PROJECTS WITH ARDUINO & RASPBERRY PI

MOTOR CONTROL

Dogan Ibrahim

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&
Raspberry Pi Zero W

Dogan Ibrahim

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● British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

● **ISBN 978-1-907920-66-0**

© Copyright 2017: Elektor International Media b.v.
Prepress Production: D-Vision, Julian van den Berg
First published in the United Kingdom 2017
Printed in the Netherlands by Wilco

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PREFACE

Arduino is probably the most widely used platform for developing microcontroller based projects. It is used by students all over the world, by electronic hobbyists, and by anyone else interested in developing a microcontroller based project. One of the strong points of Arduino is that it is an open source computer hardware and is therefore supported by large number of developers and groups. Arduino hardware is based on the popular Atmel AVR and ARM Cortex processors. The boards are equipped with sets of analog and digital input-output pins that may be interfaced to various external devices for monitoring and control applications. Arduino programs are widely developed using te Integrated Development Environment (IDE) which uses a dialect of features from the C and C++ programming languages.

Raspberry Pi Zero W is the latest low-cost member of the Raspberry Pi family of single board computers, which extends the basic family features by the addition of wireless LAN and Bluetooth connectivity. This is a tiny board costing about $15 and including a 1 GHz single-core BCM2835 CPU, RAM, and wireless chip supporting 2.4 GHz Wi-Fi 802.11n and Bluetooth 4.0. Raspberry Pi Zero W uses the Linux distribution Rasbian operating system, designed specifically for the Pi. The board includes large number of input-output ports and supports various peripheral protocols, such as I2C, SPI, UART and so on. The processor can be programmed using the highly popular Python programming language.

This book is about DC electric motors and their use in Arduino and Raspberry Pi Zero W based projects. Many tested and working projects are given in the book for real-time control of standard DC motors, stepper motors, and servo motors, and mobile robots.

One of the interesting and strong points of this book is that it gives complete projects for remote control of a mobile robot from mobile phones, using the Arduino Uno as well as the Raspberry Pi Zero W as the controller processors. These projects are developed using Wi-Fi as well as the Bluetooth connectivity.

I hope you like reading the book and find it useful for your next motor control or robotic project.

Prof Dr Dogan Ibrahim
London, 2017

CHAPTER 1 • ELECTRIC MOTORS

1.1 Overview

In this Chapter we will be looking at the types and basic principles of the electric motors, namely the DC motors which are commonly used in microcontroller based systems such as robotics, factory automation, domestic and industrial control and so on.

1.2 Types Of Electric Motors

An electric motor is an electrical machine that converts electrical energy into mechanical energy in the form of linear or rotational movements (or torque). Electric motors operate with the principles of magnetic fields where a force is generated between the motor's magnetic field and the current through its windings and this force causes linear or rotational movement.

Electric motors are classified into two categories as follows:

- AC motors
- DC motors

Within these categories, there are subdivisions where Figure 1.1 shows some important motor types in these subdivisions.

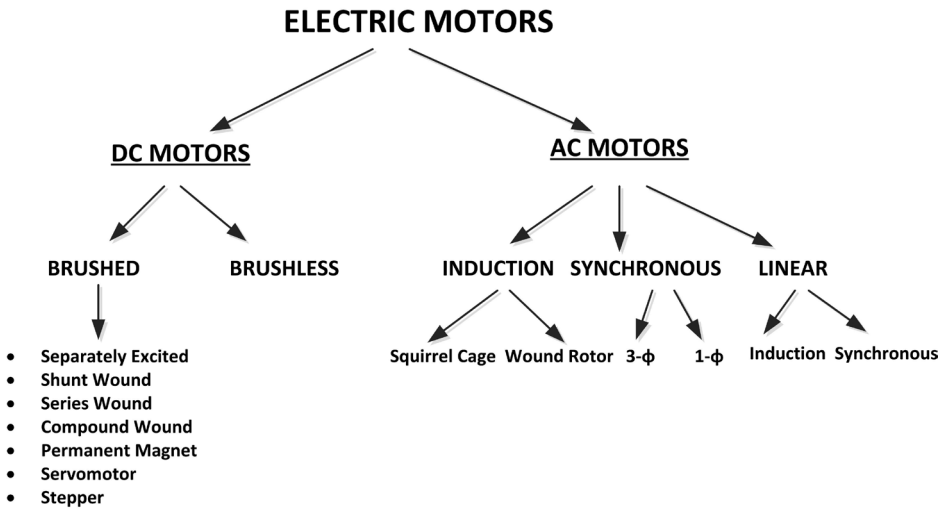

Figure 1.1 Electric motor types

Alternating Current (AC) motors are not commonly used in robotics because most robots are powered with batteries which are DC voltage. AC motors are generally used in industrial automation applications where very large torques may be required, such as in conveyor belts, cranes and so on.

