Inverter-based FLC of BLDC's Speed

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Abstract

In this report, the model of a brushless DC Motor (BLDC motor) is imported into Simulink. A fuzzy logic based controller (FLC) is used to control the BLDC's speed making use of electronic inverters.

1 Introduction

Modern technology is not complete without electric drives, which power a broad range of equipment and gadgets, from industrial robots to electric cars. Electric motors, which turn electrical energy into mechanical energy to move a load, are at the centre of many electric drives. The brushless DC motor is one kind of electric motor that has grown in popularity recently.

In comparison to their brushed predecessors, brushless DC (BLDC) motors are more efficient, last longer, and require less maintenance. They are extensively employed in fields including aerospace, robotics, and electric vehicles that call for high performance and precise control.

Electronic speed controllers (ESCs), which modify the voltage and current provided to the motor to regulate its speed, are generally used to drive BLDC motors. having BLDC motors, a variety of speed control techniques are available, each having pros and cons of its own.

2 Literature Review

2.1 Brushless DC Motors (BLDC Motors)

Brushless Direct Current (BLDC) Motor is an increasingly popular choice of motor used in automotive, aerospace and industrial automation equipment and instrumentation. BLDC motors main distinction is that they have no brushes and instead commutate electronically. These motors combine the advantages of DC, AC and universal motors.

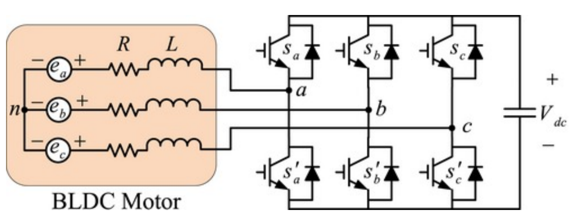

Figure 1: The Circuit Model of BLDCs

As in all motors, BLDC motors have two main parts which are the rotor and stator. BLDC motors are synchronous motors meaning that the magnetic fields generated from the stator and rotor both rotate at the same frequency. The stator in BLDC motors is an electromagnet which are available in single, 2 and 3 phases configurations with the 3 phase one being the most popular and widely used. The rotors are made of permanent magnets. motors can be either outrunner or inrunner. Inrunners have higher speed while outrunners have higher torque. BLDC motors have 3 important specifications. Their Kv rating, the stator size, and motor framework. The Kv rating expresses the speed of the motor in Revolutions Per Minute (RPM) per 1 volt . Stator size is written in the form xxyy to describe the dimensions of the motor's stator. The first two values represented by the x's are the diameter of the stator while the second pair of numbers indicated by the y's represent the height of the stator both in millimeters. A motors framework is denoted by a combination of letters and numbers in the form xxNyyP. The two numbers represented by x's before the N are the number of electromagnets in the stator while the numbers that replace the y's before the P are the number of permanent magnets in the rotor.

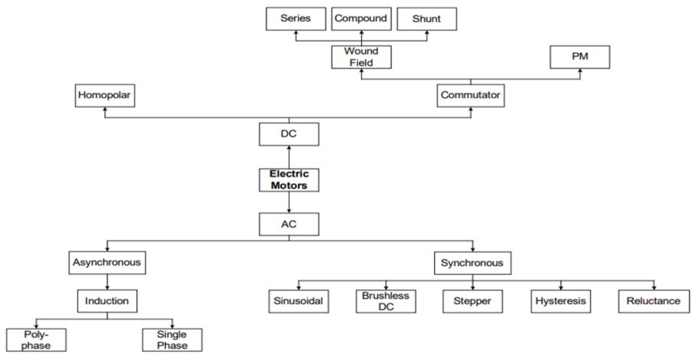

Figure 2: Motors Hierarchy

2.1.1 Theory of Operation

As mentioned BLDC motors are commutated electronically, where the three windings are energized in a specific sequence. However, in order to do so it is necessary to know the rotor position. This is done by embedding three hall sensors in the stator separated 120 degrees apart. The sensors output 0 or 1 indicating whether a north or south pole is being sensed. The combination of the three reading is used to determine the rotor position and hence which winding are to be energized next in the sequence. To maintain the motor running the magnetic field produced by the stator should continuously shift as the rotor catches up.

2.1.2 Speed-Torque Characteristics

Operation must be in the continuous region which is bounded by the rated torque to ensure current doesn't exceed rated, the max voltage which generates the largest triangle to avoid the insulation breaking down and it is preferred to remain under the rated speed.

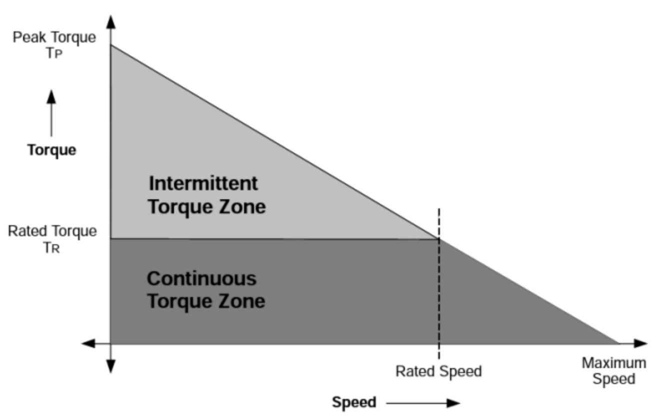

Figure 3: Speed-Torque Characteristics of BLDCs

2.1.3 Advantages and Disadvantages of BLDCs

BLDCs have a plethora of advantages that make them the optimal choice for many applications but that does not come without several drawbacks. Their advantages and disadvantages are as follows.
Advantages:
They have a long operating life with low maintenance, noiseless operation and high and variable speed ability of AC motors while having a high starting torque and maintaining a linear speed-torque characteristics of DC motors. They have a high-power density just below that of universal motors and a significantly high efficiency between 85-90
Disadvantages:
Their main disadvantage being their high cost.

2.2 Speed Control Techniques for DC Brushless Motors

DC brushless motors (BLDC) are widely used in various applications such as electric vehicles, robotics, appliances, and industrial automation due to their high efficiency, reliability, and long lifespan. One of the key aspects of controlling a DC brushless motor is regulating its speed according to the desired application requirements. In this report, we will discuss various speed control techniques for DC brushless motors, including their principles, advantages, and limitations.

2.2.1 Pulse Width Modulation (PWM)

PWM is a commonly used speed control technique for DC brushless motors. It involves switching the motor's supply voltage on and off rapidly to control the average voltage applied to the motor . The duty cycle of the PWM signal determines the effective voltage and, thus, the speed of the motor. Higher duty cycles result in higher average voltages, leading to increased motor speed, while lower duty cycles reduce the average voltage, resulting in lower motor speed.
Advantages:

1. Simple and cost-effective method for speed control.
2. Provides precise speed control with good efficiency.
3. Allows for smooth and gradual speed changes.
4. Can be easily implemented with microcontrollers or dedicated motor controllers.

Limitations:

1. Generates harmonics and electromagnetic interference (EMI) due to the rapid switching of the supply voltage.
2. Requires additional circuitry such as diodes and capacitors to filter out the harmonics and EMI.
3. May produce audible noise and vibration at certain duty cycles.
4. Limited in achieving high speeds in some applications.

2.2.2 Sensor-Based Control

Sensor-based control techniques use position sensors, such as Hall-effect sensors or encoders, to determine the rotor position of the brushless motor . This information is used to control the motor's speed accurately. By knowing the exact rotor position, the motor controller can apply the appropriate voltage to the motor windings, resulting in precise speed control.

