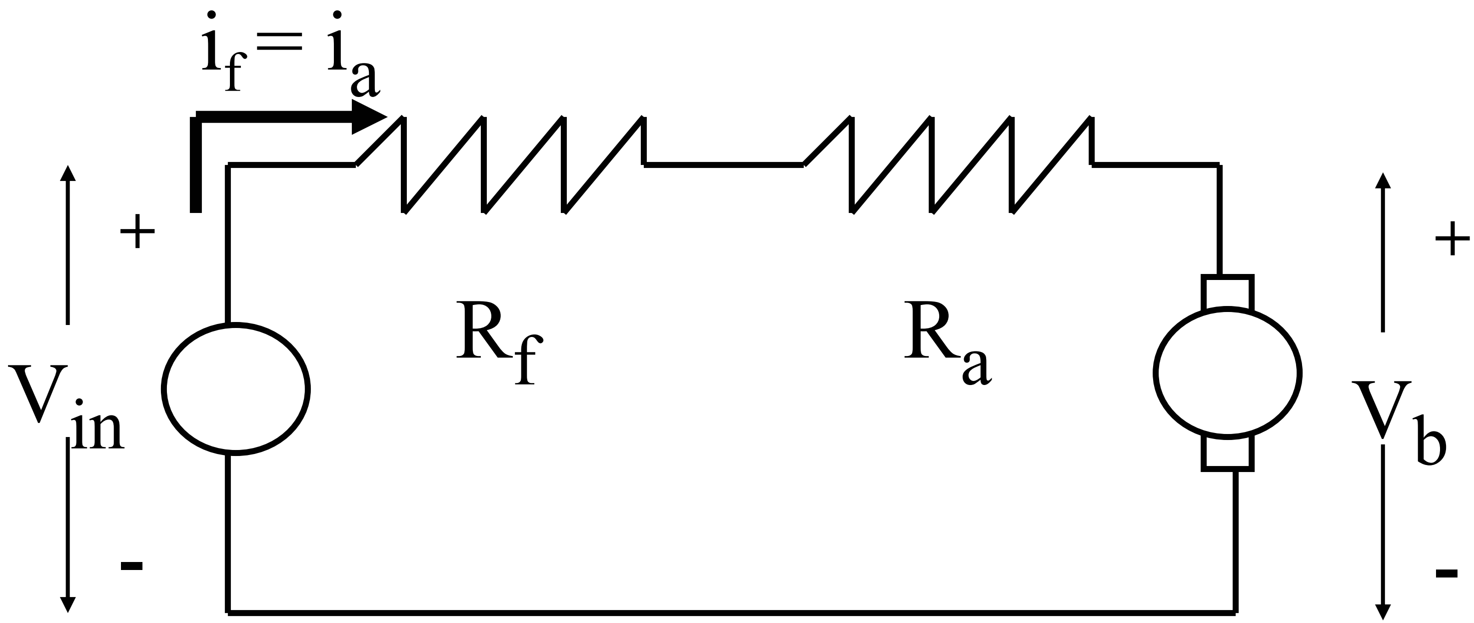
$$\tau = k_a i_a = 0$$

No current

DC Motor - Magnetic Field Generation

- Magnetic field on the stator can be generated two ways
  - with a permanent magnet (PM)
  - electro-magnetically with <u>wound coils</u>
- Wound DC motors
    - Series wound
    - Shunt wound
    - Compound wound (series and shunt windings)

