Closed Loop Fault-Tolerant Algorithm for Brushless DC Motor Drives

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Abstract

DC motors can be either brushed type, which is mechanically commutated, or brushless, which is commutated electrically. In brushless DC (BLDC) motors, hall effect sensors are used in place of a mechanical commutator and brushes. The location of the rotor is detected by hall sensors in brushless dc motors. This study verifies a brand-new fault-tolerant control method that can function even if one or more hall sensors fail. Additionally, a speed estimation method that can estimate speed is also confirmed. By doing so, the necessity for a speed sensor is removed, improving the motor's dependability. The proposed method is significantly easier to apply to any of the hall sensors than existing methodologies. Simulations in MATLAB/Simulink confirm the effectiveness of the suggested approach.

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Chapter 1

Introduction

Electric Vehicles are a need in this climate-affected world. Electric vehicles(EVs) can reduce harmful greenhouse gas emissions while also reducing the dependence on imported petroleum for the transport sector. For driving Electric Vehicles, a reliable motor drive system is a must. There are four major types of electric motor drives used for EVs, Brushed DC Motor drives, induction motor drives, Switched Reluctance Motor Drives, and Brushless DC Motor (BLDCM) drives.

BLDCMs are incredibly appropriate for EVs due to their high power densities, speed-torque characteristics, high efficiency, and large speed ranges, and require little or no maintenance. Brushless construction leads to reduced motor size, control being possible, high reliability, and maintenance-free operation [1].

The commutation in the BLDC motor is handled by a power electronics converter rather than a mechanical commutator [2]. The rotor position, which can be determined by sensors or sensorless methods, is necessary for the converter to operate accurately. The back-EMF zero-crossing approach is the most popular sensorless method. Due to additional voltage and current sensors, the majority of sensorless techniques are complicated and occasionally expensive. The most widely used sensor-based techniques involve Hall effect sensors, which are inexpensive and simple to install. To determine the position of the rotor, hall sensors installed on a BLDC motor with a 120-degree phase difference are used. The gating pulses for the converter are established by decoding these hall sensors. In light of this, any failure of a hall sensor, which may result from a variety of factors including an intense working environment, vibration, defective connections, etc., will result in the motor operating unstably.

BLDC motors possess a significant advantage in terms of efficiency, capable of converting electrical energy to mechanical energy with up to 90% efficiency, surpassing AC or DC motors. This means that they provide the same level of power while consuming less energy, reducing carbon emissions and resulting in cost savings. To ensure their long lifespan, minimize maintenance costs, and provide reliable operation under harsh conditions, it is crucial to design and manufacture fault-resistant BLDC motors.

The failure of a BLDC motor due to faults can lead to significant downtime and costly repairs [3]. By developing BLDC motors with fault-resistant features like thermal protection, sensor feedback, and overcurrent protection, they can operate continuously and reliably, reducing the need for frequent maintenance and repairs.

In summary, developing fault-resistant BLDC motors is essential to improving performance under adverse operating conditions, enhancing safety in certain applications, and reducing maintenance costs and downtime.

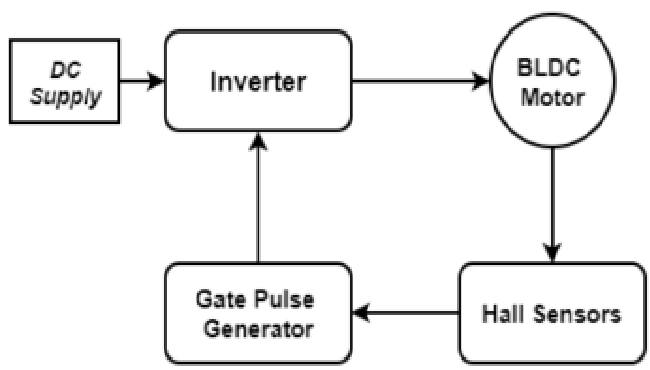

Figure 1.1: Block diagram of a BLDC motor

Figure 1.1 above depicts the basic block diagram of a BLDC motor drive. Therefore, a fault-tolerant control system that can diagnose the specific defect and is capable of reconstructing the signal is preferred in order to increase the dependability of the hall effect sensor-based BLDC motor.