In this book we are only interested in the following types of DC only electric motors:

- Brushed DC motors
- DC Servo motors
- DC stepper motors

The advantages of the brushed DC motors are:

- They are low-cost
- They operate with low DC voltages
- They are small in size
- It is easy to control their speeds
- They are widely available in all sizes
- They have good torque-speed characteristics

The disadvantages of the brushed DC motors are:

- The brushes wear out in brushed DC motors and may need replacement
- Brushes generate electrical sparks which could fire or explosions in certain environments
- Brushes generate RF noise that may interfere with nearby electronic equipment such as TVs, radios etc.
- Professional quality DC motors are expensive

1.3 Brushed DC Motors

Brushed DC motors normally have two terminals and when voltage is applied across these terminals the motor rotates proportionally. Brushed DC motors (BDC) are widely used in most electronic toys and in other low-cost motor applications (Figure1.2). They are very low-cost, easy to drive, and are available in many sizes and shapes, with and without gear mechanisms. Unlike other motor types (e.g. brushless DC, and AC), brushed DC motors do not require a controller to switch to switch the current in the motor windings. As shown in Figure1.3, all BDC motors are made up of:

- A stator
- A rotor
- Brushes and a commutator

Figure 1.2 Small brushed DC motor

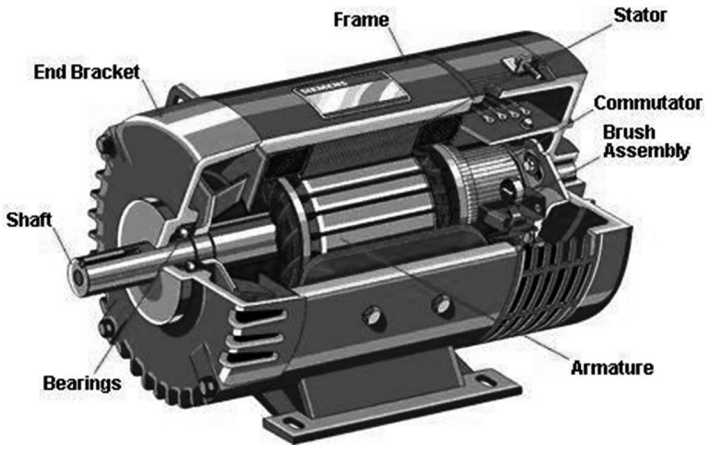

Figure 1.3 A typical BDC motor

The stator generates a stationary magnetic field that surrounds the rotor. This field is generated by either permanent magnets placed around the rotor, or by electromagnetic windings surrounding the rotor.

The rotor (see Figure 1.4) is also called the armature and it is made up of windings which produce magnetic field when energized by applying a DC voltage. The magnetic poles of the rotor are attracted to opposite magnetic poles of the stator, thus causing the rotor to turn.

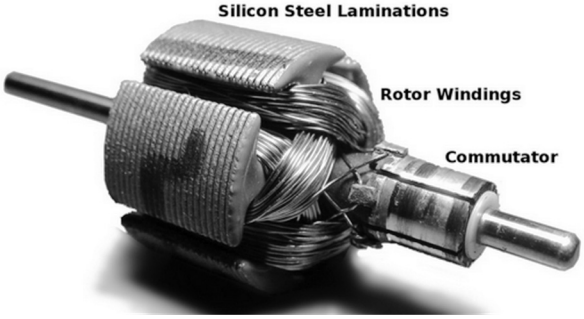

Figure 1.4 The rotor

The commutator (Figure 1.5) is placed on the axel of a BDC motor and as the motor turns, carbon brushes provide supply voltage to the rotor windings through the commutator. The brushes come in contact with different segments of the commutator, thus providing the required supply voltage to different windings of the rotor. Note that the commutator is part of the rotor and as the rotor turns so does the commutator.