Series Wound DC Motor



V_{in} = input voltage

R_a = armature resistance

R_f = field resistance

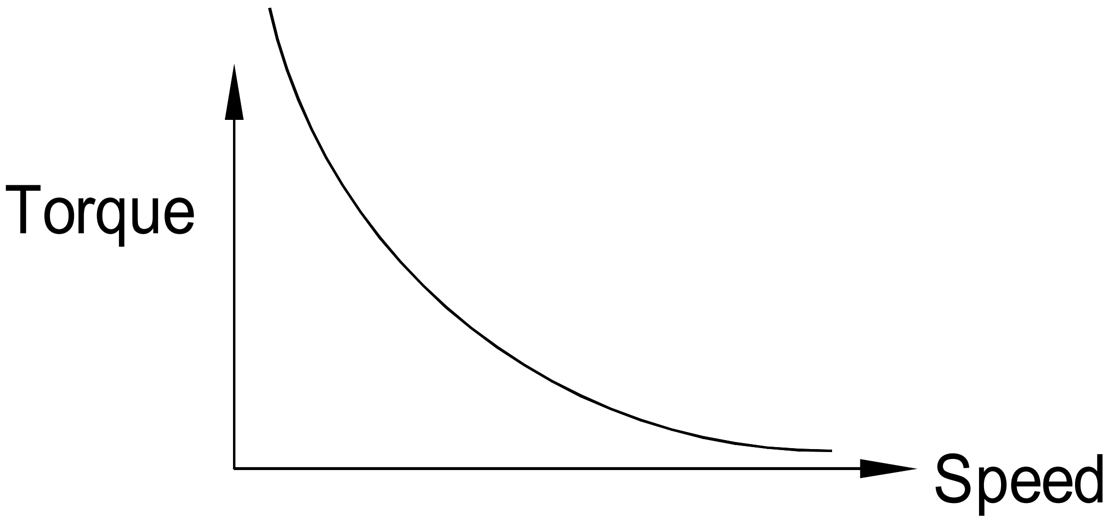
V_b = back EMF

i_a = armature current

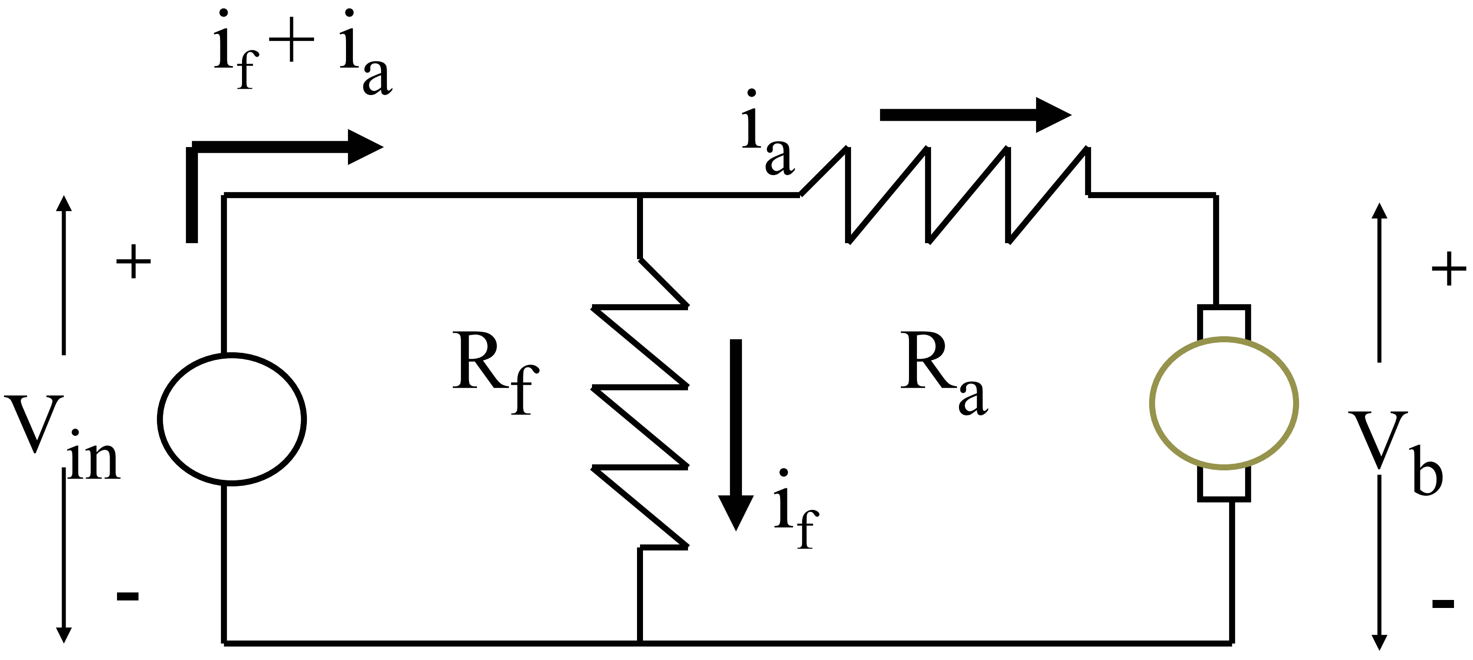
i_f = field current

Series Wound DC Motor

- Large starting torque available
- R_f is small
  - a few turns of large gage wire are used