Chapter 2

Literature Survey

The history of Brushless DC (BLDC) motors dates back to the 1960s when they were developed as a better alternative to brushed DC motors. However, it wasn't until the 1980s that BLDC motors became more widely used due to advances in electronics and magnetic materials.

The first commercial application of BLDC motors was in computer hard disk drives, where they were used for high-speed spindle rotation. In the 1990s, BLDC motors began to be used in automotive applications, such as power steering systems and cooling fans. Electric vehicles, drones, and robotics are a few of the applications that have seen an increase in the use of BLDC motors. This is because they surpass conventional brushed DC motors in terms of efficiency, low maintenance, lifespan, and high-speed performance.

Hall sensors are used to control the switching logic of a BLDC motor malfunction sometimes and fault identification and correction in these sensors are a major issue and work is being done on this.

These issues were first addressed as follows:

1. Early defect detection: In the early days of BLDC motors, fault detection was mostly focused on straightforward techniques such as manual motor performance monitoring or visual examination.

2. Development of diagnostic methods: In the 1980s and 1990s, as semiconductor technology advanced, diagnostic methods like temperature sensing, back-emf sensing, and motor current and voltage monitoring spread.

3. The incorporation of fault detection in motor controllers: In the 2000s, fault detection features for motor controllers became more readily accessible. To continually monitor motor

performance, identify defects, and initiate the necessary corrective steps, such as fault isolation, fault tolerance, or system shutdown, these controllers used complex algorithms.

Researchers started concentrating on developing fault-tolerant control methods for BLDC motors in the late 1990s and early 2000s, which could identify and correct faults in real-time. In order to identify changes in motor action and alter the control inputs accordingly, complex signal processing and control algorithms had to be developed.

Several papers were published emphasizing fault-tolerant systems for BLDC motors. A paper published in 2005 presented a fault detection and fault-tolerant control strategy for an interior permanent magnet (IPM) motor drive system used in electric vehicles.

A research paper by A. Tashakori and M. Ektesabi in 2013 suggests a fault-tolerant control system that can account for malfunctioning Hall effect sensors. The suggested system can change the motor drive system's control parameters to ensure stable operation even in the presence of faults and is built to identify and diagnose sensor problems. It offered a straightforward and efficient fault tolerant control scheme for BLDC motors which can compensate for failures of the Hall effect sensor. The suggested method enables steady operation even in the presence of sensor defects, which can increase the reliability and efficiency of motor drive systems.

Another paper published in 2018 by M. A. Hassanin, F. E. Abdel-Kader, S. I. Amer, and A. E. Abu-Moubarka, titled “Operation of brushless dc motor to drive the electric vehicle,”, presents a fault detection and correction technique for BLDC motors used in electric vehicles. The technique uses a sensorless control approach and detects faults in the motor phase windings by monitoring the motor current and voltage waveforms.

A paper released in the year 2020 by A. Mousmi, A. Abbou, and Y. El Houm presented a binary diagnosis technique for Hall effect sensors in BLDC motor drives. The technique uses a binary decision tree and machine learning algorithms to detect faults in the sensor outputs and correct them in real-time.

Several researchers have proposed various solutions for fault detection and correction of Brushless DC Motors. Methods for speed control and improved efficiency are also being proposed.

Chapter 3

BLDC MOTORS

The next version of a normal DC motor is a brushless DC motor (BLDC). Copper windings are present on both the stator and rotor of conventional DC motors. Carbon brushes are used for the commutation processes while the rotor rotates. In order to switch the rotor winding to have a positive torque, brushes help in the commutation process. However, brushes require more maintenance and are more prone to damage.

