BRUSHLESS DC MOTOR

Topics Covered

- Brushed DC Motors.
- Brushless DC Motors.

Prerequisites

- The QNET Mechatronic Actuators has been setup and tested. See the QNET Mechatronic Actuators Quick Start Guide for details.
- You have access to the QNET Mechatronic Actuators User Manual.
- You are familiar with the basics of LabVIEW™.

1 Background

Direct Current motors, or DC motors, are synchronous motors that convert electrical energy into mechanical energy using electromagnetism by leveraging the fact that identical and opposing magnetic poles repel and attract each other, respectively. In general, a DC motor consists of a stationary component called stator, or housing, that encloses a rotating part called rotor, or armature. The two most common types of DC motors are brushed and brushless DC motors.

1.1 Flemming's Left Hand Rule

In general, a current flowing through a wire induces an magnetic field that is perpendicular to the wire, while also experiencing a force that is perpendicular to both the wire and the magnet field. This relationship can be visualized using Flemming's left hand rule: Using your left thumb, index and middle fingers as mutually perpendicular axis, the direction of the resulting force (thumb), magnetic field (index finger) and direction of current flow (middle finger) can be obtained. Here, it is assumed that the direction of the mechanical force is literal, the direction of the magnetic field is from the north to the south pole, and the direction of the electric current is in line with that of conventional current (positive to negative). There are several mnemonics to memorize what quantity is related to which finger, one of which is the *FBI* rule that associates the SI units for force (F), magnetic flux density (B) and current (I) with the fingers starting from the thumb to the middle finger, as in Figure 1.1.

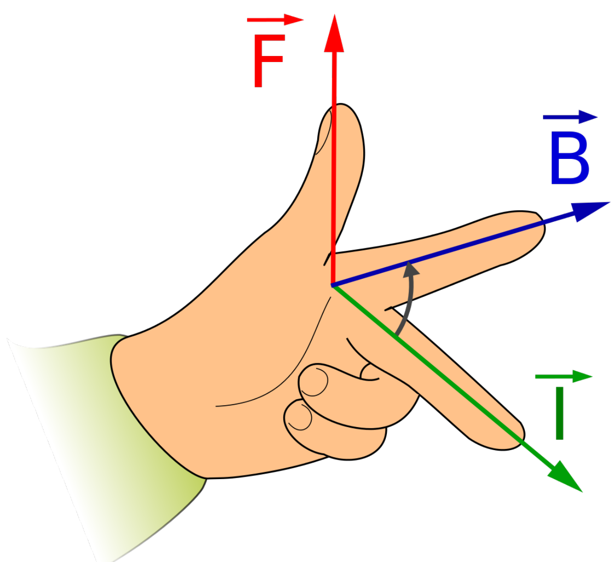


Figure 1.1: Flemming's left hand rule [1]

Note that this rule can be extended to Flemming's right hand rule when it used to determine the direction of an induced current in generators.

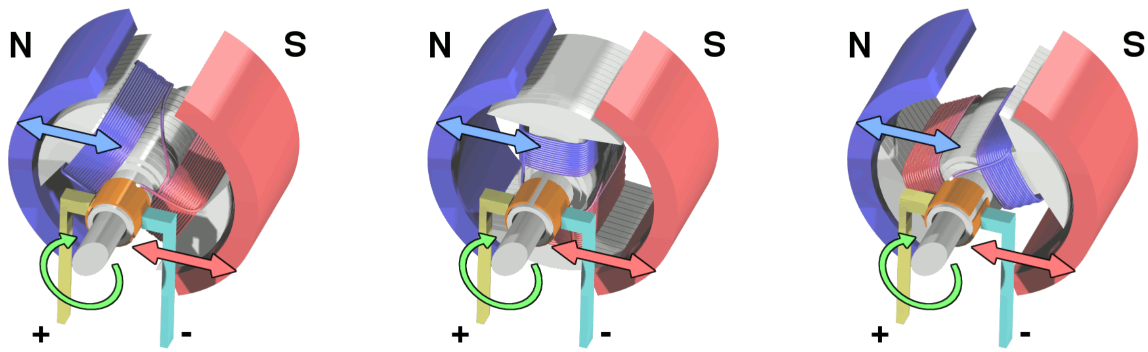
1.2 Brushed DC Motors

A brushed DC motor generates torque by housing a permanent magnet in the stator and commutating an electromagnet in the rotor as it rotates. Carbon brush assemblies are used to pass an electrical current through a commutator to the rotor as it rotates, hence the name brushed DC motor. Changes in the magnitude of the applied voltage lead to changes in the rotor's magnetic field, thus the rotational speed can be varied by changing the applied voltage.

