Brushed DC Motor
PWM Speed Control with the NI myRIO, Optical Encoder, and H-Bridge

NI myRIO
The motor is connected to the outputs of the bridge. Depending on the type of H-Bridge used, internal protection to the transistor of the bridge may not exist. In this case, external protection circuitry needs to be provided. This protection consists of diodes connected in anti-parallel to the transistors. Shottky diodes are preferred for inductive loads. The motor rated voltage needs to be supplied to the bridge in order to allow the motor to develop rated torque. If the bridge is supplied with voltage higher than the motor rated voltage, damage may occur to the motor. A sensing resistor ($R_s$) can be used to monitor the motor current and shutdown the transistors if the motor rated current or the bridge maximum current is exceeded.
Brushed DC Motor / Encoder System

Dual H-Bridge

<table>
<thead>
<tr>
<th>Enable</th>
<th>Inputs</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN = 1</td>
<td>IN1 = 1, IN2 = 0</td>
<td>Forward Move</td>
</tr>
<tr>
<td></td>
<td>IN1 = 0, IN2 = 1</td>
<td>Reverse Move</td>
</tr>
<tr>
<td></td>
<td>IN1 = IN2</td>
<td>Motor Fast Stop</td>
</tr>
<tr>
<td>EN = 0</td>
<td>IN1 = X, IN2 = X</td>
<td>Motor Coast</td>
</tr>
</tbody>
</table>

1 - High, 0 - Low, X - Don't care
The torque command from the control system can be split into two PWM signals. A dead-band control is used to avoid short circuits on the bridge with inductive loads while switching direction, as the transistor that is commanded to turn off stays conducting for a short period of time due to the motor back-EMF when the other transistor on the same branch may be commanded to turn on for the switching in direction. Thus, if the voltage command is within the dead-band, all four transistors are turned off. If the voltage command is positive and higher than the dead-band threshold, a signal is applied to the “PWM FWD Direction” output. Similarly, if the voltage command is negative and lower than the dead-band threshold, signal is applied to the “PWM REV Direction” output.
LabVIEW Front Panel
Brushed DC Motor / Encoder System

LabVIEW Block Diagram
# Pittman DC Servo Motor 8322S001

## Assembly Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Voltage</td>
<td>$E$</td>
<td>V</td>
<td>12</td>
</tr>
<tr>
<td>No-Load Speed</td>
<td>$S_{NL}$</td>
<td>rpm (rad/s)</td>
<td>7,847 (822)</td>
</tr>
<tr>
<td>Continuous Torque (Max.)$^1$</td>
<td>$T_C$</td>
<td>oz-in (N-m)</td>
<td>1.6 (1.1E-02)</td>
</tr>
<tr>
<td>Peak Torque (Stall)$^2$</td>
<td>$T_{PK}$</td>
<td>oz-in (N-m)</td>
<td>7.4 (5.2E-02)</td>
</tr>
<tr>
<td>Weight</td>
<td>$W_M$</td>
<td>oz (g)</td>
<td>7.7 (218)</td>
</tr>
</tbody>
</table>