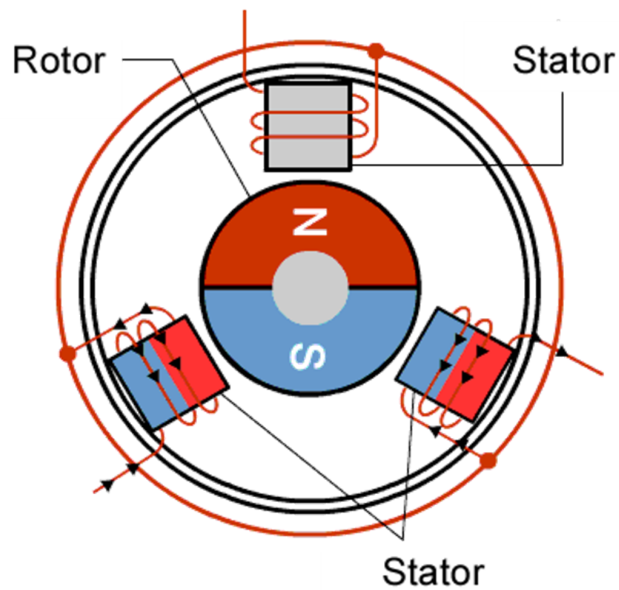

Figure 3.1: BLDC motor with rotor and permanent magnet (taken from [4])

There are no brushes in BLDC. By decreasing maintenance, we are doing away with brushes to create a better motor. The controller provides current pulses to the motor windings which maintains the control of speed and torque. Another difference from DC motors is that mechanical commutation is replaced by electrical commutation. Commutation with electronics has a large scope of capabilities and flexibility.

BLDC motor provides high efficiency in producing torque in large amounts in a wide speed range. Permanent magnets rotate around a fixed armature and this solves the problem of connecting current to the armature.

3.1 Merits of Brushless DC Motor

There are various reasons to prefer a BLDC motor in operations because of its merits.

1. Less overall maintenance due to the absence of brushes.
2. Reduced size with far superior thermal characteristics.
3. Higher speed range and lower electric noise generation.
4. It has no mechanical commutator and associated problems.
5. High efficiency and high output power-to-size ratio due to the use of a permanent magnet rotor.
6. High speed of operation even in loaded and unloaded conditions due to the absence of brushes that limits the speed.
7. Smaller motor geometry and lighter weight than brushed-type DC and induction AC motors.
8. Long life as no inspection and maintenance is required for commutator systems.
9. Higher dynamic response due to low inertia and carrying windings in the stator.
10. Less electromagnetic interference.
11. Low noise due to the absence of brushes.

3.2 Types of BLDC Motors

There are two types of BLDC motors.

1. Inner rotor motor
2. Outer rotor motors,

They differ only in design and their working principles are the same.

3.2.1 Inner Rotor Motor:

In an inner rotor design, the stator windings encircle the rotor, which is situated in the middle of the motor. Rotor magnets do not insulate heat inside, and heat dissipates easily because the rotor is located in the core. Because of this, inner rotor motors produce a lot of torque and generally, we use this type of motor more as compared to outer rotor motors.

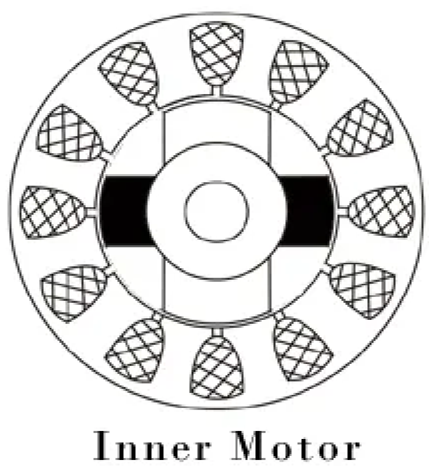

Figure 3.2: BLDCM Inner Motor

3.2.2 Outer Rotor Motor:

In this type of motor, the rotor surrounds the winding which is located in the core of the motor. The magnets in the rotor prevent the motor's heat from dissipating by trapping it inside. Such as a motor's low cogging torque and lower-rated operating current.

Figure 3.3: BLDCM outer rotor motor.

3.3 Working Principle and Operation of BLDC Motor

The construction of BLDC, like any other motor, has a stator and rotor. The stator (stationary part) will have a coil and the rotor (rotating part) will have magnets. The general working theory is that the interaction of the magnetic field between stator coils and rotor magnet will create torque which in turn makes the motor rotate. Its continuous rotation can be explained as follows:

- Assume the rotor is in the position shown in the figure above. The interaction between the north (Red) of the rotor and the south (Green), as well as vice versa, causes it to attract and maintain this position.
- The magnet's north pole is now aligned with the south of the stator when the stator's south is turned.
- The rotor can be made to rotate by continuously turning the stator pole. This is the basic explanation for how BLDC works.
- The stator coils must be linked to an inverter in order to rotate the stator pole. The stator pole is rotated or changed when the inverter changes the direction of the current in the motor.

