This document is work in progress and will shortly be updated,

Brushed DC (Direct Current) Motor

The brushed DC motor is still a commonly used machine, although it is slowly being replaced by permanent magnet brushless DC machines (BLDC's) in which the commutator has been replaced by power electronics.

The fundamental equations for the brushed machine and an equivalent circuit diagram are shown below:

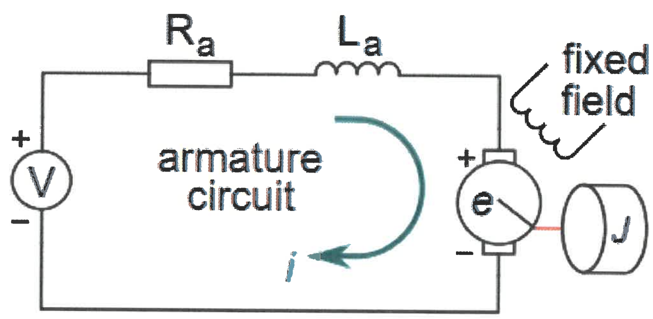


Figure 1

Figure 1 shown the electric circuit of the DC motors armature. This contains the electrical resistance term (Ra), inductance (La), and the back EMF (e). Rotor mechanical terms are the motor torque (T), and rotor inertia (J).

Using these and applying circuit analysis techniques such as Kirchhoff's voltage law, gives the following equations:

$$v = e + iR_a + L_a\frac{di_a}{dt}$$

In this case v is the input voltage to the DC motor, this which will be supplied by the H-bridge in this project and this will be discussed in more detail later.

Assuming that the magnetic field produced by the field winding (or permanent magnets) is constant, the torque produced by the DC motor will be proportional to the armature current and the motor torque constant k_t.

$$T = k_t i$$

The back EMF of the machine is proportional to the rotor velocity ω_r, which we can also think of as the change in rotor position with time $(d\theta_r/dt)$. Therefore:

$$e = k_e\omega_r = k_e\frac{d\theta_r}{dt}$$

It is often considered that the torque and back EMF constants are equal, therefore:

$k_t = k_e$

H-bridge Theory

The H-bridge, also known as full-bridge, is an system consisting of four electronic switches which is capable of creating a bi-directional current and reversible voltage across its load. This function comes in handy when driving a motor because it allows a change in the direction of its rotation and, if the application allows it, even to use it as a generator.

The H-bridge can be thought of as composed of two half-bridges (two Mosfets in series) used simultaneously. The H-bridge allows the motor to work as a generator in both directions of rotation therefore it is considered a 4-quadrant converter. The half-bridge is capable of bi-directional current but not reversible voltage and thus is considered a 2-quadrant one. Therefore, the latter is mainly used in motor drive applications with single-direction motors such as oil pump motors and small fans. Another difference between the two types of circuits is the voltage output for a given supply voltage, that is the amplitude of the voltage applied to the load. It is double that of the DC link in the case of a H-bridge, and exactly VDC in case of the half-bridge.

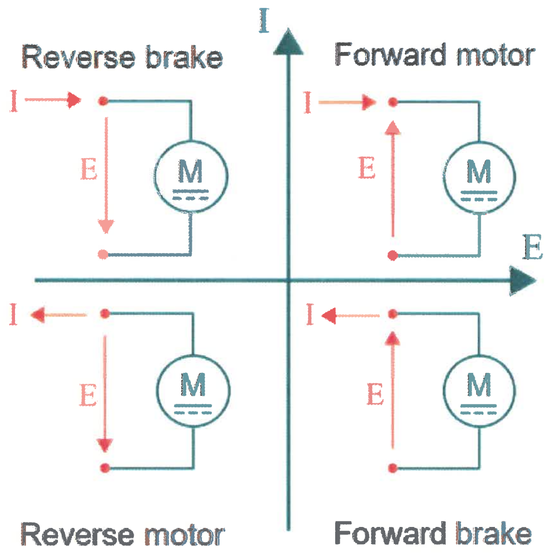
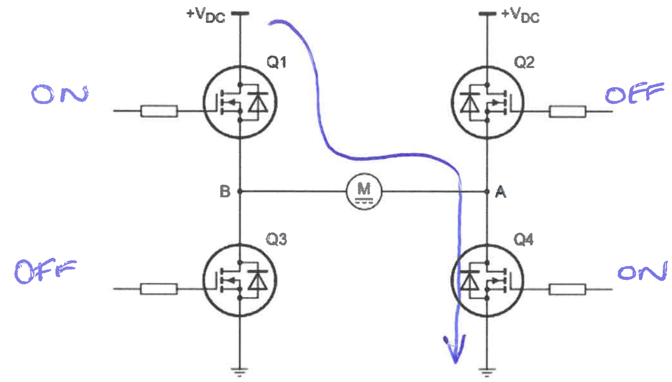