## Motor Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque Constant</td>
<td>$K_T$</td>
<td>oz-in/A (N-m/A)</td>
<td>1.94 (1.37E-02)</td>
</tr>
<tr>
<td>Back-EMF Constant</td>
<td>$K_E$</td>
<td>V/krpm (V/rad/s)</td>
<td>1.43 (1.37E-02)</td>
</tr>
<tr>
<td>Resistance</td>
<td>$R_T$</td>
<td>Ω</td>
<td>3.10</td>
</tr>
<tr>
<td>Inductance</td>
<td>$L$</td>
<td>mH</td>
<td>1.57</td>
</tr>
<tr>
<td>No-Load Current</td>
<td>$I_{NL}$</td>
<td>A</td>
<td>0.25</td>
</tr>
<tr>
<td>Peak Current (Stall)$^2$</td>
<td>$I_P$</td>
<td>A</td>
<td>3.88</td>
</tr>
<tr>
<td>Motor Constant</td>
<td>$K_M$</td>
<td>oz-in/√W (N-m/√W)</td>
<td>1.12 (7.91E-03)</td>
</tr>
<tr>
<td>Friction Torque</td>
<td>$T_F$</td>
<td>oz-in (N-m)</td>
<td>0.35 (2.5E-03)</td>
</tr>
<tr>
<td>Rotor Inertia</td>
<td>$J_M$</td>
<td>oz-in-s$^2$ (kg-m$^2$)</td>
<td>1.4E-04 (9.9E-07)</td>
</tr>
<tr>
<td>Electrical Time Constant</td>
<td>$\tau_E$</td>
<td>ms</td>
<td>0.52</td>
</tr>
<tr>
<td>Mechanical Time Constant</td>
<td>$\tau_M$</td>
<td>ms</td>
<td>15.6</td>
</tr>
<tr>
<td>Viscous Damping</td>
<td>$D$</td>
<td>oz-in/krpm (N-m-s)</td>
<td>0.015 (1.0E-06)</td>
</tr>
<tr>
<td>Damping Constant</td>
<td>$K_D$</td>
<td>oz-in/krpm (N-m-s)</td>
<td>0.92 (6.2E-05)</td>
</tr>
<tr>
<td>Maximum Winding Temperature</td>
<td>$\theta_{MAX}$</td>
<td>°F (°C)</td>
<td>311 (155)</td>
</tr>
<tr>
<td>Thermal Impedance</td>
<td>$R_{TH}$</td>
<td>°F/watt (°C/watt)</td>
<td>75.9 (24.4)</td>
</tr>
<tr>
<td>Thermal Time Constant</td>
<td>$\tau_{TH}$</td>
<td>min</td>
<td>7.8</td>
</tr>
</tbody>
</table>

## Encoder Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Channels</td>
<td>3</td>
</tr>
<tr>
<td>Resolution</td>
<td>500</td>
</tr>
</tbody>
</table>

---

*Brushed DC Motor / Encoder System*  
*K. Craig*
Pittman DC Servo Motor 8322S001

**Encoder**
500 counts/rev

<table>
<thead>
<tr>
<th>Wire</th>
<th>Function</th>
<th>Color</th>
<th>Pins</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GND</td>
<td>Black</td>
<td>GND</td>
</tr>
<tr>
<td>2</td>
<td>Index</td>
<td>Green</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>CH A</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Vcc</td>
<td>Red</td>
<td>5V</td>
</tr>
<tr>
<td>5</td>
<td>CH B</td>
<td>Blue</td>
<td></td>
</tr>
</tbody>
</table>

Brushed DC Motor / Encoder System

K. Craig
- OPERATING SUPPLY VOLTAGE UP TO 46 V
- TOTAL DC CURRENT UP TO 4 A
- LOW SATURATION VOLTAGE
- OVERTEMPERATURE PROTECTION
- LOGICAL "0" INPUT VOLTAGE UP TO 1.5 V
  (HIGH NOISE IMMUNITY)

**L298**

Dual Full Bridge Driver

Brushed DC Motor / Encoder System
Topics

• **Brushed DC Motor**
  – Physical & Mathematical Models, Hardware Parameters

• **H-Bridge Operation**

• **Feedback Control Design**
  – MatLab / Simulink Design and Auto-Code Generation
Brushed DC Motor / Encoder System

Brushed DC Motor

Schematic

Pittman DC Servo Motor
For a permanent-magnet DC motor $i_f = \text{constant}$.

**Physical Modeling**
• **Physical Modeling Assumptions**
  - The copper armature windings in the motor are treated as a resistance and inductance in series. The distributed inductance and resistance is lumped into two characteristic quantities, $L$ and $R$.
  - The commutation of the motor is neglected. The system is treated as a single electrical network which is continuously energized.
  - The compliance of the shaft connecting the load to the motor is negligible. The shaft is treated as a rigid member.
  - The total inertia $J$ is a single lumped inertia, equal to the sum of the inertias of the rotor and the driven load.
- There exists motion only about the axis of rotation of the motor, i.e., a one-degree-of-freedom system.
- The parameters of the system are constant, i.e., they do not change over time.
- The damping in the mechanical system is modeled as viscous damping $B$, i.e., all stiction and dry friction are initially neglected.
- The optical encoder output is decoded in software. Position and velocity are calculated and made available as analog signals for control calculations. The motor is driven with a PWM control signal to a H-Bridge. The time delay associated with this, as well as computation for control, is lumped into a single system time delay.
• **Mathematical Modeling Steps**
  - Define System, System Boundary, System Inputs and Outputs
  - Define Through and Across Variables
  - Write Physical Relations for Each Element
  - Write System Relations of Equilibrium and/or Compatibility
  - Combine System Relations and Physical Relations to Generate the Mathematical Model for the System
Physical Relations