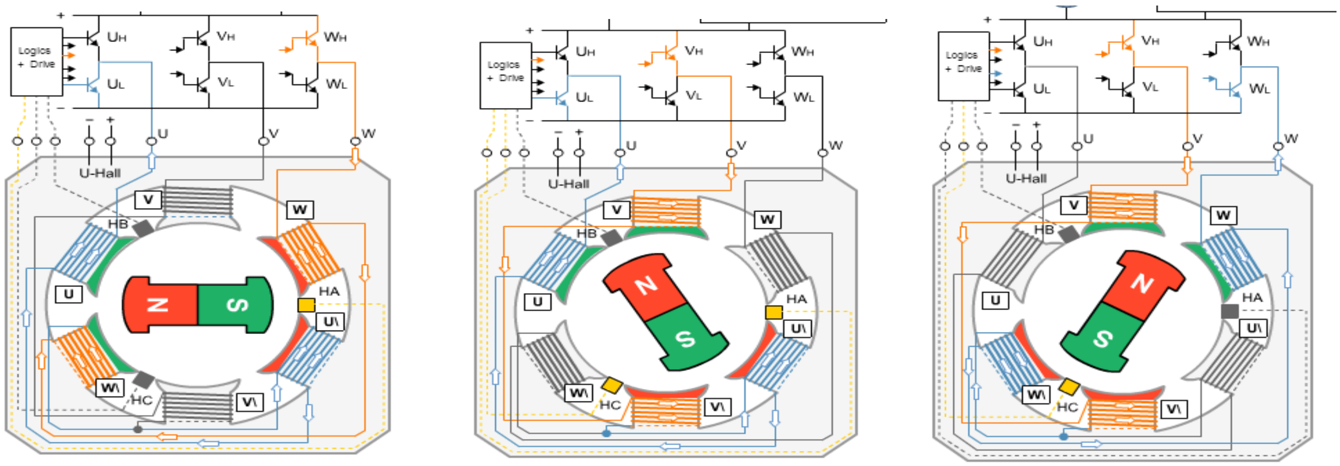

Figure 3.4:Three-Phase BLDC Motor Commutation.

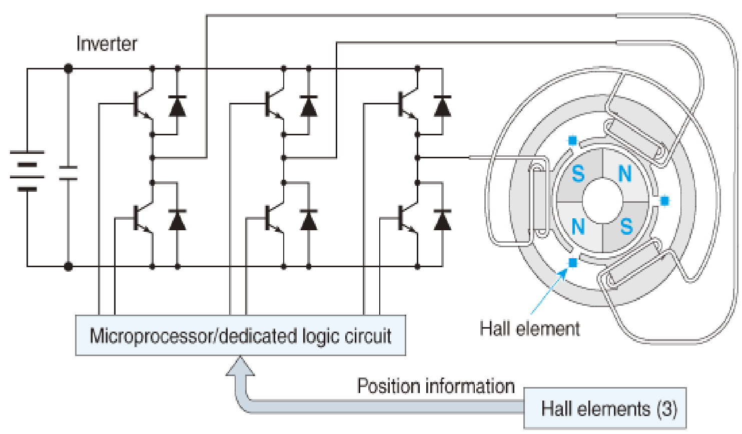

Figure 3.5:Inverter.

3.4 Types of BLDC Controls

3.4.1 Sensor BLDC Motor(Control Using Hall Sensors)

A Hall effect sensor is a transducer that varies its output voltage in response to a magnetic field. Hall effect sensors are used for proximity switching, positioning, speed detection, and current sensing applications. Hall sensor identifies the rotor position by sensing the magnets' polarity and then sends a signal to the power electronics controller so that the controller will excite the corresponding stator windings so that the torque is continuous. The advantage of the hall sensor is its semiconductor-based and also contactless sensing.