Advantages:

1. Provides accurate speed control with high performance and efficiency.
2. Allows for smooth and precise control of motor speed across a wide range

3. Offers good torque control, especially at low speeds and during motor startup.
4. Suitable for applications that require precise speed and position control, such as robotics and servo systems.

Limitations:

1. Requires additional hardware, such as position sensors, which can add complexity and cost.
2. Sensors can be prone to wear and tear, affecting the motor's reliability.
3. Increased wiring complexity due to the need for sensor connections.
4. May not be suitable for applications where sensorless operation is desired, such as in cost-sensitive applications.

2.2.3 Sensorless Control

Sensorless control techniques eliminate the need for external position sensors by using the back-emf (electromotive force) of the motor windings to estimate the rotor position. The motor controller measures the back-emf of the motor windings and uses algorithms to determine the rotor position based on the changes in the back-emf.

Advantages:

1. Simplifies motor design by eliminating the need for external sensors.
2. Reduces cost and complexity by eliminating sensor-related components
3. Increases reliability as there are no sensors prone to wear and tear.
4. Suitable for applications where sensorless operation is desired, such as in cost-sensitive applications.

Limitations:

1. Less accurate compared to sensor-based control, especially at low speeds and during motor startup.
2. Can be affected by motor parameter variations, temperature changes, and other factors.
3. May require complex algorithms and signal processing techniques for accurate rotor position estimation.
4. Limited in achieving very high speeds and precise control in some applications.

2.3 Inverters

An inverter is an electronic device used to covert AC supply to DC . It consists of an input source, more commonly a DC source such as a battery, switches (mainly power electronic switches such as BJTs), a filter and an output transformer. As mentioned earlier, the source is typically a DC battery or source. The power electronic switches are used in order to control the current flow through the inverter circuit, which in turn determines the nature of the output waveform. The filter is used in order to regulate and smooth the output, more specifically in reducing harmonics. Lastly, the transformer is used to either step up or step down the inverter's output voltage to meet the load requirements.

2.3.1 Types

There are various types of inverters available such as square wave inverters, pure sine wave inverters as well as modified sine wave inverters. The difference between these types lies in their output waveform, where pure sine wave inverters produce smooth, high-quality waveforms which makes it suitable for delicate electrical equipment. Modified sine wave inverters produce a stepped waveform while square wave inverters produce square-like waveforms.

2.3.2 Control

In order to control the output waveform of the inverter several methods can be deployed, such as pulse width modulation (PWM), hysteresis control as well as vector control. Vector control is one of the more sophisticated methods that implements complex algorithms to control the speed and torque of the motor. Hysteresis control is a simpler control method that compares the inverter's output voltage with a reference voltage, Lastly, PWM is the more commonly used method of control where the inverter's duty cycle is varied via the switches as well as the switching frequency in order to control the inverter's output voltage and frequency. Brushless DC motors are DC motors that don't use brushes to transfer power to the rotor. They control the rotor's position instead by electrical commutation. Compared to brushless DC motors, conventional brushed DC motors are less trustworthy, less efficient, and have a shorter lifespan. When inverters and fuzzy logic controllers (FLCs) are combined to drive brushless DC motors, the FLC takes the place of the traditional control system that would have been utilised with the inverter. FLCs use fuzzy logic to select the appropriate output voltage and frequency for the inverter based on input data from sensors that measure the motor's speed and position as well as other elements like temperature and voltage. FLCs provide a number of benefits when used with inverters to control brushless DC motors. FLCs are robust and have the ability to manage complicated, non-linear systems. They are also easy to install and may be modified to meet specific control requirements. FLCs can improve the motor's efficiency by reducing the amount of power lost as heat. They can improve the motor's reliability and enhance the motor's lifetime by reducing wear and tear.

2.3.3 Applications

Inverters are used in various applications, one of particular interest being motor drives. They are used in controlling the speed and torque output of the motor. Another prominent application of inverters is their use in renewable energy systems converting DC power from solar panels to AC power that can in turn be used in households as well as businesses. In power backup systems, inverters are used to convert stored dc power from batteries to AC power that can be used during blackouts as a backup source until blackouts are over. One more application for inverters is in uninterruptible power supply (UPS) systems. UPS systems offer backup power during power outages. They convert DC power from batteries into AC power that may be used to power electrical devices. In addition to the ones already listed, inverters are deployed in various other industries such as the military, marine, and aerospace sectors. To convert DC power from batteries or generators into AC power that avionics and other electrical systems can use, inverters are employed in aircraft applications. To convert DC power from batteries or generators into AC power that navigational and communicational devices can use, inverters are employed in maritime applications. Many different electrical devices and systems are powered by inverters in military applications.

2.3.4 Summary

In conclusion, inverters are deployed in a plethora of applications and are essential components of modern power systems. They are controlled using techniques such as FLCs, PWM, hysteresis control, and vector control. When selecting the optimal inverter for a given application, consideration should be given to factors including output power, input voltage, efficiency, and waveform quality.

2.4 Controller: Fuzzy Logic Controller (FLC)

In the study of artificial intelligence, fuzzy logic is a particular area of focus. It is predicated on the value of information that is neither categorically true nor incorrect. Humans can and should utilise the same knowledge that they do in everyday life to support their intuition and apply broad guidelines to regulate circumstances. The unintended impacts of the system response can be combated by acquired information, which is a potent tool. A particularly flexible set of if-then rules are used by fuzzy logic controllers. The proper membership functions are then affected by the solution. Fuzzy Logic transforms the numerical values of any variable (crisp data) into what is known as Linguistic variable (fuzzy data) [6]. One of the key benefits of FLC is that they overcome the drawbacks of PID (proportional integrative derivative) controller such as lag or time delays or responses of step functions.

2.4.1 Architecture

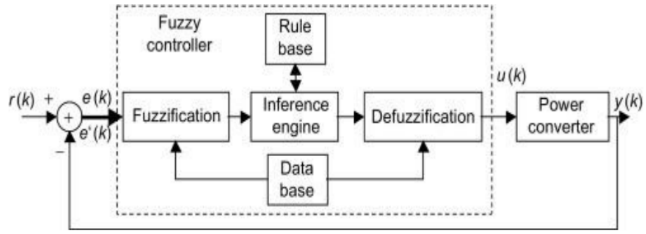

Figure 4: Basic Architecture of FLCs

Major Components:

1. Fuzzifier: Convert the crisp input values into fuzzy values
2. Fuzzy Knowledge Base: It stores the knowledge about all the input-output fuzzy relationships and also has the membership function which defines the input variables to the fuzzy rule base and the output variables to the plant under control.
3. Fuzzy Rule Base: It stores the knowledge about the operation of the process of domain.
4. Inference Engine: It acts as a kernel of any FLC. Basically, it simulates human decisions by performing approximate reasoning.
5. Defuzzifier: Convert the fuzzy values into crisp values getting from fuzzy inference engine.

2.4.2 Assumptions in FLC Design

While designing fuzzy control system, the following six basic assumptions should be made:

1. The plant is observable and controllable: It must be assumed that the input, output as well as state variables are available for observation and controlling purpose.
2. Existence of a knowledge body: It must be assumed that there exist a knowledge body having linguistic rules and a set of input-output data set from which rules can be extracted.
3. Existence of solution: It must be assumed that there exists a solution.
4. ‘Good enough’ solution is enough: The control engineering must look for ‘good enough’ solution rather than an optimum one.
5. Range of precision: Fuzzy logic controller must be designed within an acceptable range of precision
6. Issues regarding stability and optimality: The issues of stability and optimality must be open in designing Fuzzy logic controller rather than addressed explicitly.