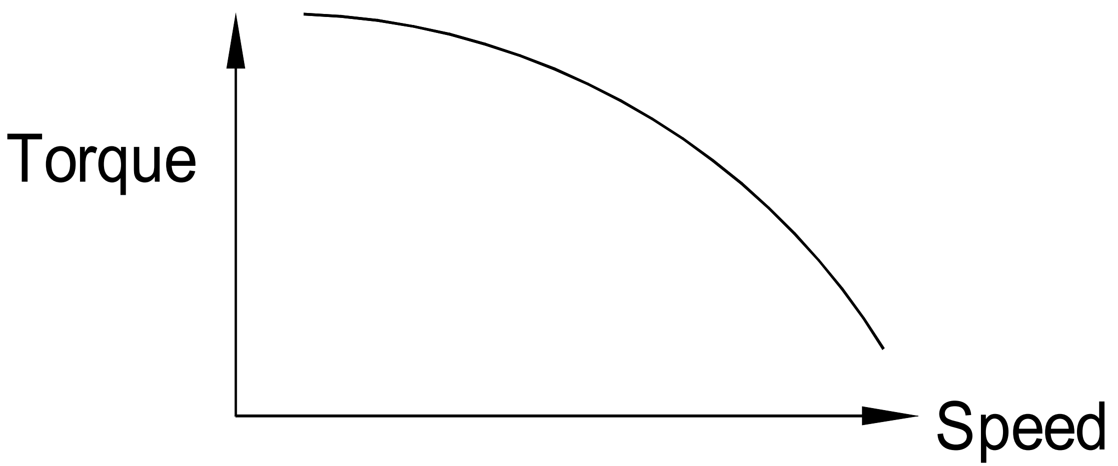


Shunt Wound DC Motor



Shunt Wound DC Motor

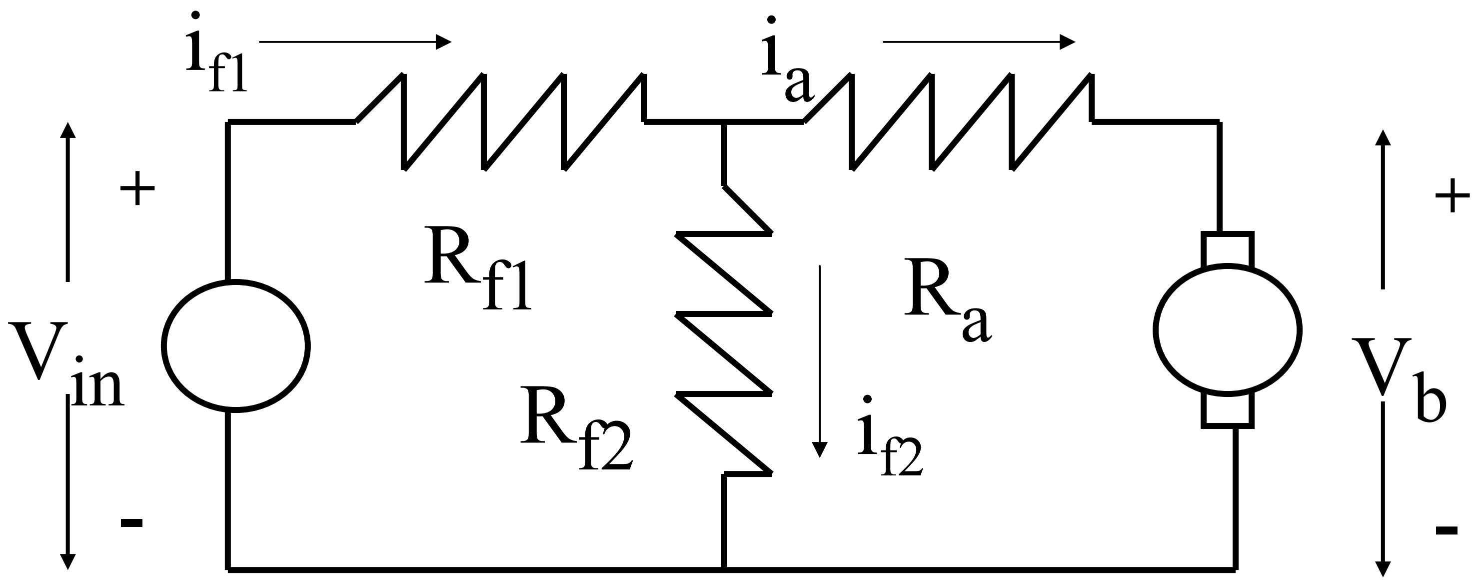
- Used for both fixed & variable speeds
- R_f is large
  - several turns of small gage wire are used