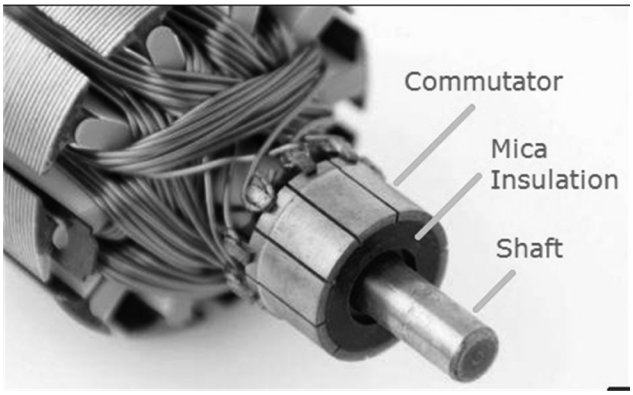

Figure 1.5 The commutator

1.3.1 Permanent Magnet BDC Motors

In a permanent magnet BDC motor the stator field is generated by permanent magnets (see Figure 1.6). i.e. the stator is a pair of permanent magnets. These motors have the advantages that they can be very small, and there are no field circuit copper losses. They have the disadvantages that the torque produced is low since the permanent magnets produce weak flux densities compared to externally supported magnetic fields. There is also the risk of demagnetization which can stop the motor functioning. Figure1.7 shows the circuit diagram of a permanent magnet BDC motor.

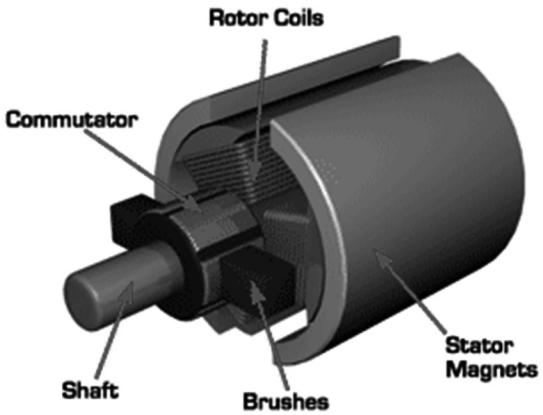

Figure 1.6 Permanent magnet BDC motor

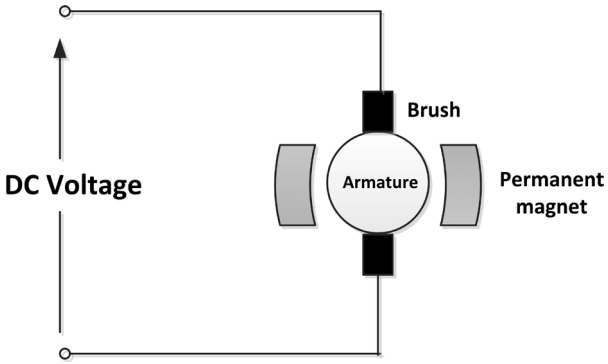

Figure 1.7 Circuit diagram of a permanent magnet BDC motor

1.3.2 Series Wound BDC Motors

In a series wound BDC motor the field coil is in series with the armature and thus, the field current is equal to the armature current. The advantage of these motors is that they produce high torque. These motors have the disadvantage that it is difficult to control their speed, and also the maximum speed is limited to around 5000 rpm. Figure 1.8 shows the circuit diagram of a series wound BDC motor.

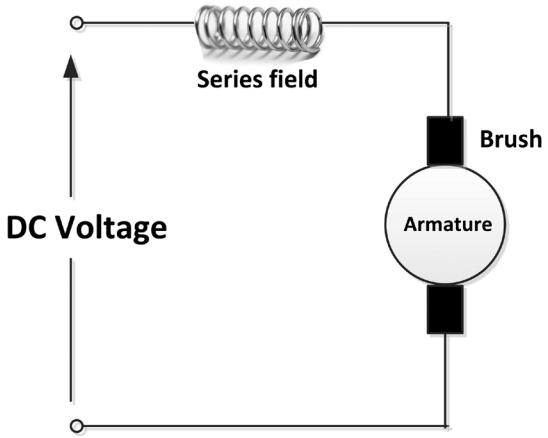

Figure 1.8 Circuit diagram of series wound BDC motor

1.3.3 Shunt Wound BDC Motors

Shunt wound BC motors have the field coil in parallel with the armature and thus the current in the field coil and the armature are independent of each other. The advantage of these motors is that they have excellent speed control properties. The speed can easily be changed by inserting a resistor in series with the armature or with the field coil. Figure 1.9 shows the circuit diagram of a shunt wound BDC motor.