2.4.3 Advantages

1. Cheaper: Developing a FLC is comparatively cheaper than developing model based or other controller in terms of performance.
2. Robust: More robust than PID controllers because of their capability to cover a huge range of operating conditions.
3. Customizable

4. Emulate human deductive thinking: Basically, FLC is designed to emulate human deductive thinking, the process people use to infer conclusion from what they know

5. Reliability: More reliable than conventional control system.

6. Efficiency: Provides more efficiency when applied in control system.

2.4.4 Disadvantages

1. Requires lots of data: Needs lots of data to be applied.

2. Useful in case of moderate historical data: Not useful for programs much smaller or larger than historical data.

3. Needs high human expertise: The accuracy of the system depends on the knowledge and expertise of human beings.

4. Needs regular updating of rules: The rules must be updated with time.

2.4.5 Applications

FLC systems find a wide range of applications in various industrial and commercial products and systems. The applications of FLC systems include :

1. Aircraft Flight Control
2. Missile Control
3. Adaptive Control
4. Liquid-Level Control
5. Automobile Speed Controller
6. Braking System Controller
7. Robotic Control
8. Elevator (Automatic Lift) Control
9. Cooling Plant Control
10. Water Treatment
11. Boiler Control
12. Nuclear Reactor Control
13. Power Systems Control
14. Air Conditioner Control (Temperature Controller)
15. Knowledge-Based System

3 Methodology

In this section, the application of an FLC to control the speed of a BLDC is discussed. The model was simulated using MATLAB's Simulink.

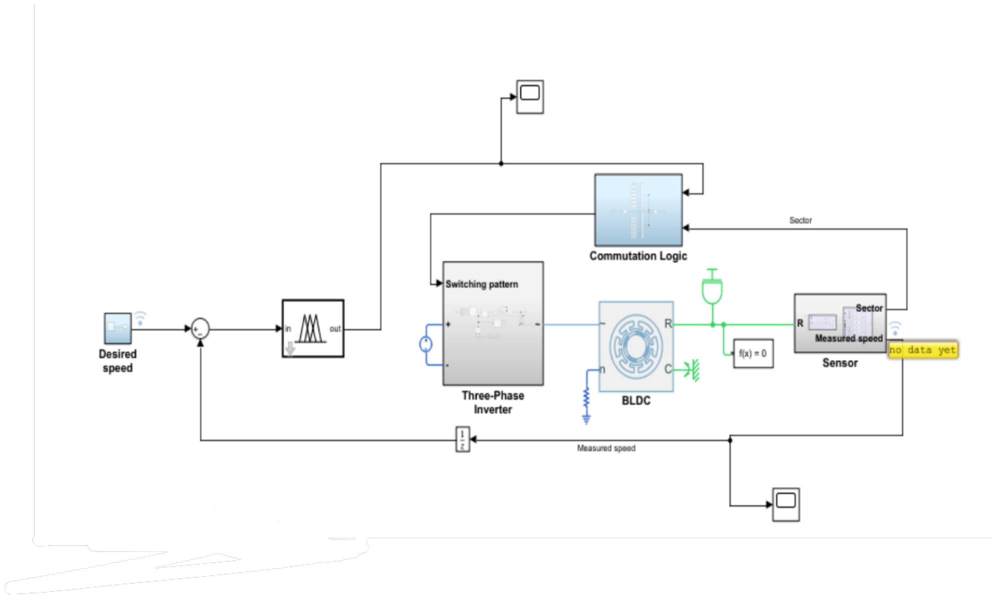

Figure 5: The Simulink Model

Firstly the model of the BLDC used is going to be explained.

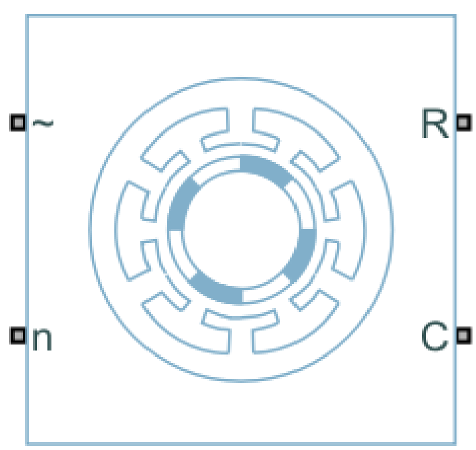

Figure 6: BLDC Simulink Block

The model has two input ports and two output ports. The output ports R and C refer to the motor's rotor and casing respectively. These output ports are used to obtain the rotor's relative position. The input port ˜ represents a composite three-phase port.Composite three-phase ports represent three individual electrical conserving ports with a single block port. The BLDC model has three phases and is actuated by activating two phases at a single time instance. The composite port takes as input the potential different across each phase. Deciding which two phases will be activated and the manner of their activation will be expanded upon later. The three-phase BLDC is constructed as follows:

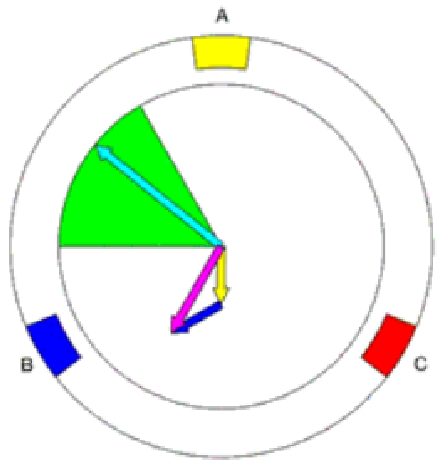

Figure 7: Three-phase BLDC construction

The BLDC motor is electronically commutated by energizing 2 phases at a time we can make the rotor rotate to attempt to align with the stator magnetic field. There are six different possible alignment positions separated each by 60 degrees and if we commutate the correct 2 phase each 60 degrees then the motor will spin. This known as six step commutation or trapezoidal control.

As seen from the complete simulink diagram, the input to the BLDC is controlled using a three-phase inverted block which in turn is based on a commutation logic block. The commutation logic block looks as follows:

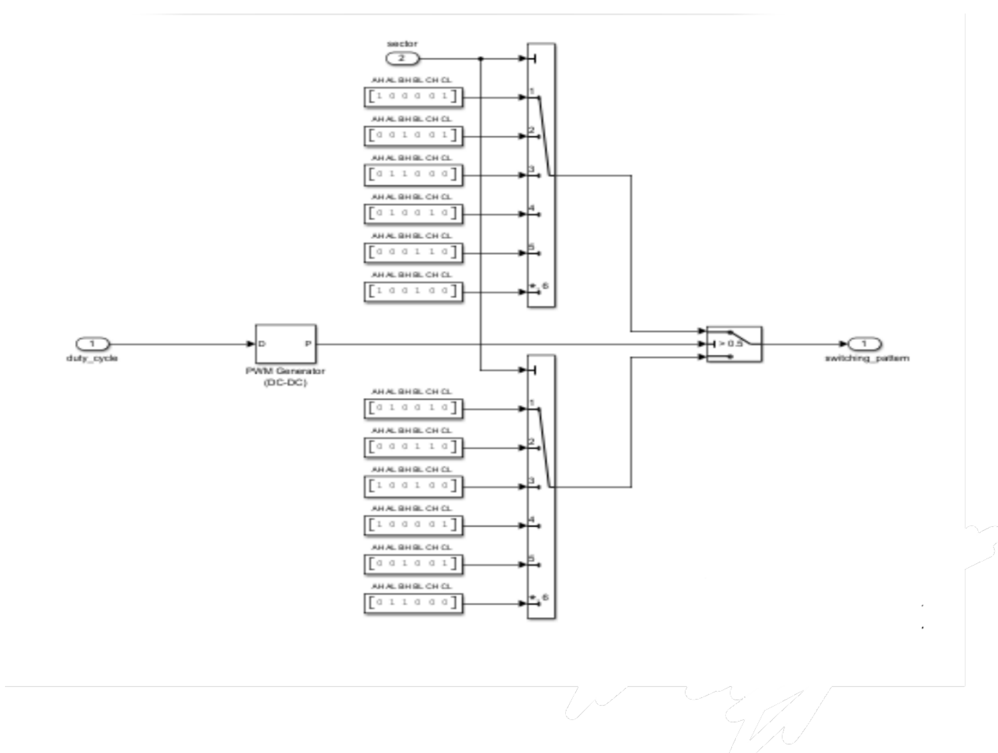

Figure 8: Commutation Logic Block

The commutation logic block takes two inputs, the duty cycle and the rotor's position. The BLDC model used has four pole pairs. For simplification purposes, the operation is explained using a BLDC with a single pole-pair. Now getting into how the switching pattern is chosen. Using the duty cycle, one of two switching pattern's are activated to enable both speeding up and speeding down. Assume the rotor is stationary in the position shown below:

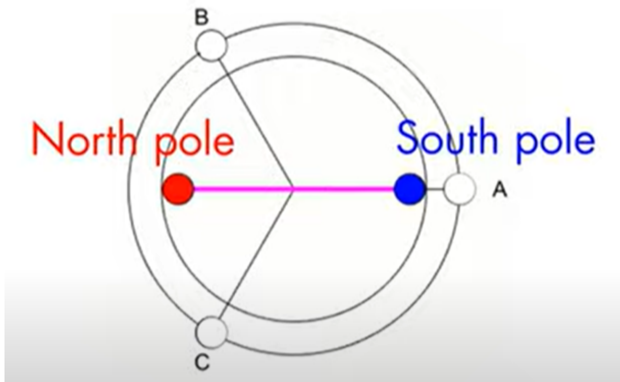

Figure 9: Rotor's Stationary Position

In this diagram, the rotor's north and south pole are shown. None of the phases are activated and hence the rotor is stationary. All three stator phases are separated by 120 degrees. To better understand how the rotor would rotate now imagine phases B and C are energized, (B high(red) and C Low(blue)), the phase B would repel the north pole of the rotor and the phase C would attract the north pole of the rotor causing it to rotate counter-clockwise.

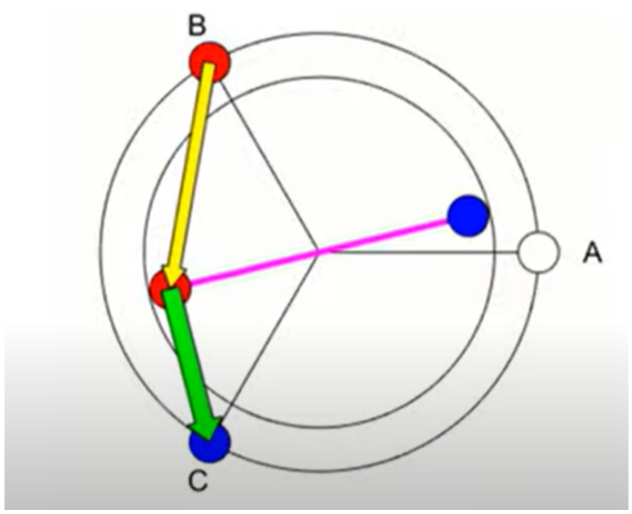

Figure 10: Rotor rotating CCW

Conversely, if the phases B and C's polarity where switched, the rotor's north pole would would instead be repelled by phase C and attracted by phase B causing it to roate clockwise. Every 60 degrees, the activated phases are switched in this manner once the attraction or repulsion forces between the already activated phase and the rotor's poles become less significant, closer phases are activated to ensure continuous rotation. The value of the duty cycle enables one of two switching pattern.
As discussed above, the activated phases can be hence activated based upon the rotor's position and thus a sensor should

be used in order to measure the rotor's position. In the model implemented, a hall-effect sensor is used to measure the rotor's position in order to determine which of the the six sectors it resides in to activate the corresponding phases. The sensor blocks is as follows:

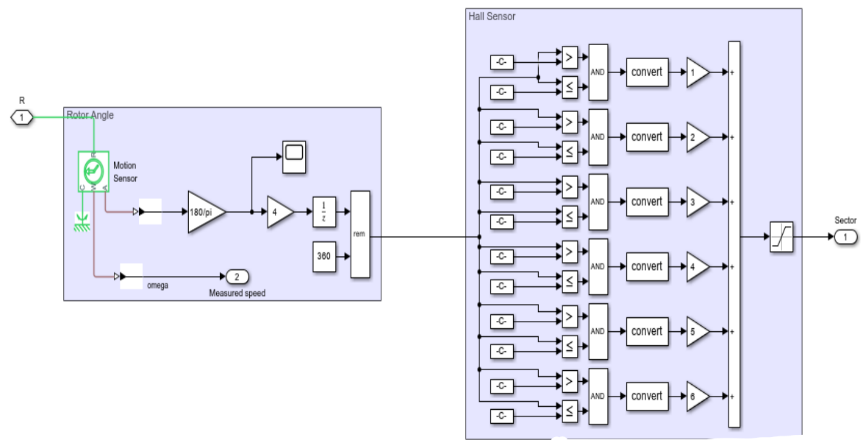

Figure 11: Sensor Block

A motion sensor is used to detect the rotor's speed. The speed of the rotor is multiplied by a gain 180/pi to convert from radians to degrees. This would return the rotors speed as degrees per second which is then integrated with respect to time to determine the rotor's angular position. Since six-sector commutation is used, the rotor's full rotation is divided into 60 degree sectors. The sensor block compares the rotor's angular position with the upper and lower bounds of each sector to determine the sector the rotor is currently present in. The sector number is provided as an input to the commutation logic block described above.

The commutation block only provides the switching pattern of the phases through logics 1 and 0 to both high and low activation of each phase as well as the duty cycle. The block responsible for delivering the actual potential difference to the phases is the three-phase inverter block. The inverter block consists of two sides, a high side and a low side with each stator phase connected to two inverters to enable both positive and negative potential differences across each respective phase. The three-phase inverter block looks as follows:

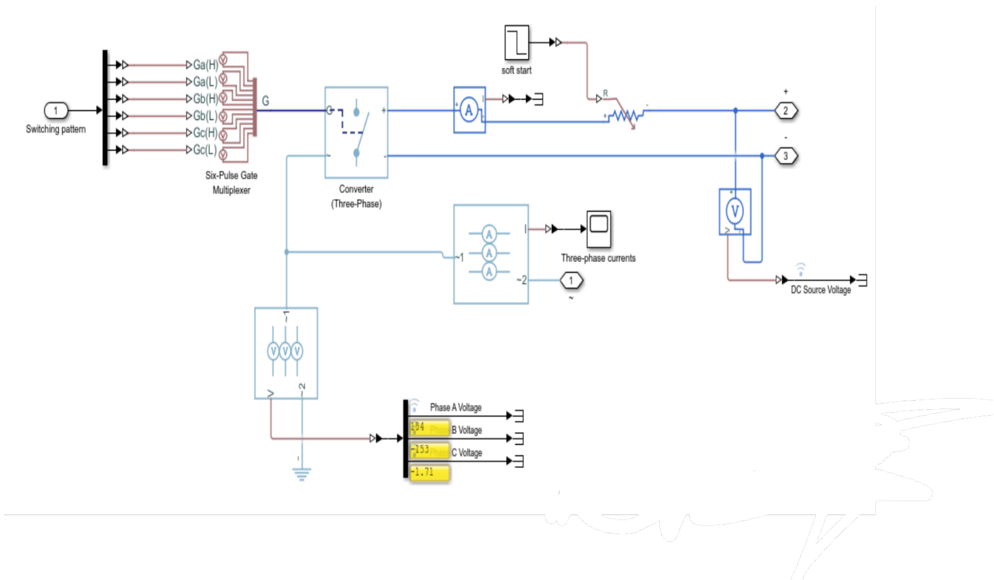

Figure 12: Three-phase inverter block

The three phase inverter takes the output of the commutation logic block as input and has the DC source for the motor connected to it switching the phases with the right pattern and frequency to meet the duty cycle and pattern inputs provided by the commutation block.

