AN1150

Brushed Motors and How to Drive Them

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Introduction

Brushed DC motors (BDCs) are one of the simplest ways to produce motion from electrical power, and are inexpensive and easy to operate. This document will explain how BDCs function, and how to drive them.

Basics

All brushed DC motors are made of the same four key components; the stator, the rotor, the commutator and the brush. Varying the arrangement of these parts gives us five varieties of BDC.

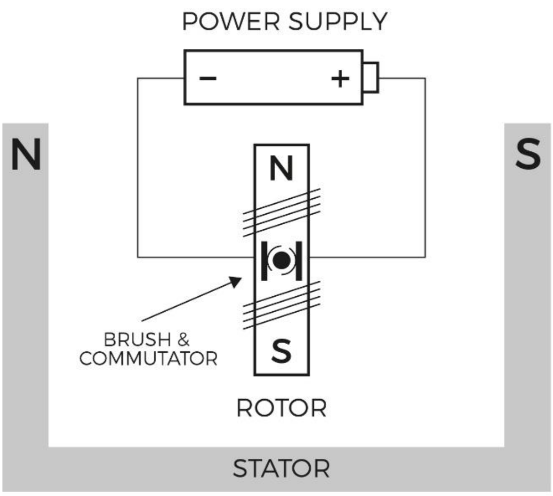

Figure 1. Two pole brushed motor

The Stator

The stator is a stationary magnet that encases the rotor, and produces the static magnetic field with which the rotor interacts with. This can be made of a permanent magnet, or an electromagnet.

The Rotor

Alternatively known as the **Armature**, the rotor is made up of one or more windings of wire wrapped around a ferrous metal (usually iron) core, making it an electromagnet. When current passes through the coil, a magnetic field is created which interacts with the field of the stator to create motion, and as the rotor turns, this magnetic field is flipped by changing the direction of the current so that the North pole of the rotor is forever 'chasing' the South pole of the stator. This is known as **Commutation.**

The Commutator

The commutator is a segmented conductive copper sleeve around the axle of the rotor which causes the current passing through the rotor windings to flip, by physically disconnecting from the **brush** as the system rotates, and reconnecting into a different pair of segments. This reverses the polarity of the magnetic field each time and allows for smooth motion.

The Brush

The brush is a spring loaded conductor, usually made of a Carbon material, which slides along the surface of the commutator, mechanically connecting the power supply to the windings of the rotor in an alternating sequence. Each BDC features a pair of brushes, acting as two terminals for the power supply.

Because the brushed DC motor commutates itself internally as it spins, no external controller is required to produce constant motion. However, the brush and commutator can become worn down by constant use and may eventually require maintenance.

Torque is a measurement of twisting force, and in a DC motor with a constant load it is inversely proportional to the rotational speed.

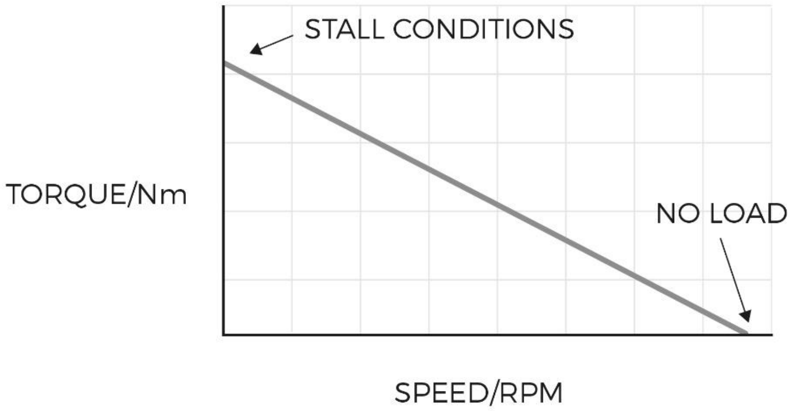

Figure 2. Relationship between torque and speed

Varieties

There are 5 varieties of BDC: the Permanent Magnet, the Shunt-wound, the Series-wound, the compound-wound and the Separately Excited. The latter four use an electromagnet in the stator. The most common variants are the permanent magnet and separately excited, due to their versatility.

Permanent Magnet

These BDCs use a permanent magnet as the stator, and are the most common. Usually appearing in very low power applications, they are more efficient and lighter than other BDCs. However, over time the magnets can lose their magnetic properties. This makes them slightly less durable than the other categories, but much cheaper. Reversing the rotor current will reverse the direction of rotation. This type of motor is often used where precise speed control is not needed, but directional control is, such as toys, electrical toothbrushes and windshield wipers.