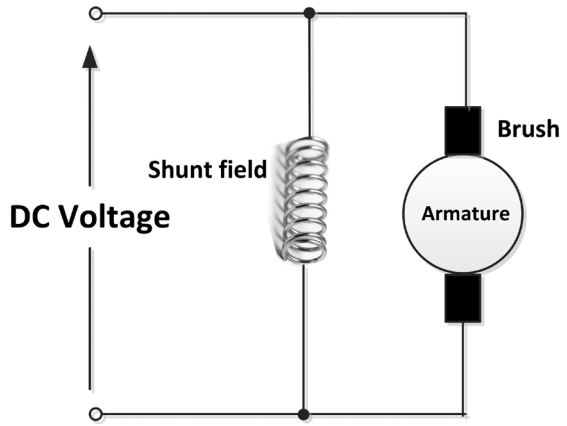

Figure 1.9 Circuit diagram of a shunt wound BDC motor

1.3.4 Compound Wound BDC Motors

These motor are a combination of shunt wound and series wound motors. These motors have the advantages that they have higher torque than series wound motors and their speed control is stable. Figure 1.10 shows the circuit diagram of a compound wound BDC motor.

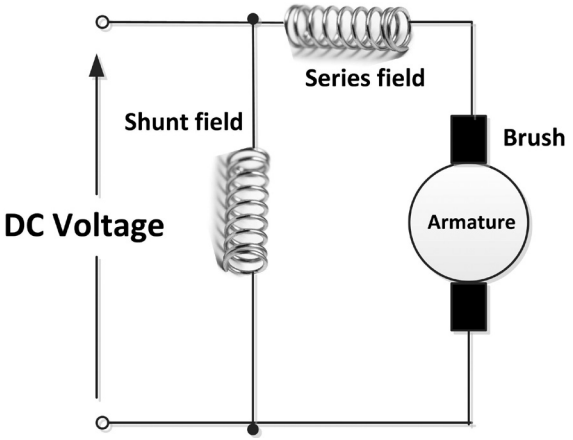

Figure 1.10 Circuit diagram of a compound wound BDC motor

1.3.5 Separately Excited BDC Motors

In a separately excited BDC motor the field coils are supplied from an independent source and thus the field current is not affected by changes in the armature current. These motors have high torques and stable speed control properties. Figure 1.11 shows the circuit diagram of a separately excited BDC motor.

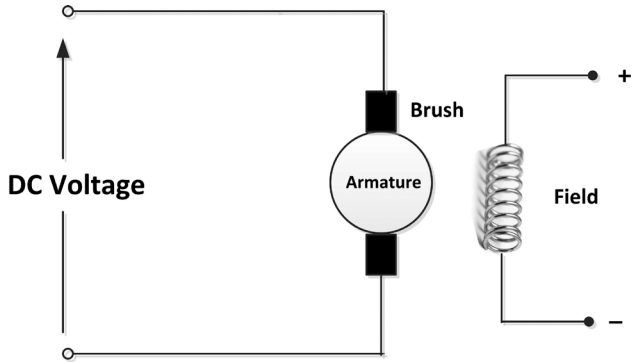

Figure 1.11 Circuit diagram of a separately excited BDC motor

1.3.6 Servo Motors

A servo motor allows for precise control of angular position of its rotor. It usually consists of a DC motor coupled with a sensor for feedback so that the rotary position of the motor can be controlled accurately. Servo motors run in closed loop mode to provide high performance and accuracy. These motors are commonly used in radio controlled cars, boats, helicopters, aeroplanes etc.

Servo motors are normally operated with PWM type pulses (positive going square waveform pulses) with a period of 50Hz (20ms period). In most types, a 1.5ms pulse puts the motor in a stationary position, a 1ms pulse turns the motor 90 degrees to one direction, and a 2ms pulse turns the motor 90 degrees in the opposite direction. Some types of servo motors are modified such that they rotate continuously. Figure 1.12 shows a small servo motor.