\[ V_L = L \frac{di_L}{dt} \quad \quad V_R = Ri_R \quad \quad T_B = B\omega \]

\[ T_j = J\alpha = J\dot{\omega} \quad \quad J = J_{\text{motor}} + J_{\text{load}} \]

\[ T_m = K_t i_m \quad \quad V_b = K_b \omega \]

\[ P_{\text{out}} = T_m \omega = K_t i_m \omega \quad \quad P_{\text{in}} = V_b i_m = K_b \omega i_m \]

\[ \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{K_t}{K_b} \]

\[ P_{\text{out}} = P_{\text{in}} \quad \quad K_t (\text{oz} - \text{in} / \text{A}) = 1.3524 K_b (\text{V} / \text{krpm}) \]

\[ K_t (\text{Nm} / \text{A}) = 9.5493 \times 10^{-3} K_b (\text{V} / \text{krpm}) \]

\[ K_t (\text{Nm} / \text{A}) = K_b (\text{V} - \text{s} / \text{rad}) \]
System Relations + Equations of Motion

\[ V_{in} - V_R - V_L - V_b = 0 \]

\[ T_m - T_B - T_J = 0 \]

\[ i_R = i_L = i_m \equiv i \]

**KVL**

\[ V_{in} - Ri - L \frac{di}{dt} - K_b \omega = 0 \]

\[ J \frac{d\omega}{dt} + B \omega - K_t i = 0 \]

\[
\begin{bmatrix}
\frac{d\omega}{dt} \\
\frac{di}{dt}
\end{bmatrix} =
\begin{bmatrix}
-K_b & \frac{K_t}{J} \\
-\frac{B}{J} & \frac{1}{L}
\end{bmatrix}
\begin{bmatrix}
\omega \\
i
\end{bmatrix} +
\begin{bmatrix}
0 \\
\frac{1}{L}
\end{bmatrix} V_{in}
\]
Steady-State Conditions

\[ V_{in} - Ri - L \frac{di}{dt} - K_b \omega = 0 \]

\[ V_{in} - R \left( \frac{T}{K_t} \right) - K_b \omega = 0 \]

\[ T = \frac{K_t}{R} V_{in} - \frac{K_t K_b}{R} \omega \]

\[ T_s = \frac{K_t}{R} V_{in} \quad \text{Stall Torque} \]

\[ \omega_0 = \frac{V_{in}}{K_b} \quad \text{No-Load Speed} \]
Transfer Functions

\[ V_{in} - Ri - L \frac{di}{dt} - K_b \omega = 0 \]

\[ J \frac{d\omega}{dt} + B \omega - K_t i = 0 \]

\[ V_{in}(s) - (Ls + R)I(s) - K_b \Omega(s) = 0 \]

\[ (Js + B)\Omega(s) - K_t I(s) = 0 \]

\[
\frac{\Omega(s)}{V_{in}(s)} = \frac{K_t}{(Js + B)(Ls + R) + K_t K_b} = \frac{K_t}{JLs^2 + (BL + JR)s + (BR + K_t K_b)}
\]

\[ = \frac{K_t}{JL} \left( \frac{B}{J} + \frac{R}{L} \right)s + \left( \frac{BR}{JL} + \frac{K_t K_b}{JL} \right) \]
Brushed DC Motor / Encoder System

Block Diagram

\[ V_{in} \rightarrow \Sigma \rightarrow \frac{1}{L_s + R} \rightarrow i \rightarrow K_t \rightarrow T_m \rightarrow \frac{1}{J_s + B} \rightarrow \omega \]

\[ K_b \]
Simplification

\[ \tau_m = \frac{J}{B} \gg \tau_e = \frac{L}{R} \]

\[ V_{in} - R_i - K_b \omega = 0 \]
\[ J \frac{d\omega}{dt} + B \omega - K_t i = 0 \]

\[ J \frac{d\omega}{dt} + B \omega = K_t i = K_t \left( \frac{1}{R} \left( V_{in} - K_b \omega \right) \right) = \frac{K_t}{R} \left( V_{in} - K_b \omega \right) \]

\[ \frac{d\omega}{dt} + \left( \frac{K_t K_b}{R J} + \frac{B}{J} \right) \omega = \frac{K_t}{R J} V_{in} \]

\[ \frac{d\omega}{dt} + \left( \frac{1}{\tau_{motor}} + \frac{1}{\tau_m} \right) \omega = \frac{K_t}{R J} V_{in} \]

\[ \frac{d\omega}{dt} + \left( \frac{1}{\tau_{motor}} \right) \omega = \frac{K_t}{R J} V_{in} \quad \text{since} \quad \tau_m \gg \tau_{motor} \]
Brushed DC Motor / Encoder System