Hall sensor has three terminals. One is for power +5v and the other is for ground. The third terminal is variable which depends on the sensor facing a North Pole or South Pole. Depending on the north or South Pole faced, the hall sensor will be given either 1 or 0 as output. For BLDC motors, there are three Hall sensors placed electrically 120 degrees apart. Three sensors will give 8 combinations of binary numbers, they are 000, 001, 011, 010, 100, 101, 110, 111. The combinations 000 and 111 are ignored by the program and use other conditions and controller decodes to rotor position and then switch corresponding switches on to excite the related stator winding,

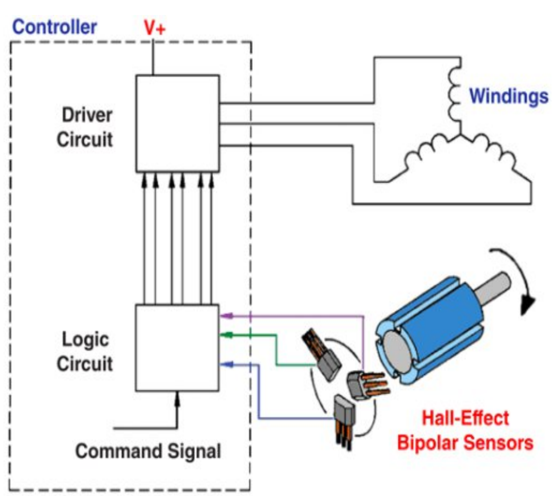

Figure 3.6:BLDCM with bipolar hall sensors(taken from [5])

As noted previously, depending on whether the sensor faces the north or south pole, the digital output will be +5 or 0V.

Its merits include:

1. Hall sensors are installed inside, which can detect the position of the rotor and start smoothly;
2. The motor can be started at zero speed with a Hall sensor.

If the rotor position is detected by the sensor, the sensor requires a wired connection to the controller unit through which it can send the signal. So sensors add additional hard-wired connections to the motor. The use of sensors and additional hard wires increases the machine size and also increases the cost of the controller unit.

3.4.2 Sensorless BLDC Motor

A brushless DC motor without hall effect sensors is a sensorless brushless DC motor (sensorless BLDC motor). Hall effect sensors are employed by sensored brushless motors to provide precise rotor position information to the brushless motor controller. This can be helpful for sustaining fixed speeds and is especially helpful during startup because the rotor position determines the motor's start-up procedure.

It has the following demerits:

1. Generally, sensorless motors do not perform well at low speeds, they provide better performance only at high speeds because when the motor is stationary, no back EMF is generated and so startup is affected by operating in an open loop and back EMF magnitude is small at low speeds, so it makes us difficult to measure which results in inefficient operation.

2. Circuit losses.

3. Delayed response due to filtering circuit.

3.4.3 Comparison

Sensorless BLDC MOTOR	Sensored BLDC MOTOR
A sensorless brushless DC motor has no built-in sensors.	A sensored brushless DC motor uses built-in hall sensors to identify the rotor position at any one time.
This means that the controller has to drive the motor without knowing the position of the rotor at startup.	This information is then sent to the controller which can then synchronize the motor drive directly to the position of the rotor.
No sensors are present.	Typically a motor will have 3 hall sensors, placed at 120-degree intervals around the rotor.

Table 3.1: Comparison table for different types of BLDC Control Motors

3. 5 Fault Detection in BLDC MOTOR:

Fault detection is an important aspect to maintain the performance of the BLDC motor and to maintain its efficiency. As in the case of the electrical vehicle if one of the hall sensors fails. It suddenly stops the motor. So it is very important to detect the fault in the BLDC motor and design a mechanism to resolve the fault when the motor goes in the faulted condition.

Ha	Hb	Hc	Active Switches	Sector
1	1	0	Q_1, Q_6	1
0	1	0	Q_3, Q_6	2
0	1	1	Q_3, Q_2	3
0	0	1	Q_5, Q_2	4
1	0	1	Q_5, Q_4	5
1	0	0	Q_1, Q_4	6

Table 3.2: Truth table of Hall sensors in case of healthy condition

If the motor runs in good condition without fault then the motor goes from sector 1 to 2 then 3 and so on and accordingly the switches get on which is more clearly elaborated with the help of the truth table so in a good working condition there is no state with Ha=1, Hb=1, and Hc=1 and there is also no state with Ha=0, Hb=0, and Hc=0, all together this two types of states do not occur in a good condition.