Wound Motor Speed Control

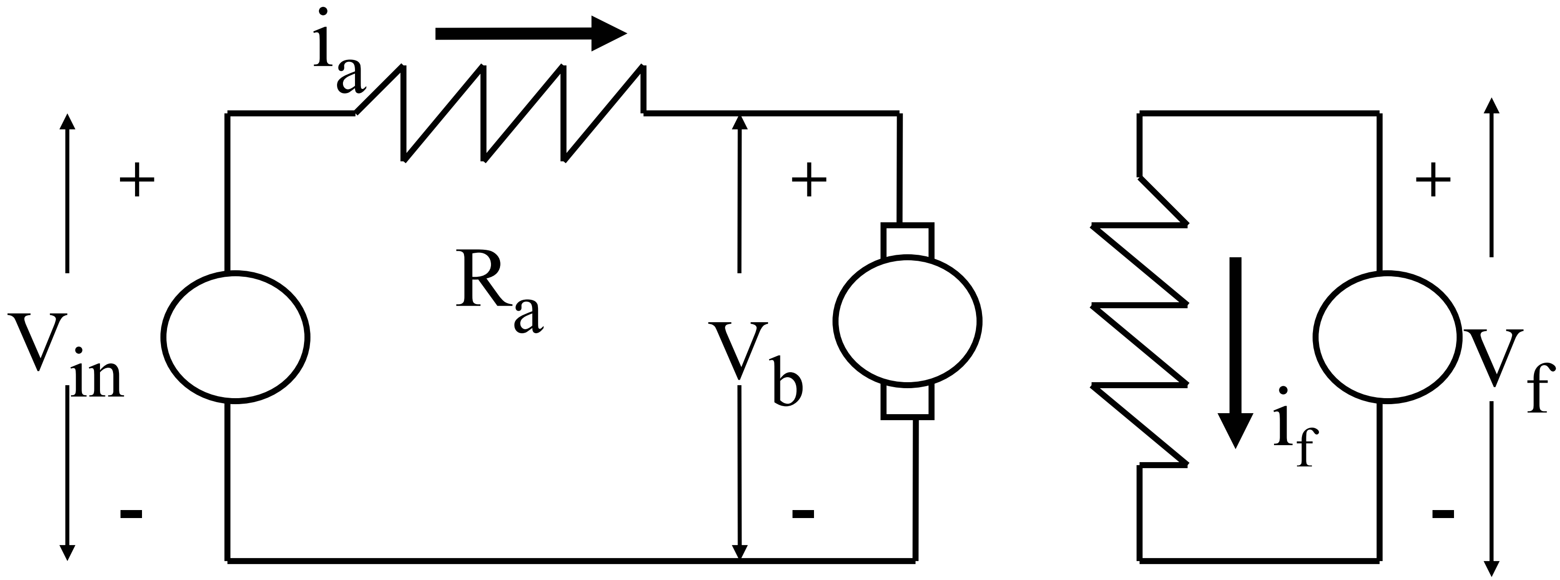
- Change V_{in}
  - increase or reduce speed
- Increase field resistance
  - reduces $i_f \rightarrow$ reduces K_a and K_b
- Increase armature resistance
  - reduces $V_b \rightarrow$ reduce ω

Compound Wound DC Motor



Has both a series and a shunt wound field

Separately Excited DC Motor



Acts like a permanent magnet DC motor
(if a constant field excitation is used)