The functionality of a simple two-pole brushed DC motor can be explained with Figure 1.2 where the commutator is shown in orange, and the brushes are located at the ends of the yellow and blue power connections. Here,

[1] José Fernando - Universidad de Granada

Figure 1.2a depicts a (random) starting position. The rotor coil is powered through the commutator ring and the carbon brushes to induce a magnetic field that is opposite to the external field from the stator, hence both north and south poles repel each other. The direction of the rotation of the rotor can be obtained using Flemming's left hand rule. The armature continues to rotate through the position where the magnetic field of the rotor is perpendicular to that of the stator as in Figure 1.2b. Once the rotor is almost horizontally aligned again as in Figure 1.2c, the resulting torque drops to zero and the commutator reverses the direction of the current through the coil, hence reversing the magnetic field.



(a) (b) (c)

Figure 1.2: Brushed DC Motor [2]

The torque achieved is highest in a holding position and decreases with an increase in speed.

1.3 Brushless DC Motors

A brushless DC motor generates torque by housing a permanent magnet in the rotor and commutating several electromagnets in the stator. There is no need for brushes to pass an electrical current to the rotor, thus the name brushless DC motor. The design of a brushless DC motor is more complicated than that of a brushed motor, as additional sensors are needed to detect the angular position of the armature and more complex circuitry and feedback control is necessary to ensure proper commutation of the electromagnetic fields in the stator. This often results in a high initial cost than a comparable brushed DC motor. That being said, the lack of brushes inherently leads to a longer life span and little or no maintainable costs since the mechanical elements are not in direct contact and are therefore less likely to wear over time.

Typically, rotary encoders, back EMF measurements, or Hall effect sensors are used to determine the angular position of the rotor. With this information, a motor controller generates AC signals that drive the electromagnets in the stator. This makes brushless DC motors more efficient than brushed DC motors since the applied voltage is pulsed as opposed to direct. Alternating current in this context does not imply a sinusoidal waveform but rather bi-directional current that can follow an arbitrary waveform. The brushless DC motor on the QNET Mechatronic Actuators has built in Hall effect sensors, which are transducers that vary their output voltage in response to a magnetic field. These kind of sensors are most frequently used for proximity switching and current sensing, as well as position and speed control of brushless DC motors.

In a typical configuration, there are three Hall effect sensors separated by 120° placed around the stator that can detect the position of the armature similar to Figure 1.3. There are a total of six possible combinations of active/inactive Hall effect sensor states before the sensing pattern is repeated. This implies that a 2-pole rotor completes a full revolution for one pattern cycle, whereas only half or a quarter of a rotation are completed for a 4-pole and 8-pole rotor, respectively. Note that the other two theoretical combinations of sensors - all high or all low - can never be reached and represent a faulty state.

[2] Eric Pierce

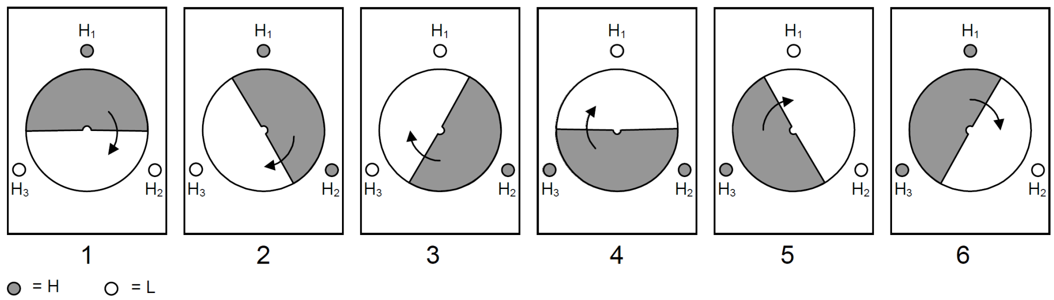


Figure 1.3: Hall effect sensors

To achieve maximum torque, the angle between the magnetic field of the stator and the rotor should be $\pm 90°$, depending on the desired directionality. The winding configuration in the stator is either a *Delta* or *Wye* configuration, see Figure 1.4. A Delta configuration connects the windings in a triangular shape, where two windings are connected to a common node at all times as in Figure 1.4a. This configuration provides low torque at low speeds, but also allows for a high top speed. Conversely, the Wye configuration in Figure 1.4b provides a high torque at low speeds and a lower top speed.