Figure 1.12 Small servo motor

1.3.7 Stepper Motors

Stepper motors (see Figure 1.13) rotate in discrete steps when electrical pulses are applied across its terminals in the correct sequence. The sequence of the applied pulses determine the direction of rotation, while the speed of the motor shaft rotation is directly related to the frequency of the input pulses, and the length of rotation is related to the number of applied pulses. Stepper motors are ideal for open loop position control applications such as in printers, plotters, PCB drilling machines and any other applications requiring precise control of the rotor position. Stepper motors have the disadvantage that the torque produced is not very large.

Figure 1.13 A small stepper motor

Basically, there are two types of stepper motors: unipolar and bipolar. The main difference between these two types is the applied voltage levels. Unipolar stepper motors (see Figure 1.14 for its circuit diagram) operate with positive voltages only (e.g. 0 and +12V). Bipolar motors (see Figure 1.15 for its circuit diagram) on the other hand operate with positive and negative voltages (e.g. -5V and +5V). As shown in the figures, unipolar motors require an additional wire in the middle of each coil. Bipolar motors have the advantages that they produce larger torques since the current flows in the entire coil and generates stronger electromagnetic field, and also they require one less wire for operation.

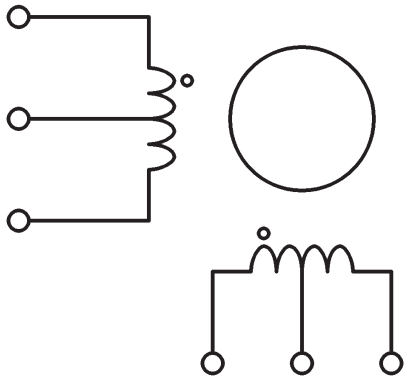

Figure 1.14 Circuit diagram of the unipolar stepper motor

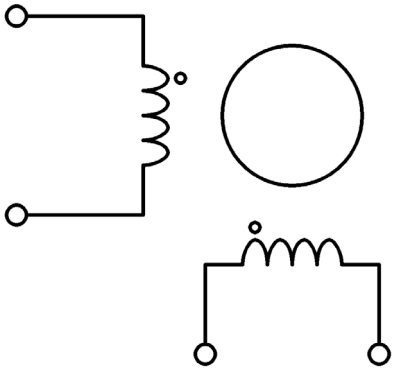

Figure 1.15 Circuit diagram of the bipolar stepper motor

1.4 Brushless DC Motors

In a brushless DC motor (BLDC) the rotor is a permanent magnet and the stator has windings. This is basically like a bushed DC motor turned inside out. There are no brushes or a commutator in a brushless DC motor and because of this these motors last longer and require little or no maintenance. In addition, brushless motors do not generate electrical sparks and are therefore cleaner, less noisy, and more reliable. The disadvantage of these motors is that they are more expensive. The sequence of voltages applied to the stator windings replace the function of the commutator and turn the motor. The control of a brushless DC motor is very different from the normal brushed DC motor as it requires sensors to detect the rotor angular position before applying the voltage pulses. Speed control of brushless DC motors are achieved using electronic Speed Control (ESC) modules.

1.5 Motor Selection

Choosing an electric motor for an application is an important task when designing a mobile robot or any other electric car. Some of the important motor specifications to consider during a choice are:

- Torque
- Speed
- Accuracy
- Operating voltage
- Cost
- Physical size and weight

1.5.1 Torque

Torque is the turning ability of an electric motor. The higher the torque the more power the motor has while turning an object. Torque is similar to force, but it is the rotational (or twisting) force rather than linear force. Torque is calculated by multiplying the force applied to an object with the perpendicular distance from the pivot point to the point where the force is applied. A simple example is to imagine pushing a door to open. The applied force causes the door to rotate about its hinges (the pivot point). The closer you are to the hinges the harder it is to open the door because you apply a smaller torque. In SI units torque is measured in Newton-metres, or Nm for short.

The required torque to drive the wheels of a robot (or an electric car) depends upon the following factors:

- Rolling resistance
- Slope resistance
- Accelerating force

Rolling Resistance

The rolling resistance occurs as a result of the rolling motion of the wheel and it depends upon the type of surface the wheel is on. The rolling resistance can be calculated as:

$$R = W \times C_r$$

and

$$W = m \times g$$

Where, **W** is the gross vehicle weight, **m** is the mass of the vehicle, **g** is the acceleration due to gravity ($9.81 m/s^2$), and C_r is the rolling resistance coefficient, given in Table 1.1 for some common surfaces.