Ha	Hb	Hc	Faulted Sector	Sector
1	1	0	1	1
1	1	0	1	2
1	1	1	0	3
1	0	1	5	4
1	0	1	5	5
1	0	0	4	6

Table 3.3: Truth table of Hall sensors in case of faulted condition(Ha=1)

Therefore the fault detection method is based on these two conditions which occur in a faulted condition of the motor. ‘000’ and ‘111’ occurs only in the faulted condition(3.5.2). Also the no. of ‘1’ and ‘0’ does not exceed 3 in one electrical rotation in a healthy condition (3.5.1). So to detect this a digital logic has been designed in which Ha, Hb, and Hc are given as the inputs and if the sum comes equal to ‘0’ or ‘3’ then it is a faulted condition that needs to be eliminated for proper functioning of the motor.

3. 6 Algorithm for Fault Clearing in BLDC motor:

- **Fault detection:** Any malfunction of inverter switches or the hall sensors during high-frequency PWM switching effects directly on the applied voltage of the BLDC motor.
- **Corrected Gate Pulse Generation System:** This system takes over when the fault is detected i.e. F=1, the gate pulses are generated based on the generated hall signals, Haa, Hbb, and Hcc from the corrected sector value instead of actual hall signals. Once fault is detected, the sector value is updated using k and n using before fault values of n.

- **Speed estimation system:** It is necessary for the closed-loop speed control to know the motor's actual speed and compare it with the reference speed. However, the time required will be more significant by using the mechanical speed sensor that leads to slow control over the motor. So it is better to go with the speed estimation technique.

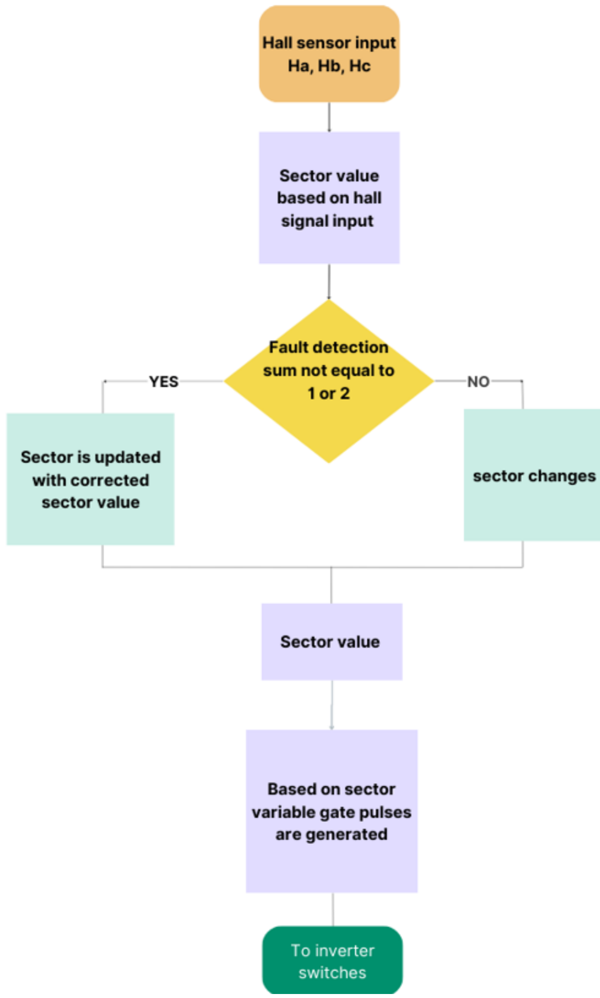

Figure 3.7:Flowchart of the process

Chapter 4

Results

The schematic for a fault-tolerant control system for a BLDC motor drive system consists of several blocks as shown in Figure 4.1, that work together to control the speed and torque of the motor. These blocks can include:

- **PI Speed Controller:** The Proportional-Integral (PI) Speed Controller is responsible for regulating the speed of the BLDC motor by adjusting the current sent to the motor based on the difference between the actual and desired speed.
- **PWM Current Controller:** The Pulse Width Modulation (PWM) Current Controller generates the signals that control the power electronics block by modulating the width of the pulses in the output waveform, which regulates the current flowing through the motor.
- **Inverter**: The Inverter is a power electronic circuit that converts the DC voltage from the power supply into AC voltage to drive the BLDC motor.
- **Fault Tolerant Block:** Generates corrected sector with fault detection and isolation mechanism, used in BLDC motor control systems to ensure reliable and efficient operation even in the presence of faults such as sensor failures.