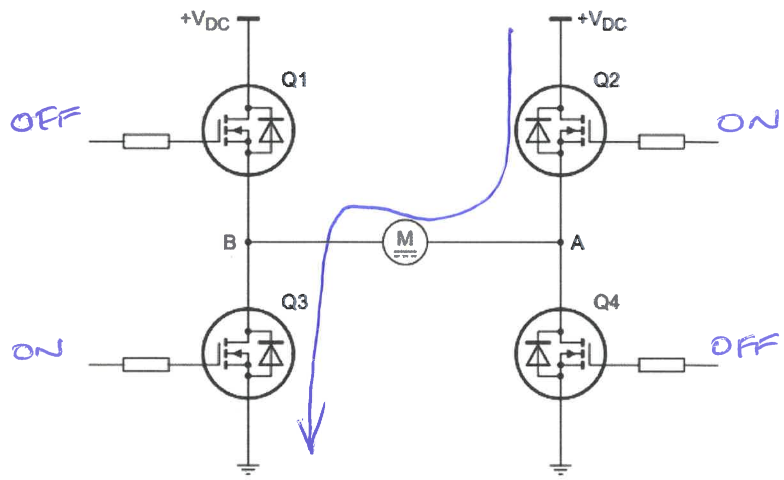
Figure 2

Simple Direction Control

Forward Rotation of the machine can occur by turning on the left-side upper switch (Q1) and the right-side lower switch (Q4). This causes current to flow through the motor in one direction, making it rotate in one direction.



Reverse Rotation occurs by turning on the left-side lower switch (Q3) and the right-side upper switch (Q2). This reverses the current flow through the motor, making it rotate in the opposite direction.



Controlling Speed with PWM (Pulse Width Modulation):

The easiest and most popular way to drive a DC motor using a H-bridge is by using pulse width modulation (PWM). Here the Mosfets are switched at a constant frequency with the control signal having variable duty cycle. This allows the average voltage across the motor to vary and thus control the rotor angular velocity. An example of which is shown in the figure below.

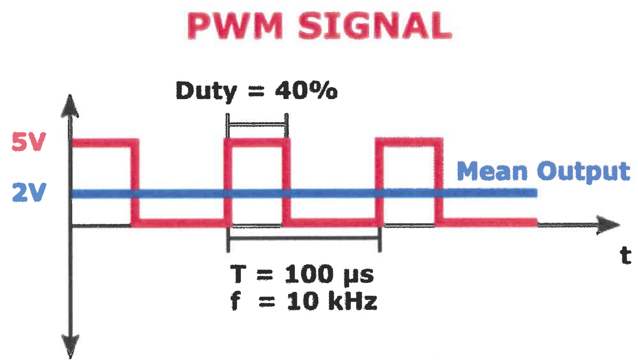


Figure 3

This system works by rapidly switching a signal between ON and OFF states, creating a square wave signal. The average voltage across the load depends on the duty cycle of this square wave. The key components to think about are the:

- Frequency: How fast the signal switches between ON and OFF.
- Duty Cycle: The proportion of time the signal stays ON during each cycle. It's usually expressed as a percentage.

How It Works:

Duty Cycle: The percentage of time the signal is ON in one period of the square wave. For example:

A 50% duty cycle means the signal is ON for half the time and OFF for the other half.

A 25% duty cycle means the signal is ON for 25% of the time and OFF for the remaining 75%.

Average Voltage: The average voltage of a PWM signal can be calculated based on the duty cycle. If the maximum voltage of the PWM signal (e.g., a digital signal) is Vmax, the average voltage is proportional to the duty cycle.

$$V_{ave} = v_{max} \times \frac{D}{100}$$

Example:

If the PWM signal has a maximum voltage of 10V and a duty cycle of 60%, the average voltage will be:

$$v_{ave} = 10 \times \frac{60}{100} = 6V$$

This means that the load will experience an average voltage of 6V over time, even though the signal itself is switching between 0 and 10..

Switching Options

The Mosfets in a H-bridge can be switched in different sequences to provide the desired voltage polarity. There are two common modes: bipolar and unipolar.

Bipolar

Bipolar control allows two Mosfets to be switched ON at a time, see Fig. 4.