Surface	**Rolling Resistance**
Concrete	0.010
Asphalt	0.012
Snow (2 inches)	0.025
Mud (firm)	0.037
Mud (soft)	0.150
Grass (firm)	0.055
Sand (firm)	0.06

Table 1.1 Rolling resistances of some surfaces

Slope Resistance
The slope resistance is important when the wheel is moving on an inclined surface. The slope resistance is given by:

$$S = W \times \sin \varphi$$

Where **φ** is the inclination angle of the surface. For flat surfaces φ = 0 and therefore there is no slope resistance.

Accelerating Force
Accelerating force helps the vehicle to come to a pre-defined speed from rest in a specified period of time. It is given by:

$$A = m \times a \text{ or } A = W \times a / g$$

Where, **a** is the required acceleration, **m** is the mass of the vehicle, and **W** is the gross vehicle weight as before.

The total required motor torque can then be calculated as follows:

$$T = R + S + A$$

1.5.2 Speed
Speed requirement is easier to estimate as it depends on how fast we want the robot to run. DC motors usually run at speeds of thousands of RPMs with very low torque. In practical applications we need to use gear mechanisms between the motor shaft and the actual wheel. The resultant motor speed with a gear mechanism is given by:

$$\text{Resultant speed} = \text{Actual speed} / \text{Gear ratio}$$

1.5.3 Accuracy
Accuracy depends upon whether the motor is used for speed control or for position control. In speed control applications we want the motor speed to stay the same even if a load is applied to the motor shaft. In position control applications we want the motor shaft to rotate the required amount and then stop. Accurate motor control is normally obtained using closed loop control where feedback is used to sense the current speed of the position of the motor. With the help of this feedback the error between the desired value and the actual measured value is eliminated or minimized.

1.5.4 Operating voltage
The operating voltage is also an important factor when choosing a motor. Most electric motors used in toys and robotics are brushed DC motors operating with batteries. In general, higher voltages result is higher motor speeds but this may require more batteries. Using more batteries will make the vehicle heavier and also the cost of the batteries will increase. Common voltages used in DC motors are 3, 5, 12 and 24 Volts. It is important to realise that the motor windings may be damaged if a higher voltage than the absolute maximum

is applied to a motor. Similarly, the motor will not rotate if the applied voltage is lower than the minimum operating voltage.

1.5.5 Cost

The cost of the motor is important in robotic applications. Usually lower cost motors may not be of high quality and the brushes may need to be changed frequently. Such motors can only be used in hobby applications. A choice should be made between the desired quality and the cost.

1.5.6 Physical size and weight

Electric motors are available in many different shapes, sizes, and weights. If the motor is to be used on a robot vehicle then it is important to choose a light weight motor with as small size as possible. A lighter vehicle can be moved with less torque and this lowers the overall cost of the project.

1.6 Transfer Function of a Brushed DC Motor

The transfer function of a system is the ratio of its output to its input, represented using the Laplace transform. It is important to know the transfer function of a system before feed-back can be applied to it for closed loop control. In this section we shall derive the transfer function of a permanent magnet brushed DC motor (or a separately excited DC motor) which is one of the most commonly used motors in robotic applications.

Figure 1.16 shows the circuit diagram of the motor where R (in Ohms) and L (in Henries) are the resistance and inductance of the motor windings, V (in Volts) is the applied DC voltage, J (in $Kg.m^2/s^{2)}$ is the inertial of the load attached to the motor, and V_e (in Volts) is the back EMF (electromagnetic force) of the motor.

