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.
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.)

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 $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$.
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 $V_{\text{back}}$ equal to $V_{\text{app}}$; zero current flowing in conductor; zero force; \textit{constant velocity}. 
How does a DC Motor work?

Wire length vector, \( \mathbf{dL} \)
Cross-section of DC motor

- Soft Iron Core (Rotor)
- Permanent Magnet (Stator)
Cross-section of DC motor

Rotor supported on bearings (free to rotate)

Generating ____ torque
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

Torque vs. Angular Position

Brushes; fixed
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, $dL$
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

\[ \begin{align*} 
V_a &= \text{applied armature voltage} \\
R_a &= \text{armature resistance} \\
i_a &= \text{armature current} \\
V_b &= \text{back EMF} 
\end{align*} \]
PMDC Motor Steady-State Equations

from circuit

from \( \frac{dV}{dL} = B \cdot v \) and \( v = r \omega \)

from \( df = i_a \cdot dL \times B \) 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 \( \omega \), and output torque \( \tau \) are related by the 3 equations
PMDC Motor Equation Part #3

At any point on load curve, \( \omega_{NL} = \text{“no-load” speed (} i_a = 0) \)
## Number Assignments - Exercise #1

<table>
<thead>
<tr>
<th>Student Group</th>
<th>Speed (RPM)</th>
<th>Speed (rad/sec)</th>
<th>Student Group</th>
<th>Speed (RPM)</th>
<th>Speed (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>250</td>
<td>26</td>
<td>#5</td>
<td>1250</td>
<td>131</td>
</tr>
<tr>
<td>#2</td>
<td>500</td>
<td>52</td>
<td>#6</td>
<td>1500</td>
<td>157</td>
</tr>
<tr>
<td>#3</td>
<td>750</td>
<td>79</td>
<td>#7</td>
<td>1750</td>
<td>183</td>
</tr>
<tr>
<td>#4</td>
<td>1000</td>
<td>105</td>
<td>#8</td>
<td>2000</td>
<td>209</td>
</tr>
</tbody>
</table>
In-Class Exercise #1

A small DC motor has these parameter constants:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_a$</td>
<td>48 volts</td>
</tr>
<tr>
<td>$K_a$</td>
<td>0.17 N-m/amp</td>
</tr>
<tr>
<td>$K_b$</td>
<td>0.17 volt/rad/s</td>
</tr>
<tr>
<td>$R_a$</td>
<td>0.9 ohms</td>
</tr>
</tbody>
</table>

Determine the output torque, $\tau_a$, 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, $\tau_a$ for your speed
Plot for In-Class Exercise #1
Manufacturer’s Data
2nd In-Class Exercise

A small DC motor has these parameter constants:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_a$</td>
<td>? volts</td>
</tr>
<tr>
<td>$K_a$</td>
<td>3.60 oz-in/amp</td>
</tr>
<tr>
<td>$K_b$</td>
<td>2.67 volt/KRPM</td>
</tr>
<tr>
<td>$R_a$</td>
<td>50 ohms</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Group</th>
<th>$V_a$, volts</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>24 VDC</td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>18 VDC</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>12 VDC</td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>6 VDC</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both 1000 and 3000 RPM

Both 5000 and 7000 RPM
In-Class Exercise #2

Torque, oz-in

Speed, RPM
In-Class Exercise - Solution

![Graph showing the relationship between torque (oz-in) and speed (RPM). The graph has a linear trend line indicating a decrease in torque as speed increases.]
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

\[ V_{\text{gen}} = \text{generated armature voltage} \quad V_b = \text{back EMF} \]

\[ R_a = \text{armature resistance} \quad i_a = \text{armature current} \]
PMDC Generator Equations

\[ V_{gen} + R_a i_a = V_b \]

\[ V_b = k_b \omega \]

\[ \tau = k_a i_a \]
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

Find the motor constants: $k_b, k_a, R_a$

- $V_a = 40$ volts
- $V_a = 60$ volts
- $V_a = 80$ volts
- $V_a = 100$ volts

Graph showing the relationship between speed (rad/sec) and torque (N-m) for different voltage levels.
DC Tachometer Equations

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

\[ i_a = \frac{1}{R_a} (V_a - V_b) = 0 \]  \hspace{1cm} \text{High impedance load, No current}

\[ V_b = k_b \omega = V_a \]  \hspace{1cm} \text{Output voltage proportional to angular velocity, } \omega

\[ \tau = k_a i_a = 0 \]  \hspace{1cm} \text{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 wound coils

► Wound DC motors
  ► Series wound
  ► Shunt wound
  ► Compound wound (series and shunt windings)
Series Wound DC Motor

\[ V_{in} = \text{input voltage} \]
\[ R_a = \text{armature resistance} \]
\[ R_f = \text{field resistance} \]
\[ V_b = \text{back EMF} \]
\[ i_a = \text{armature current} \]
\[ i_f = \text{field current} \]
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

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

![Graph showing the relationship between Torque and Speed]
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 $\omega$
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)