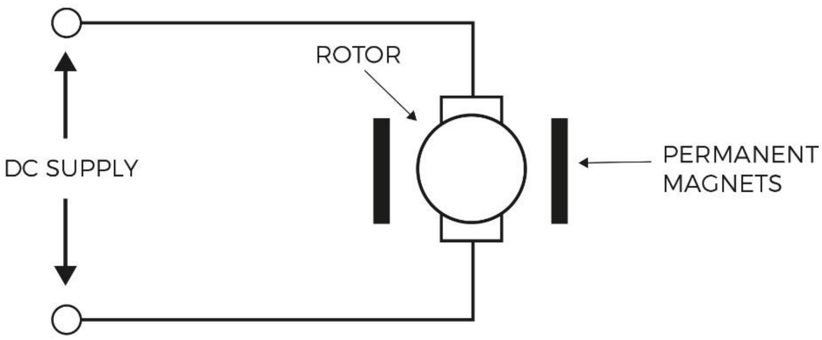

Figure 3. Permanent Magnet DC Motor.

Shunt-wound BDC

A shunt-wound BDC has the rotor coil and stator in parallel with one another, so that they can share the same power supply, but with independent current flowing through them. This gives them the best and simplest speed control, and smooth running at low speeds. However, direction of motion cannot be changed. They are mostly used in constant speed applications, such as fans, and pumps.

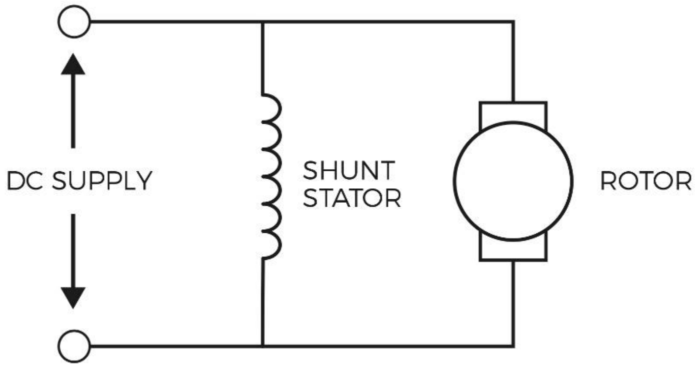

Figure 4. Shunt Wound DC Motor.

Series-wound BDC

A series wound BDC has both its rotor and stator coils in series, so the current flowing through both coils is the same. This makes speed control less accurate and directional control impossible, but allows for a high torque. Useful for their high speed and torque, they can be found in conveyor belts and cranes.

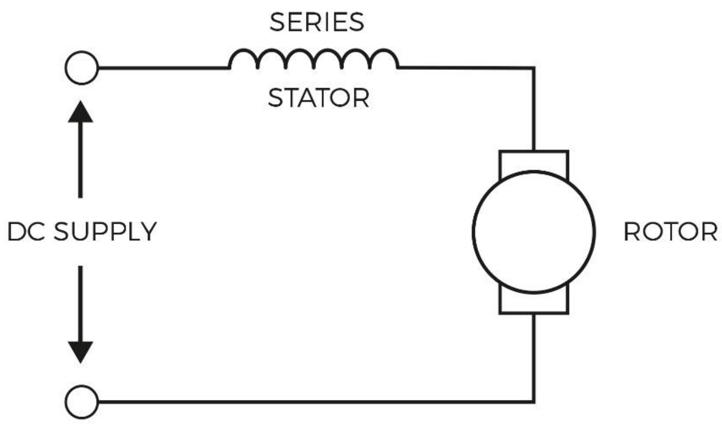

Figure 5. Series Wound DC Motor.

Compound-wound BDC

A compound wound BDC is a combination of both shunt and series wound BDCs, with a stator coil in both parallel and series. This means it inherits the characteristics of both, allowing for a higher torque than a shunt, but with more precise speed control than a series. Likewise, it cannot reverse its direction of motion. They tend to be used in applications that require high starting torque under variable loads, like elevators or rolling mills.

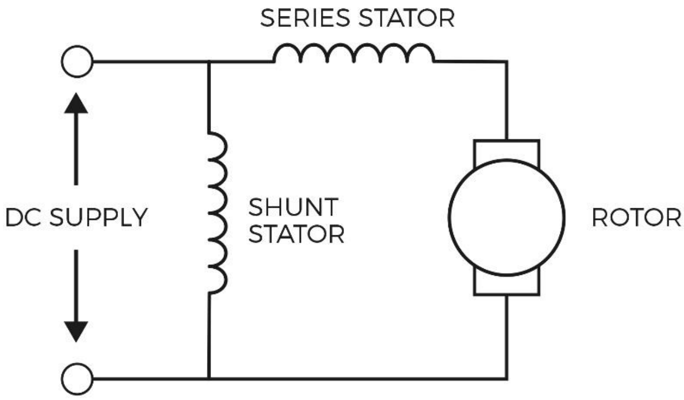

Figure 6. Compound Wound DC Motor.