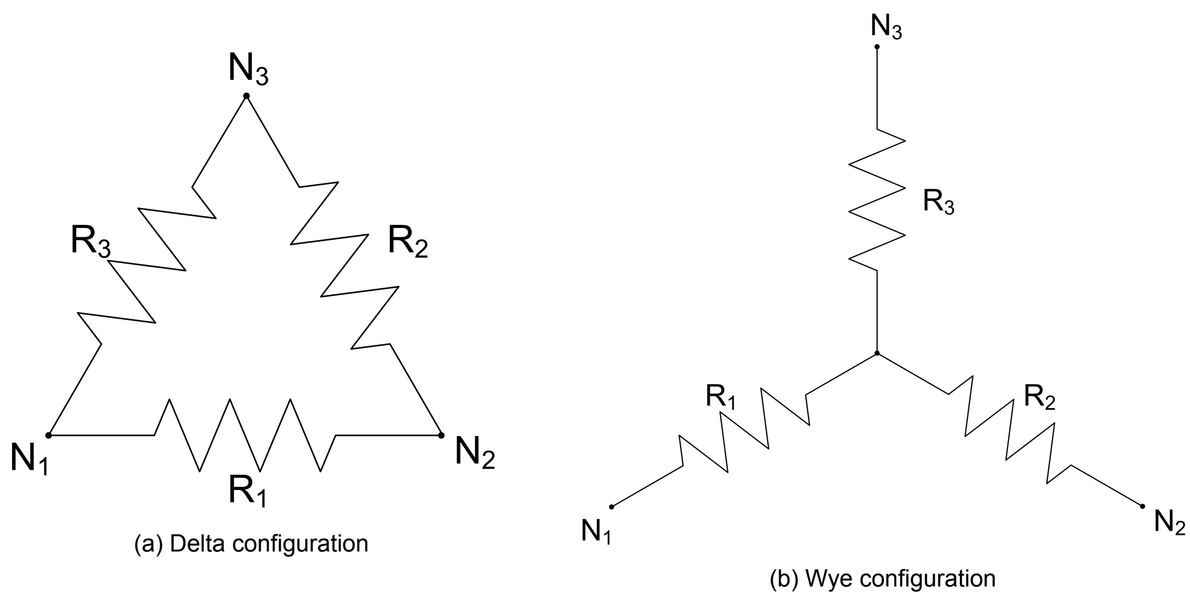


Figure 1.4: Delta and Wye configuration

The brushless DC motor on the QNET Mechatronic Actuators has stator coils wired in a Wye configuration. To control the brushless DC motor, one can use the phase/Hall effect sensor diagram in Figure 1.5. Here, the Hall effect sensor states are overlaid with the phase directions of the motor. For the first state in Figure 1.5 where only H_3 is active, one locates the matching orientation of the rotor in Figure 1.5. For a clockwise rotation, locate the phase vector that is 90° clockwise from its position to find the active phase and directionality of current. For example, in the first state A_{off}, B_+, and C_-, the A branch of the Wye configuration is inactive and the current flows from B to C, see state 1 in Figure 1.6. This process is then repeated for the other sensing states and the overall speed is determined by the frequency with which the commutation is driven.