The part of the model that determined the duty cycle and adjusts it to meet the desired speed requirement is the FLC block. The FLC block looks as follows:

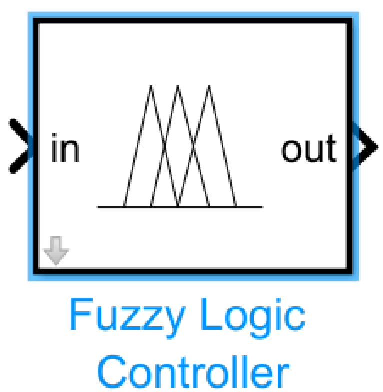

Figure 13: FLC block

The FLC block takes as input the error as the difference between a set speed (desired) and the current speed (also measured by the sensor block). Its output is a duty cycle value which is input to the commutation logic block. The input membership function (error) is designed as follows:

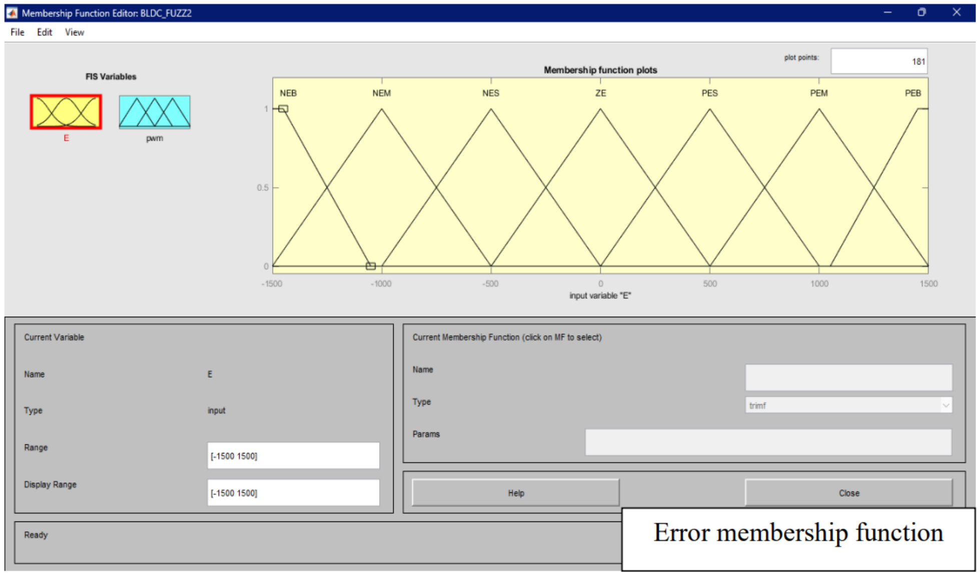

Figure 14: Error Membership Function

The input membership function consists of 7 fuzzy sets. Large/Medium/Small Negative, Zero and Large/Medium/Small positive errors. The numeric inputs are used to obtain the fuzzy values. Rule base is created and the inputs are used to identify which rules are activated. The FLC is designed to control the motor through speeds of -1500 (CW) to 1500 (CCW).

The output membership function (duty cycle) is designed as follows:

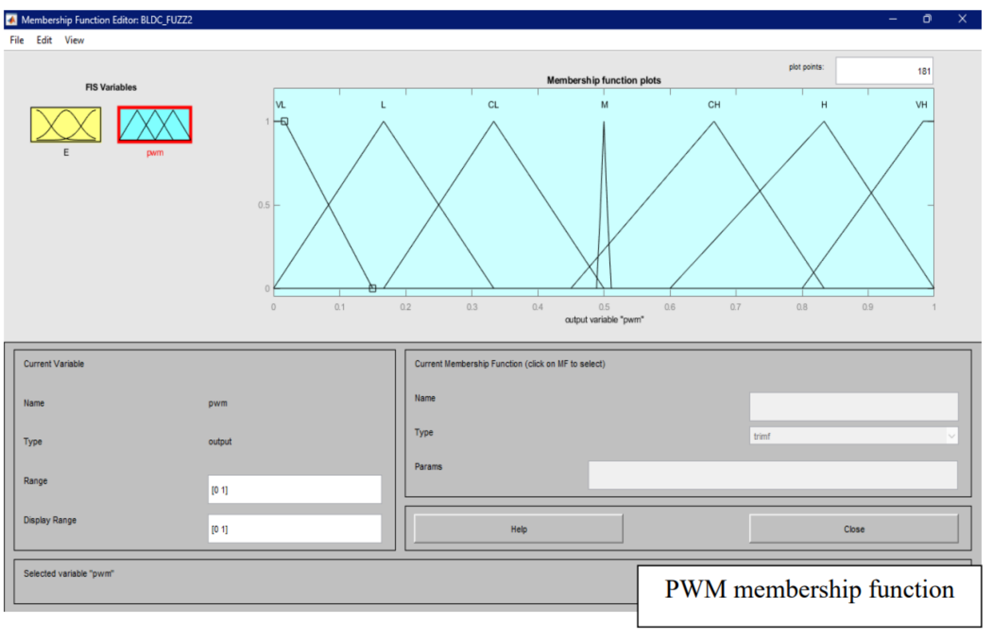

Figure 15: Duty Cycle Membership Function

The output membership function also consisting of 7 fuzzy sets is created. Very Low, Considerably Low, low, Medium, High, Considerably High and Very High. The output membership function is used for the defuzzification process to obtain numerical output for the duty cycle.

4 Simulation and Results

In order to confirm the robustness and accuracy of the designed controller, several simulations were carried out in MATLab's simulink. The results and details of these simulations are discussed in this section.
Firstly, the controller was used to track a constant speed of 400 rpms (relatively low speed). The results were as follows:

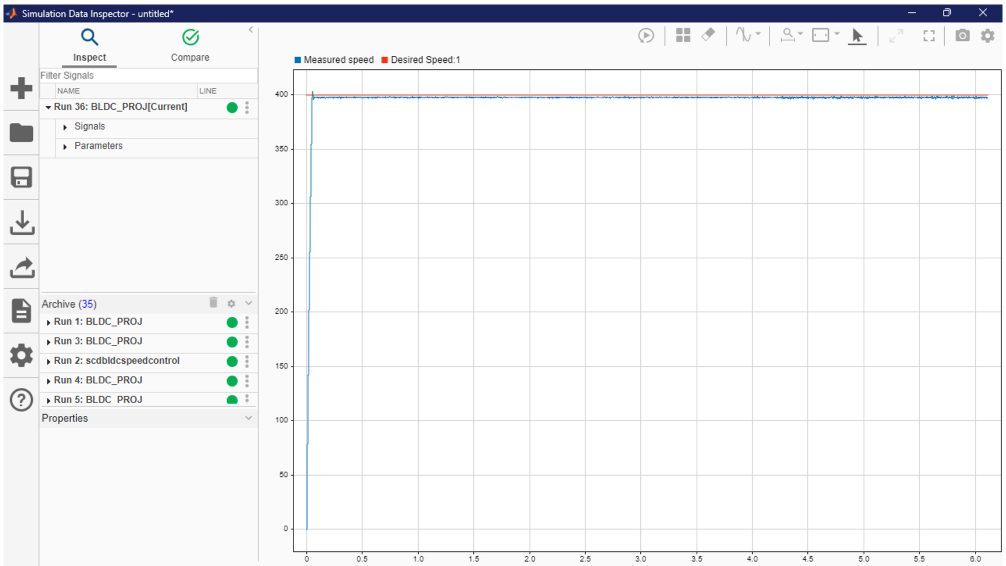

Figure 16: Desired Speed vs Actual Speed

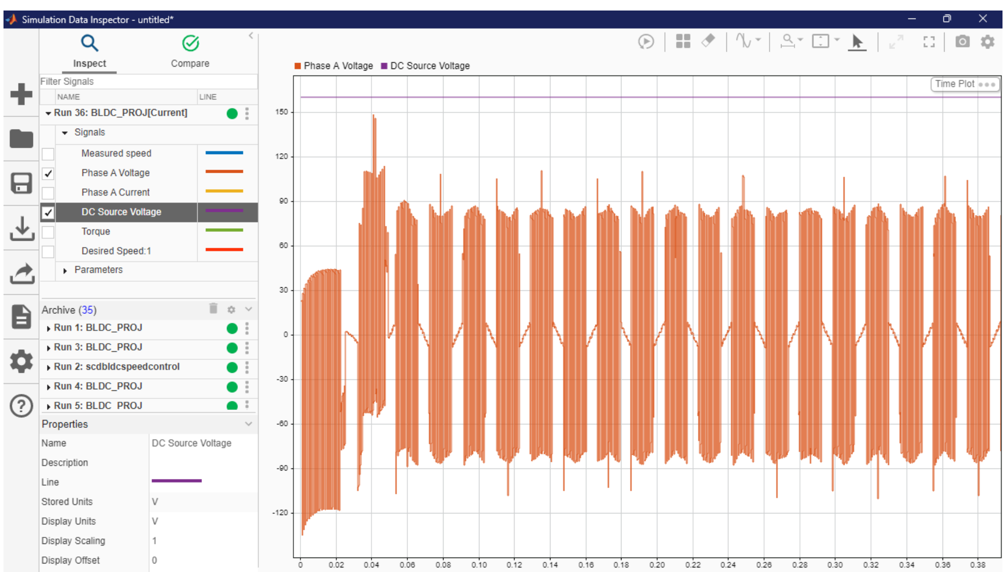

Figure 17: Phase A Voltage

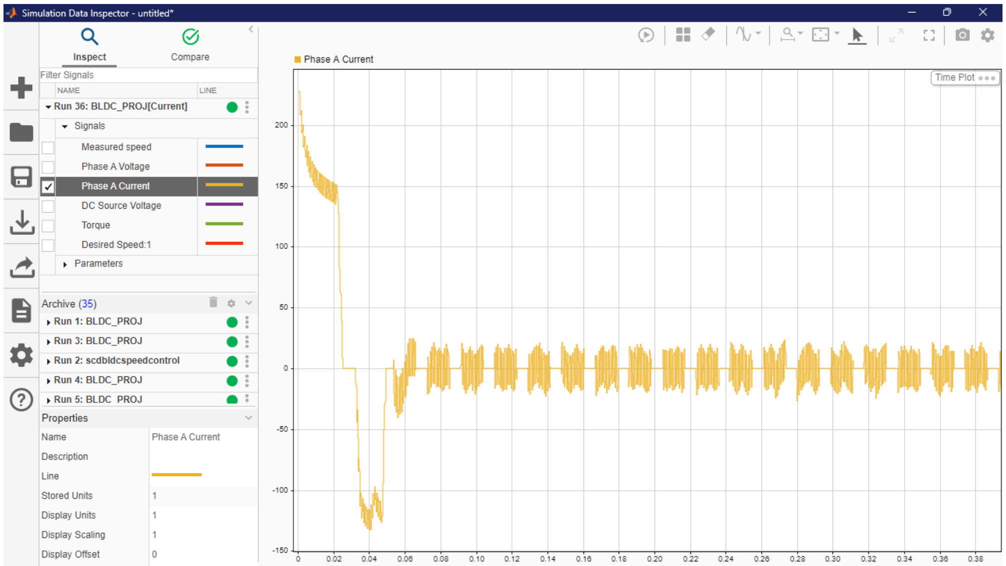

Figure 18: Phase A Current

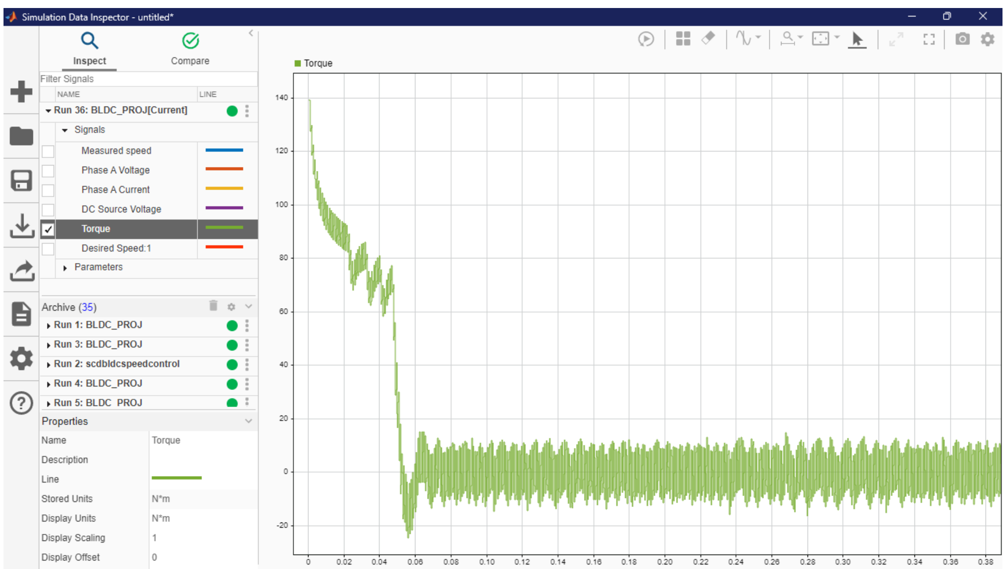

Figure 19: Torque Profile

As shown by the results, the controller is able to track the desired speed accurately. Another simulation was carried out, where the desired speed to 1200 (relatively high), the results are as follows:

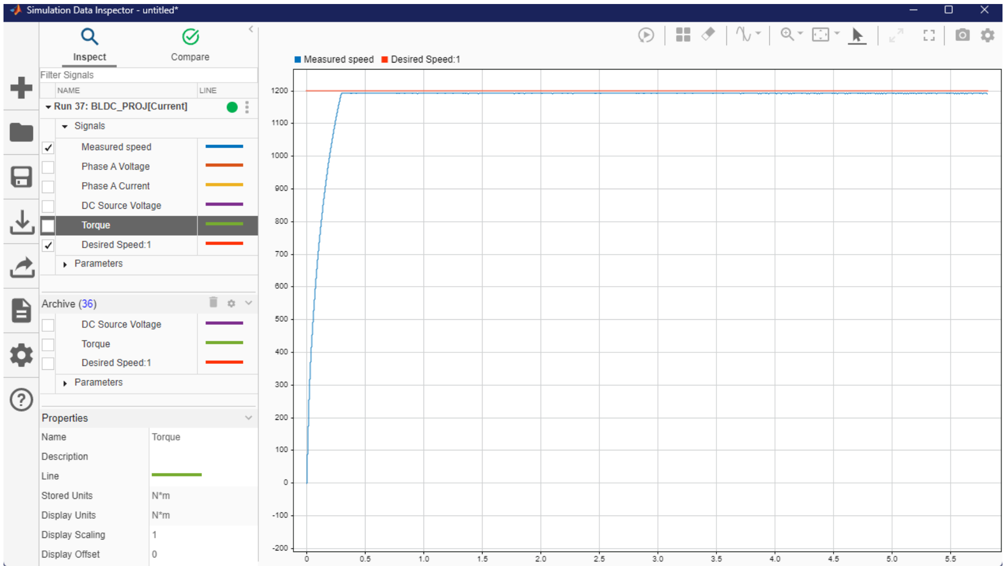

Figure 20: Desired Speed vs Actual Speed

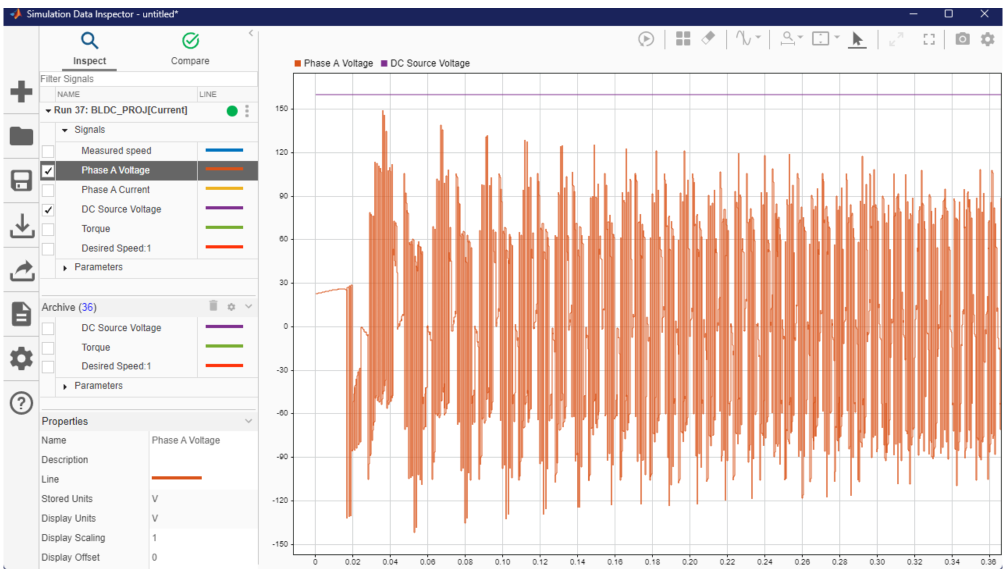

Figure 21: Phase A Voltage

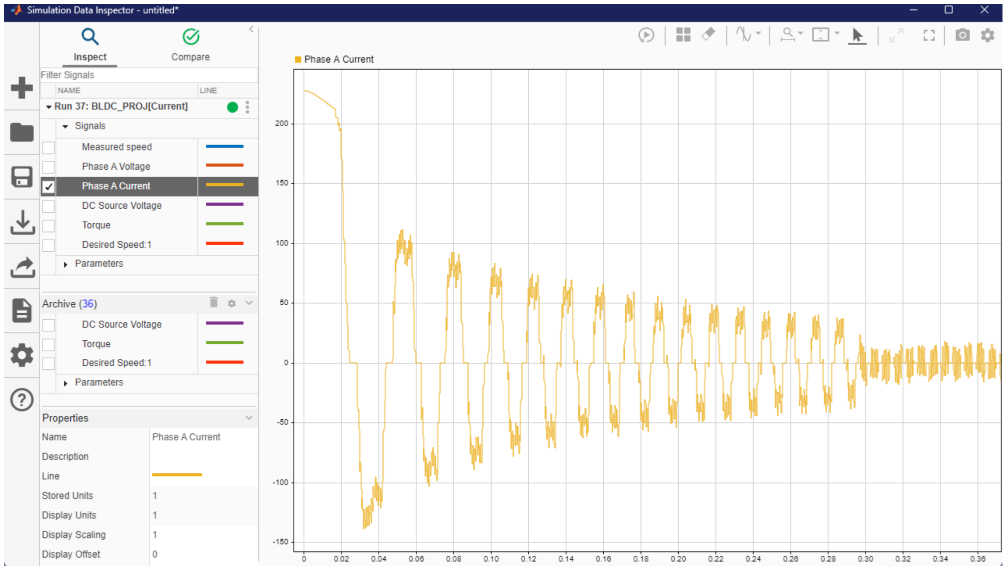

Figure 22: Phase A Current

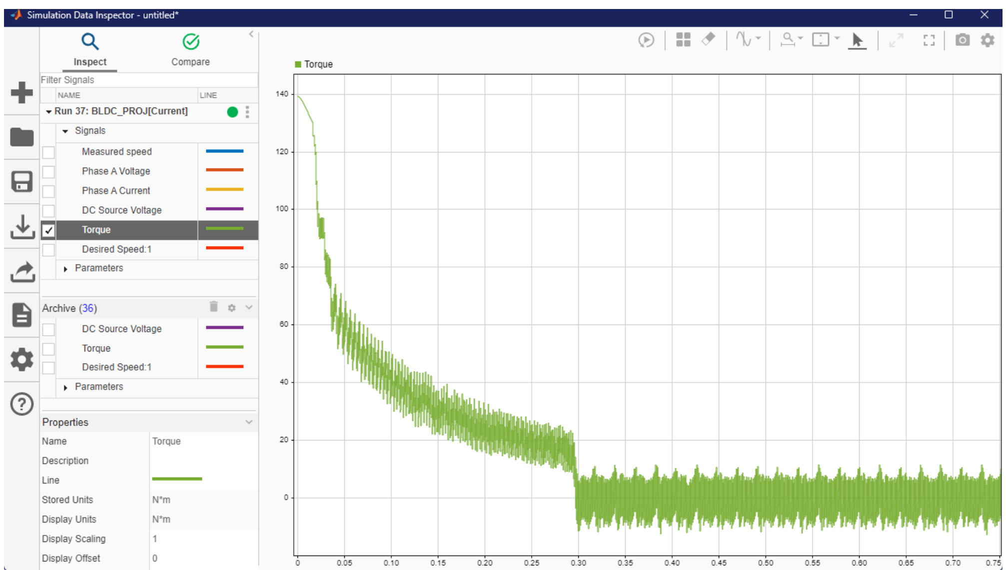

Figure 23: Torque Profile

Finally, the controller was tested to track varying desired speeds in the range 400-1200, the results are shown below:

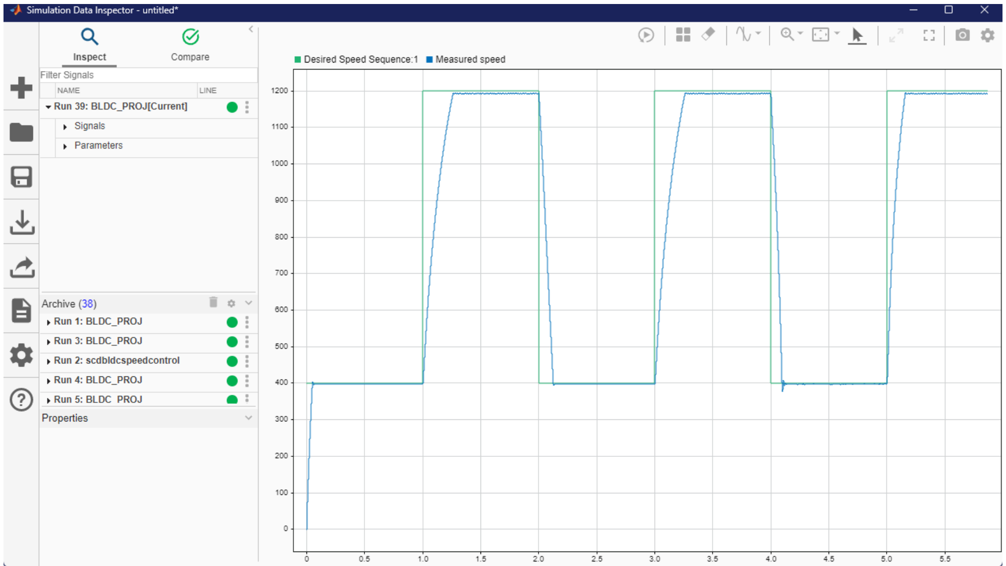

Figure 24: Desired Speed vs Actual Speed

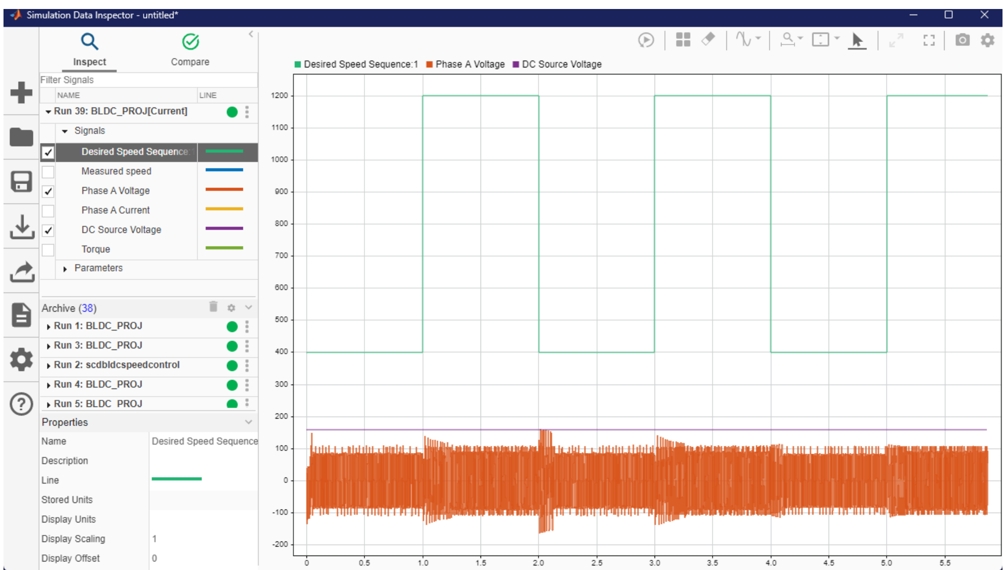

Figure 25: Phase A Voltage

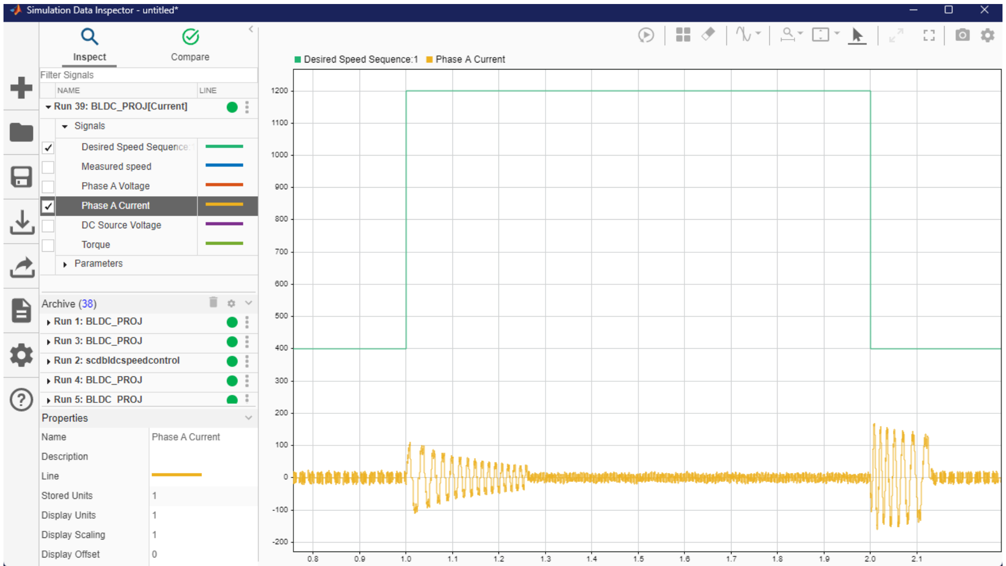

Figure 26: Phase A Current

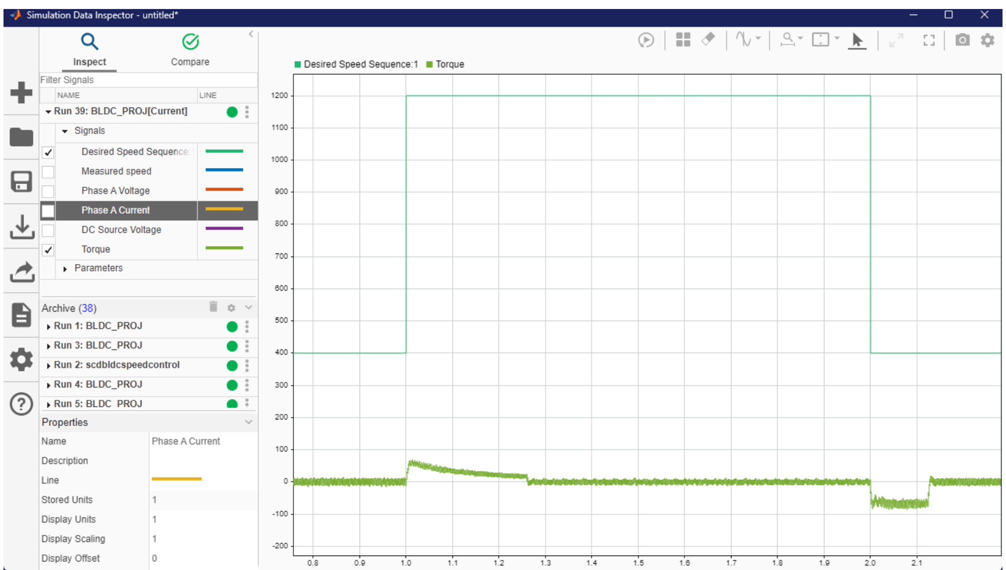

Figure 27: Torque Profile

As shown by the results, the controller was able to track varying speeds with satisfactory accuracy.

5 Conclusion

This project dealt with the design of an FLC to control the speed of a BLDC. The simulation of the model was implemented on MATLab's simulink. The BLDC used was a four pole-pair three phase BLDC as was commutated using six-sector commutation. The position of the rotor was measured as the integral of a motion sensor. The corresponding sector is output from a sensor block, which is in turn input to a commutation logic block. The commutation logic block determines the sequence of energizing the phases of the BLDC motor. The commutation logic outputs a pwm signal based on a duty cycle as well as the switching pattern which is input to a three-phase inverter block connected to the BLDC. The duty cycle is determined by a FLC which takes as input the error between the desired speed and current speed as measured by the sensor block and outputs a duty cycle to the commutation logic block. Several simulations were carried out to confirm the controller's accuracy where set speeds of 400, 1200 and varying speeds in the range 400-1200 rpms were tracked. Through the results obtained, the controller was able to track all the input speeds to a satisfying degree of accuracy.

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