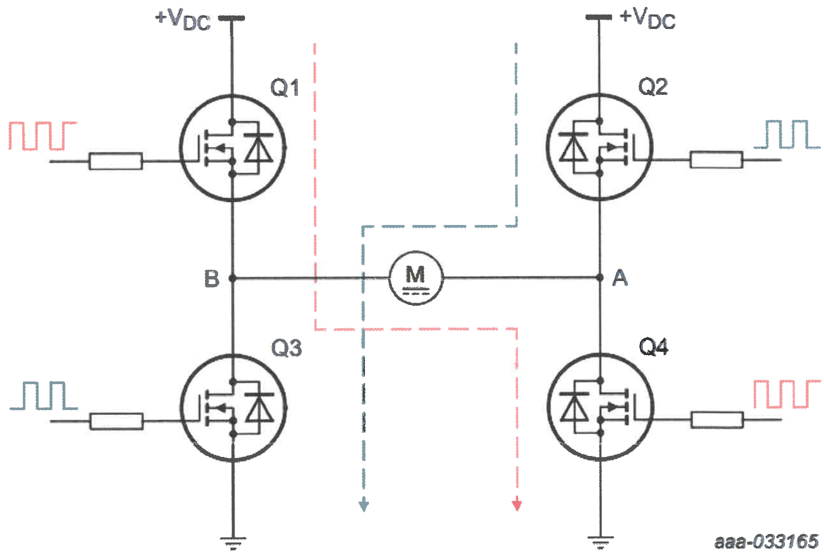


Figure 4

For example, for positive current (from point A to node B) both Q2 and Q3 are turned ON. Whereas, for negative current, Q1 and Q4 are turned ON. By switching these two pairs the direction of the current can be controlled thus applying a voltage across the motor that varies between VDC and -VDC, with an average value that depends on the duty cycle (D). Timing is very important in this mode. A time delay, known as dead-time, must be set between the turning OFF of one pair and the turning ON of the other pair, in order to avoid cross-conduction (or shoot through), that is shorting the supply, and is extremely bad. For example, Fig. 5 shows the effect of shoot through on a big power device.

Figure 5

This time delay can go from several nanoseconds to around 5 µs and, in this latter case, it will limit the switching frequency to approximately 20 kHz. Even though safer, a longer dead-time may cause non-linear output with respect to the PWM and lower efficiency. Reducing the dead-time is a matter of knowing and predicting the input parameters of the Mosfets in use.

Due to the magnetic field build up in the motor, during the delay phase some current will continue to flow, even though all the devices are turned OFF, by recirculating through the Mosfets body diodes. I will discuss this in more detail in the updated notes.

Unipolar

The unipolar drive scheme, instead, allows for the elimination of the dead time which reduces the complexity of the driver circuit. This scheme allows for the current to be regulated by keeping ON one high side Mosfet (Q2 or Q4) while switching only one low side Mosfet (Q3 or Q1). The H-bridge will allow the motor to spin in a forward or reverse rotation direction, depending on the pair of Mosfet's selected and the polarity of the motor.

Another difference with the bipolar drive scheme is the fact that the voltage across the motor will have an amplitude of VDC. For the same reason described in the bipolar drive some current will be forced to flow through one of the Mosfets body diode when the switching Mosfet is turned OFF. If we assume Q3 switching and Q2 turned ON, then when the former is switched off then the current will flow through Q1 body diode. In order to decrease the loss caused by the diode voltage drop then Q1 can be switched ON while Q3 is OFF. In this case a proper dead-time constraint must be respected.

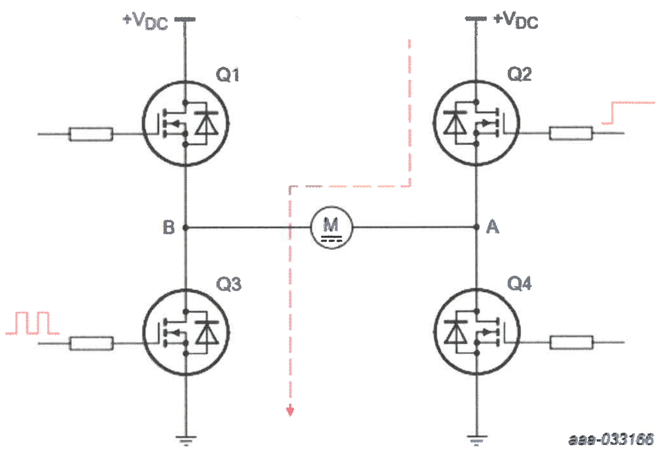


Figure 6

Mosfets (Metal-Oxide-Semiconductor Field-Effect Transistor)

Mosfets are a type of transistor that is commonly used for switching and amplification in electronic circuits. It is a key component in all digital circuits, power electronics, and analogue circuits. There are two primary types of Mosfets: N-channel and P-channel, with the N-channel Mosfet being the most commonly used in switching applications. You will be using both for your project, so you need to understand how they operate.

Structure:

- Source: The terminal where charge carriers (electrons or holes) enter the transistor.
- Drain: The terminal where the charge carriers leave the transistor.
- Gate: The terminal that controls the flow of current between the source and drain. It is insulated from the channel, usually by a thin layer of silicon dioxide.
- Body: The substrate that the Mosfet is built on.

Working Principle:

- When a voltage is applied to the Gate terminal, it creates an electric field that either enhances or depletes the charge carriers in the channel, allowing or blocking current flow between the Source and Drain terminals.
- If the gate-to-source voltage exceeds a certain threshold, an N-channel Mosfet will allow current to flow from the drain to the source, while a P-channel Mosfet works oppositely.