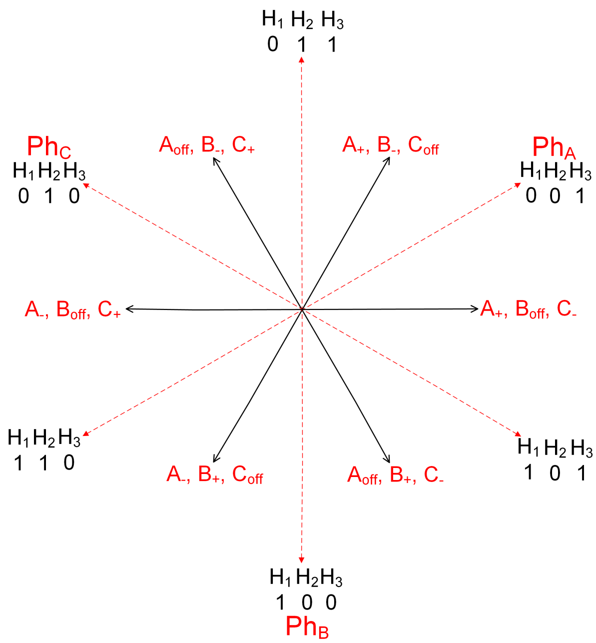


Figure 1.5: Brushless DC motor phase diagram

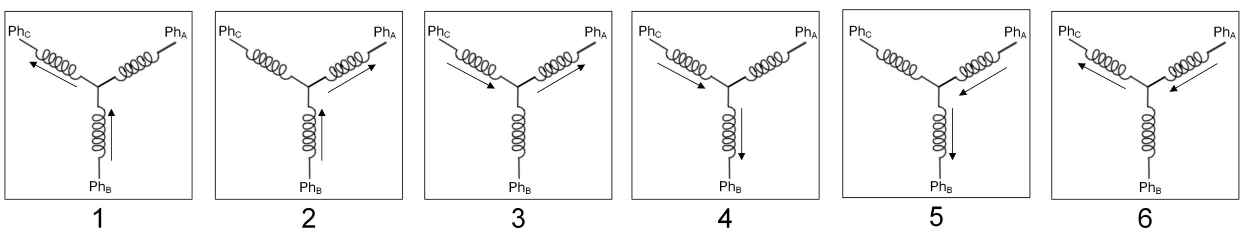


Figure 1.6: Six step commutation

The desired states can be achieved using three half H-bridges similar to Figure 1.7.

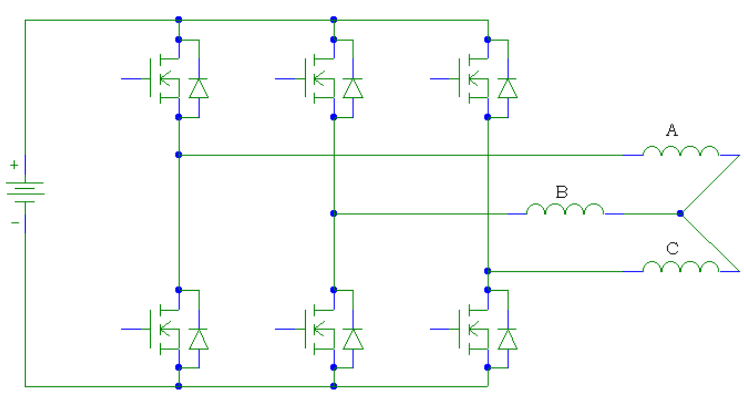


Figure 1.7: Three half H-bridges required to drive the brushless DC motor

2 In-Lab Exercise

1. Open the `QNET Actuators - Brushless Motor.vi`. **Make sure the correct Device is chosen.**
2. Based on the configuration of the brushless DC motor on the QNET Mechatronic Actuators, determine the appropriate control sequence to rotate the motor clockwise into the table, and enter the table into the VI.

   Note: The states in the table on the VI are **Z** for an off or neutral state, **H** for a positive voltage, and **L** for a negative voltage.

Sensor	A	B	C
001			
101			
100			
110			
010			
001			

Table 2.1: Brushless DC motor control sequence

3. Run the VI, change the mode switch to User Table, and push the Write Table button to send the table to the motor controller. If there are any errors in the table that might harm the motor, they will be indicated by a → symbol next to that row and the Write Table button will be disabled.
4. Increase the commanded PWM duty cycle and ensure that the motor is rotates as expected. Stop the VI.
5. Change the control mode of the motor back to the Internal Table setting and run the VI.
6. Starting with the commanded duty cycle of 0%, gradually increase the applied voltage until the motor begins to rotate. Record this value, and comment on what might be the cause of a lack of continuous movement at low voltage.
7. Next, starting again from a commanded duty cycle of 0%, stall the motor at gradually increasing commanded duty cycles. To avoid any harm from the spinning motor, stall the cog wheel with your finger at a low speed and *then* increase the applied voltage to the desired level *with the motor already stalled*. Record the resultant applied current at 5% increments, and comment on your observations.

   Note: If the motor is stalled for an extended period of time, a stall detection system will engage and cut power to the motor. Press the Stall Error Ack button to reset the stall status and restart the motor controller.

8. How might any discontinuous non-linear behaviour exhibited by the motor affect its performance, and how could it be compensated for?
9. Click on the Stop button to stop the VI.

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