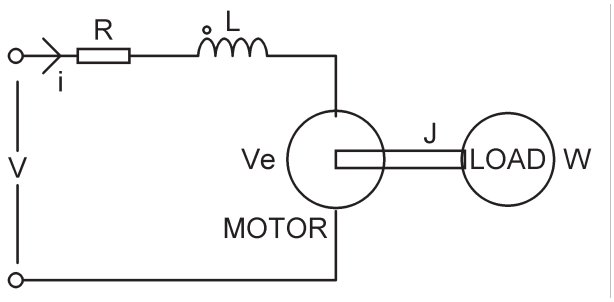

Figure 1.16 Permanent magnet DC motor

The torque generated by the motor is proportional to the current through the motor windings and it can be written as:

$$T = K_T\, i$$

Where K_T is the motor torque constant and i (in Amperes) is the current (1.1)

The back EMF is proportional to the motor angular speed W (rad/s) and is given by:

$$V_e = K_E W \tag{1.2}$$

Notice that W = dΘ/dt where Θ is the angle rotated by the motor (in radians). K_E is the motor back emf constant.

Using Kirchoff's law, we can write the following equation about the motor circuit:

$$V - V_e = Ri + L\, di/dt \tag{1.3}$$

Or,

$$V = Ri + Ldi/dt + K_E W \tag{1.4}$$

Also,

$$T = J\, dW/dt \tag{1.5}$$

From (1.1) and (1.5) we can write:

$$i = J/K_T\, dW/dt \tag{1.6}$$

using equations (1.6) and (1.4):

$$V = \frac{RJ}{K_T}\frac{dW}{dt} + \frac{LJ}{K_T}\frac{d^2W}{dt^2} + K_E W \tag{1.7}$$

In small motors the inductance L is very small and can be neglected. Equation (1.7) then becomes:

$$V = \frac{RJ}{K_T}\frac{dW}{dt} + K_E W \tag{1.8}$$

Equation (1.8) is a first order equation. Using the Laplace transforms where s is the Laplace operator, we can re-write it as:

$$\frac{W(s)}{V(s)} = \frac{1}{K_E + sRJ/K_T} \tag{1.9}$$

or,

$$\frac{W(s)}{V(s)} = \frac{K_T}{K_T K_E + sRJ} \tag{1.10}$$

We can therefore represent the transfer function of the motor as in Figure 1.17.

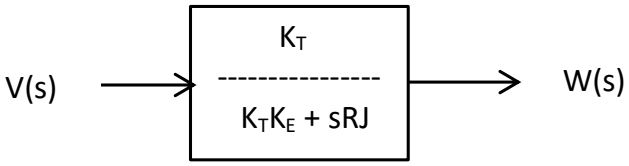

Figure 1.17 DC motor transfer function

When a step voltage V_O is applied across the motor terminals the motor speed increases exponentially until it settles down at a final value. The step response of the motor (i.e. the motor speed when a sudden step voltage is applied) can be derived by multiplying the transfer function by 1/s and then taking the inverse Laplace transform. The result is given below:

$$W(t) = \frac{V_o}{K_E}\left(1 - e^{-\frac{K_T K_E t}{RJ}}\right) \tag{1.11}$$

Initially the speed is 0, and it increases exponentially, having a final value of $W(t) = V_O/K_E$. Figure 1.18 shows the typical step response of the motor.

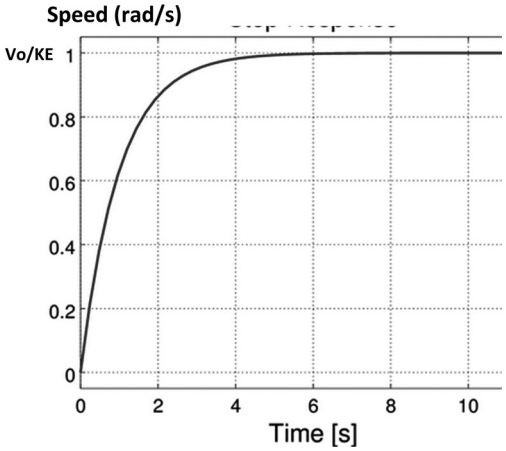

Figure 1.18 Step response of a DC motor

Notice that the term $T = RJ/K_TK_E$ is known as the motor time constant of the motor and this is the time it takes for the motor to reach 63% of its final value. Using the time constant, we can re-write equation (1.11) as:

$$W(t) = \frac{V_O}{K_E}\left(1 - e^{-t/T}\right) \tag{1.12}$$

1.7 Torque – Speed Characteristics

Torque-speed characteristics is important for a given motor as it shows the change of the available motor torque with the speed. In general, greater torque is obtained at lower speeds. Figure 1.19 shows the torque-speed characteristic curve of some brushed DC motors.