Separately Excited BDC

As the name suggests, a separately excited BDC has its rotor and stator coils operating from two different power supplies. This allows more precise speed control, and the direction of rotation can be changed by changing the polarity of the stator coils. These are used in paper machines and even ship propulsion.

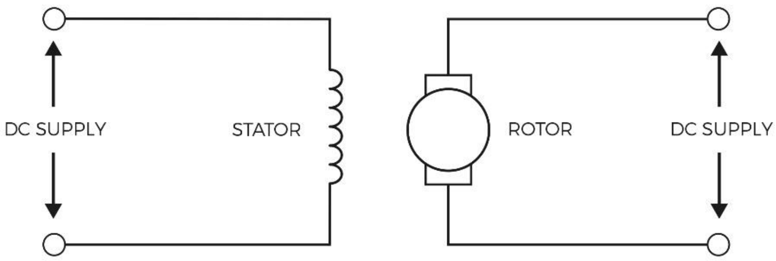

Figure 7. Separately Excited DC Motor.

Driver Circuits

If the application requires the motor to have variable speed or direction, then a driver circuit of some sort is required. These circuits operate on the principle that the voltage across the motor is proportional to the speed of rotation, so altering the voltage allows the speed of the motor to be chosen. Circuits can also control the direction the current flows through the motor, which will alter the direction of motion.

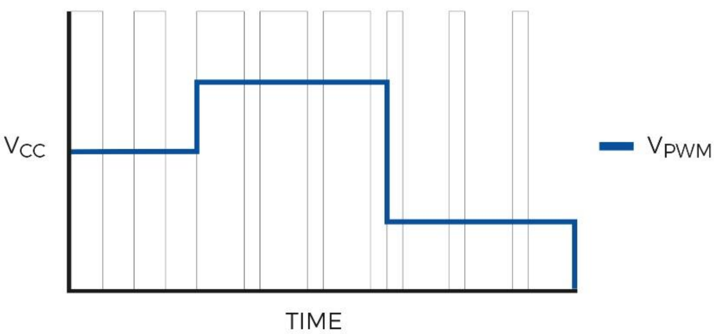

Figure 8. Relationship between wave duty cycle and PWM output voltage.

An effective way to control the voltage supplied across the motor is to use a method known as Pulse Width Modulation (PWM). By turning the power supply (or access to it) off and on again at a high enough frequency, an 'average' voltage based on the duty cycle can be attained, without making any changes to the supply itself. This is more complex, but much more efficient than the analog alternative of a potential divider.

$V_{PWM} = V_{CC}$ x Duty Cycle

The duty cycle correlates to the speed of a motor (within 10% to 90%), so if a motor is rated for 1000RPM at 12V, then a 12V PWM signal with a 50% duty cycle will cause the motor to rotate at around 500RPM.

It is best to use a frequency of around 5-20kHz; going lower will result in a shaky and noisy motor, and higher would result in unnecessary energy lost switching the MOSFETs. This sweet spot ensures minimal switching losses but acceptable performance.

PWM can be generated using a Microcontroller, or a hardware solution. These include 555 oscillator circuits, or feeding a sawtooth wave into a comparator.

High Side / Low Side

A high-side switch is one in which the load is between ground and the switch, whereas a low side involves placing the load between V_{CC} and the switch. A high-side switch requires a P-Channel MOSFET to be brought up to a higher potential than the load, which is less efficient and may require additional circuit design, so a low-side switch is preferable. If the load has any other connections to ground, then a high-side switch must be used, or the switch will be shorted out entirely. In an automotive application, high-side switches are used, so that the load can be connected to ground, the chassis.

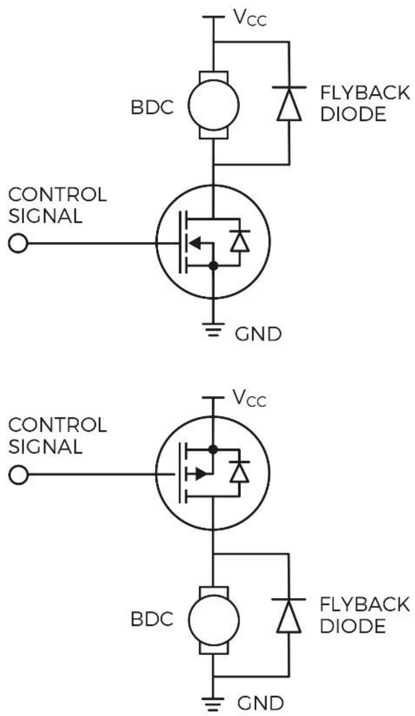

Figure 9. A Low side switch (Top) and a High side switch (Bottom).

When a motor runs, electrical energy is stored inside its coils, and when movement stops this energy is released backwards through the system. This is known as back EMF. Back EMF can cause damage if left unchecked, so we place a ‘flyback’ diode across the motor to provide a safe path to ground for the current.