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Equations of Motion

\[ E_{in} = L \frac{d\omega}{dt} + R\omega + K_B \omega \]

\[ J \ddot{\omega} + B \omega = K_T \omega \quad \text{Coulomb friction neglected} \]

Open-Loop Transfer Function \( \frac{\omega}{E_{in}}(s) \):

\[ \frac{\omega}{E_{in}} = \frac{K_T / J_L}{D^2 + \left( \frac{B}{J} + \frac{R}{L} \right)D + \left( \frac{BR}{J_L} + \frac{K_T K_B}{J_L} \right)} \]

\[ \tau_m = \frac{J}{B} \]

\[ \tau_e = \frac{L}{R} \]

\[ J \ddot{\omega} + B \omega = K_T \omega = K_T \left[ \frac{1}{R} (E_{in} - K_B \omega) \right] = \frac{K_T}{R} (E_{in} - K_B \omega) \]

\[ \tau_{motor} = \frac{K_T K_B}{R J} \quad \dot{\omega} + \left( \frac{K_T K_B}{R J} + \frac{B}{J} \right) \omega = \frac{K_T}{R J} E_{in} \quad \tau_m \gg \tau_{motor} \]

\[ \dot{\omega} + \left( \frac{1}{\tau_{motor}} + \frac{1}{\tau_m} \right) \omega = \frac{K_T}{R J} E_{in} \quad \Rightarrow \dot{\omega} + \left( \frac{1}{\tau_{motor}} \right) \omega = \frac{K_T}{R J} E_{in} \]
Analysis: Pittman 83225001 Brushed DC Servo Motor

\[ J_{\text{motor}} = 9.9 \times 10^{-7} \text{ kg} \cdot \text{m}^2 \]
\[ J_{\text{load}} = \frac{1}{2} m R^2 \]
\[ m = (\pi R^2)(t)(P_{\text{brush}}) \]
\[ R = 0.25'' \]
\[ t = 0.00625 \text{ m} \]
\[ R = 0.0185 \text{ m} \]
\[ J_L = 10.03 \]
\[ J_{\text{total}} = 10.92 \times 10^{-6} \text{ kg} \cdot \text{m}^2 \]

\[ B = 1.0 \times 10^{-6} \text{ N} \cdot \text{m} \cdot \text{s} \]
\[ K_e = 1.37 \times 10^{-2} \text{ (N-m) / A} \]
\[ K_b = 1.37 \times 10^{-2} \text{ V/ rad/s} \]
\[ R = 3.10 \Omega \]
\[ L = 1.57 \times 10^{-3} \text{ H} \]
\[ \omega = \frac{1}{K_b} e_m \]
Brushed DC Motor / Encoder System

\[ T_{\text{motor}} \dot{\omega} + \omega = \frac{1}{K_b} e_{in} \]

\[ (0.180) \dot{\omega} + \omega = (73.0) e_{in} \]

\[ T \dot{\omega} + \omega = K e_{in} \]

\[ \frac{\omega}{e_{in}} = \frac{K}{T_D + 1} \]

1st-Order ODE

\[ \begin{cases} T = 0.180 \text{ sec} \\ K = 73.0 \end{cases} \]

Verify by experiment.