Bi-directional control

To change the direction of a BDC motor, a circuit known as an ‘H Bridge’ is required. When Q1 and Q4 are on, current flows through the motor left to right, causing it to rotate. Alternatively, if Q2 and Q3 are on, the current would flow right to left, resulting in a rotation in the opposite direction.

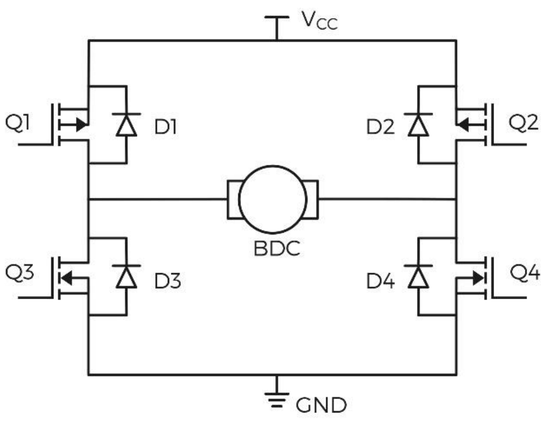

Figure 10. H-Bridge gate arrangement.

The diodes present in the diagram across each switch exist to dissipate back EMF, as mentioned before. Most circuits do not require a diode to be added, as the body diode that is present inside the MOSFET is usually adequate for this role. However, one is sometimes added if the body diode is not capable of safely dissipating the back EMF current. The following table details the effect on the motor that each state has. It is important to make sure noise and other unpredictable inputs cannot open the gates as this can potentially short the power supply, breaking the system. This can be achieved with pull-down resistors on the control signals.

When all four FETs are off, and both leads of the motor are floating, the motor is in a **Coasting** state; spinning freely until frictional resistance slows it down. This is because in an open circuit, the magnetic field of the rotor is unable to induce a current in the stator coil, and as such, no counter magnetic field is created to resist the motion.

Conversely, when Q3 & Q4 are on, and the motor is shorted across ground, the motor is in **Braking** state, coming to a halt and resisting any movement. In a shorted state, the stator resistance is minimal, and so the induced current is very high, which produces a massive counter magnetic field that strongly opposes any rotation of the coil.

	Forward	**Reverse**	**Coasting**	**Braking**
Q1	On	Off	Off	Off
Q2	Off	On	Off	Off
Q3	Off	On	Off	On
Q4	On	Off	Off	On

Feedback

Differing loads and wearing down of the commutator brush can result in faster or slower rotational speed, and if precise control is needed over the rotation, then a more complex solution utilizing feedback from the motor is required. This can be done with an additional sensor or by reading Back EMF from the coils.

Sensored

The most common sensored feedback methods are Optical Encoders and Hall Effect sensors. Optical Encoders work by attaching a slotted tach wheel to the motor, and the combination of a light source and detector on either side of it. As the motor rotates, the light source is obscured and revealed to the detector by the spokes and slots of the wheel, and the frequency of this signal is used to calculate the speed of rotation.

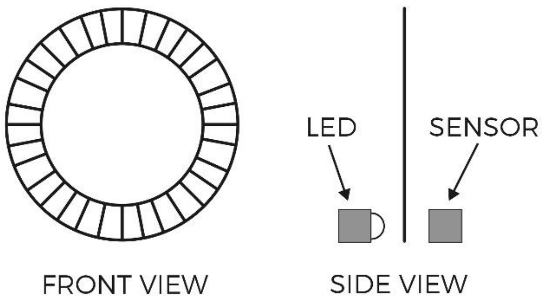

Figure 11. Optical Encoder.

Hall Effect sensors detect magnetic fields by acting as a switch when a field is present. A small magnet is placed on the rotor, and when this passes by a corresponding sensor, a signal is produced.

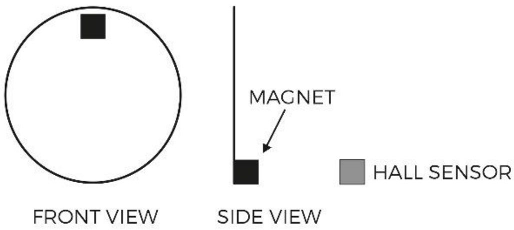

Figure 12. Hall Sensor.

Sensorless

The velocity can also be detected by reading the Back EMF of the motor. During the off cycle in a PWM pulse, the rotation of the rotor acts as a generator, and the induced voltage is proportional to its speed. Once a relationship between the voltage and speed is found using a tachometer, a microcontroller can be used to exercise precise rotation control.

Conclusion

Brushed DC Motors are reliable, inexpensive and require a minimal amount of external components. However, over time the brushes can wear down and may require maintenance.