From Pittman Data Sheet

Motor Constant \( K_m = 7.91 \times 10^{-3} \) = \( \frac{K_t}{\sqrt{R}} \) \[ \frac{N\cdot m}{\sqrt{W}} \]

\[ W = \text{watts} \]

\( \dot{T} = 2.5 \times 10^{-3} \text{ N}\cdot m \) Friction Torque (Coulomb friction dynamic)

\[ T_e = 0.52 \times 10^{-3} \text{ sec} = \frac{L}{R} \] same as \( \dot{T}_e \)

\[ T_m = 15.6 \times 10^{-3} \text{ sec} = \frac{R T}{K_t K_b} \] same as \( T_{\text{motor}} \) (note: \( J = J_m \) on data sheet)

\[ K_0 = \text{damping constant} = \frac{K_t K_b}{R} = 6.2 \times 10^{-5} \text{ N}\cdot m\cdot s \]

(same units as \( B \))

K. Craig
Steady-State Analysis

\[ E_{in} = L \frac{d\dot{r}}{dt} + R\dot{r} + K_b \omega \quad \Rightarrow \quad E_{in} = R\dot{r} + K_b \omega \]

\[ J\ddot{\omega} + B\omega = K_t \alpha \quad \Rightarrow \quad B\omega = K_t \alpha \]

Define \( T = B\omega \quad \text{(includes all load torques)} \)

\[ E_{in} - R\dot{r} - K_b \omega = 0 \]

\[ E_{in} - R \left( \frac{r}{K_t} \right) - K_b \omega = 0 \quad \Rightarrow \quad T = \frac{K_t}{R} E_{in} - \frac{K_t K_b}{R} \omega \]

\[ T = \frac{K_t}{R} E_{in} - \frac{K_t K_b}{R} \omega \]

Linear Torque-Speed Relation

\( \omega = 0 \quad \Rightarrow \quad T = \frac{K_t}{R} E_{in} \quad \text{stall torque} \)

\( T = 0 \quad \Rightarrow \quad \omega_0 = \frac{E_{in}/K_b}{K_b} \quad \text{no-load speed} \)
$E_{in} = 12\ V$

\[
\begin{align*}
T_s &= \frac{K_{e}e_{in}}{R} = 0.053\ N\cdot m \\
\omega_0 &= \frac{e_{in}}{K_b} = 876\ rad/s
\end{align*}
\]

(822 in data sheet)

\[
\text{Power } P = T\omega = \omega \left[ \frac{K_{e}e_{in}}{R} - \frac{K_{e}K_b}{R} \omega \right]
\]

\[
= \omega \left[ T_s - \frac{T_s}{\omega_0} \omega \right] = \omega T_s \left[ 1 - \frac{\omega}{\omega_0} \right]
\]

\[
P = T_s \left[ \omega - \frac{\omega^2}{\omega_0} \right]
\]

\[
\frac{dP}{d\omega} = T_s - \frac{2T_s}{\omega_0} \omega = 0 \quad \Rightarrow \quad \omega_{\text{max}} = \frac{\omega_0}{2}
\]

\[
\text{Peak Current (Stall)} = \frac{e_{in}}{R} = 3.87\ A
\]

\[
\text{No-Load Current} = 0.25\ A
\]
\[ \text{no-load speed} = 822 \text{ rad/s} \]
\[ \text{no-load current} = 0.25 \text{ A} \]

**Interpret this information**

no-load current is a measure of friction force.

\[ \text{no-load current} = 0.25 \text{ A} \]

\[ E_m = L \frac{dI}{dt} + R I + K_e I \quad \frac{dI}{dt} = 0 \]

\[ \text{no-load speed} \quad w = \frac{E_m - R I}{K_e} = \frac{12 - (2.10)(0.25)}{1.77 \times 10^{-2}} = 819.3 \text{ rad/s} \]

At this no-load speed

\[ T_m = K_e I = (1.77 \times 10^{-2})(0.25) = 3.43 \times 10^{-3} \text{ N-m} \]

At steady state

\[ T_n = T_{viscous} + T_{coulomb} \]

\[ = 6w + T_f \]

\[ = (1.0 \times 10^{-6})(819.3) + (2.5 \times 10^{-3}) = 3.32 \times 10^{-3} \text{ N-m} \]
Load Torque vs. Efficiency

Rated Armature Voltage = 12V

Load Torque $T_L = 1.5 \text{ oz-in} = (1.502 \text{ in}) \left( \frac{1 \text{ in}}{3.602 \text{ in}} \right) \left( \frac{1 \text{ m}}{39.37 \text{ in}} \right) = 1.06 \times 10^{-2} \text{ N-m}

$B = 1.0 \times 10^{-6} \text{ N-m-s}$

$K_T = 1.37 \times 10^{-2} \text{ N-m/A}$

$T_f = 2.5 \times 10^{-3} \text{ N-m}$

During steady state:

$K_T I = B \omega + T_f + T_L$

$\omega = \frac{1}{B} \left( K_T I - T_f - T_L \right)$

Also during steady state:

$e = R I + K_b \omega$

$L = \frac{E}{R} - \frac{K_b \omega}{R} = \frac{E}{R} - \frac{K_b}{RB} \left( K_T I - T_f - T_L \right)$

Solve for $I$: $I = \frac{e + \left( \frac{K_b}{B} \right) (T_f + T_L)}{R + \frac{K_b K_T}{B}}$

Substitute numbers:

$L = \frac{1}{190.8} \left[ 12 + (1.37 \times 10^4) (2.5 \times 10^{-3} + T_L) \right] = 1.004 \text{ A}$

$\omega = \frac{1}{1.0 \times 10^{-6}} \left[ (1.37 \times 10^{-2}) (L) - (2.5 \times 10^{-3}) - T_L \right] = 657.8 \text{ rad/s}$
Power Input:  \( P_{in} = EL = (12)(1.004) = 12.05 \text{ W} \)

Power Output:  \( P_{out} = TL\omega = (1.06 \times 10^{-2})(654.8) = 6.94 \text{ W} \)

Efficiency  \( \% = \frac{P_{out}}{P_{in}} \times 100 = \frac{6.94}{12.05} \times 100 = 57.6 \% \)

Losses:  \( P_L = RL^2 = (2.10)(1.004)^2 \)

\[ = 2.125 \text{ W} \]

Friction:  \( P_{friction} = (B\omega + T_f)\omega = \left[(1.0 \times 10^{-5})(654.8) + (2 \times 10^{-5})\right] \times (654.8) \)

\[ = 2.066 \text{ W} \]

Total Losses:  \( 2.066 + 2.125 = 5.191 \text{ W} \)

Power Input = Power Output + Total Losses
\[ 12.05 = 6.94 + 5.19 \]
\[ 12.05 \approx 12.13 \quad \checkmark \]
MatLab M-File

B = 1.0E-6;
Kt = 1.37E-2;
Tf = 2.5E-3;
Kb = 1.37E-2;
R = 3.10;
TL = 0:.1:7.5;
TL = TL/3.6/39.37;
e = 12;
i = (1/(R + Kb*Kt/B))*(e + (Kb/B)*(Tf + TL));
omega = (1/B)*((Kt*i) - Tf - TL);
Pin = e*i;
Pout = TL.*omega;
E = (Pout./Pin)*100;
plot(TL*3.6*39.37,E)
H-Bridge Operation

• For DC electric motors, a power device configuration called an H-Bridge is used to control the direction and magnitude of the voltage applied to the load. The H-Bridge consists of four electronic power components arranged in an H-shape in which two or none of the power devices are turned on simultaneously.

• A typical technique to control the power components is via a PWM (Pulse Width Modulation) signal. A PWM signal has a constant frequency called the carrier frequency. Although the frequency of a PWM signal is constant, the width of the pulses (the duty cycle) varies to obtain the desired voltage to be applied to the load.
• The H-Bridge can be in one of the four states: **coasting**, moving forward, moving backward, or braking, as shown on the next slide.
  
  – In the **coasting mode**, all four devices are turned off and since no energy is applied to the motor, it will coast.
  
  – In the **forward direction**, two power components are turned on, one connected to the power supply and one connected to ground.
  
  – In **reverse direction**, only the opposite power components are turned on supplying voltage in the opposite direction and allowing the motor to reverse direction.
  
  – In **braking**, only the two devices connected to ground are tuned on. This allows the energy of the motor to quickly dissipate, which will take the motor to a stop.
• The four diodes shown in anti-parallel to the transistors are for back-EMF current decay when all transistors are turned off.

• These diodes protect the transistors from the voltage spike on the motor leads due to the back-EMF when all four transistors are turned off. This could yield excessive voltage on the transistor terminals and potentially damage them.

• They must be sized to a current higher than the motor current and for the lowest forward voltage to reduce junction temperature and the time to dissipate the motor energy.
Diodes for back-EMF protection are shown. The solid line is the current flow when the transistors on the upper left corner and on the lower right corner are turned on. The dashed line shows the motor current when all transistors are turned off.
Block diagram of L298 (Dual Full Bridge Driver)