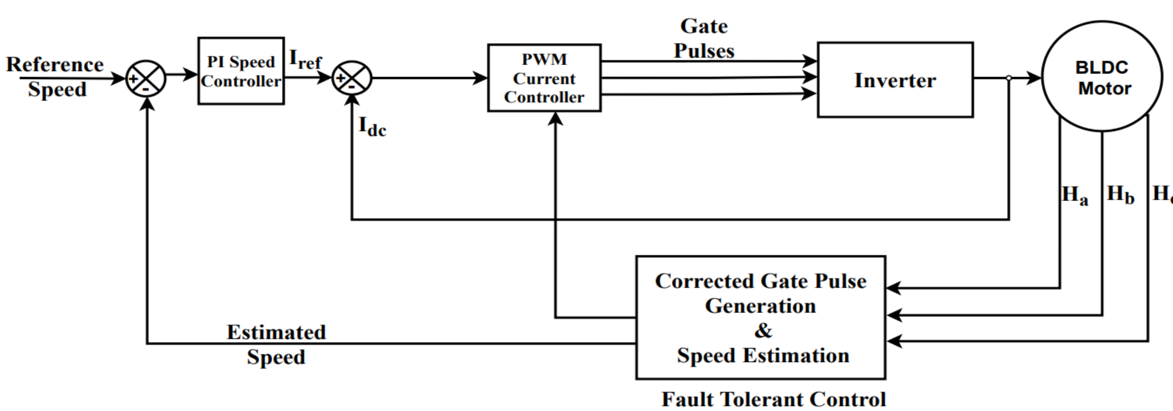

Figure 4.1: Schematic of BLDC fault tolerant control system.

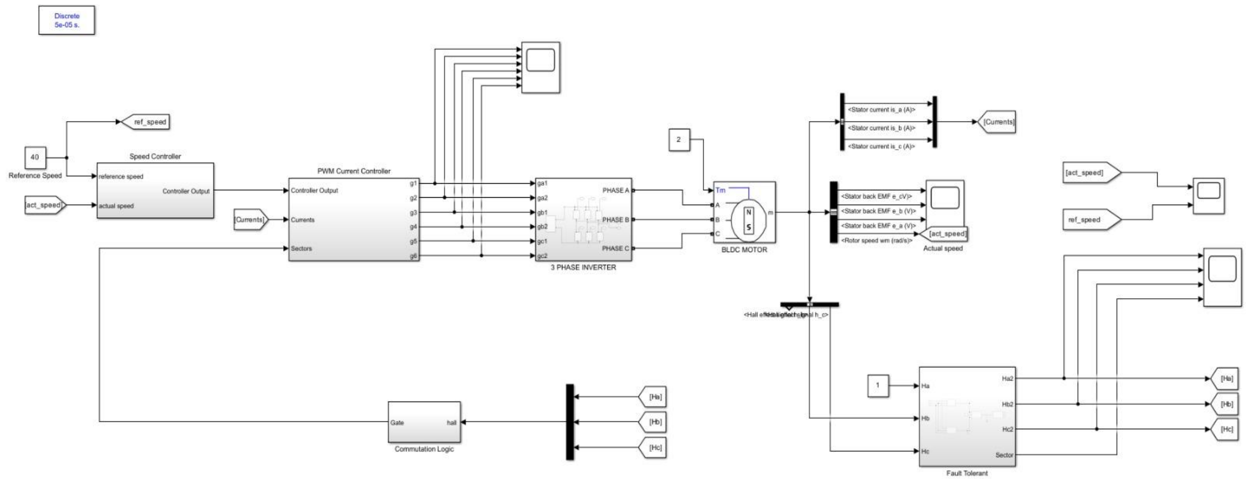

Figure 4.2: Simulation of BLDC fault tolerant control system

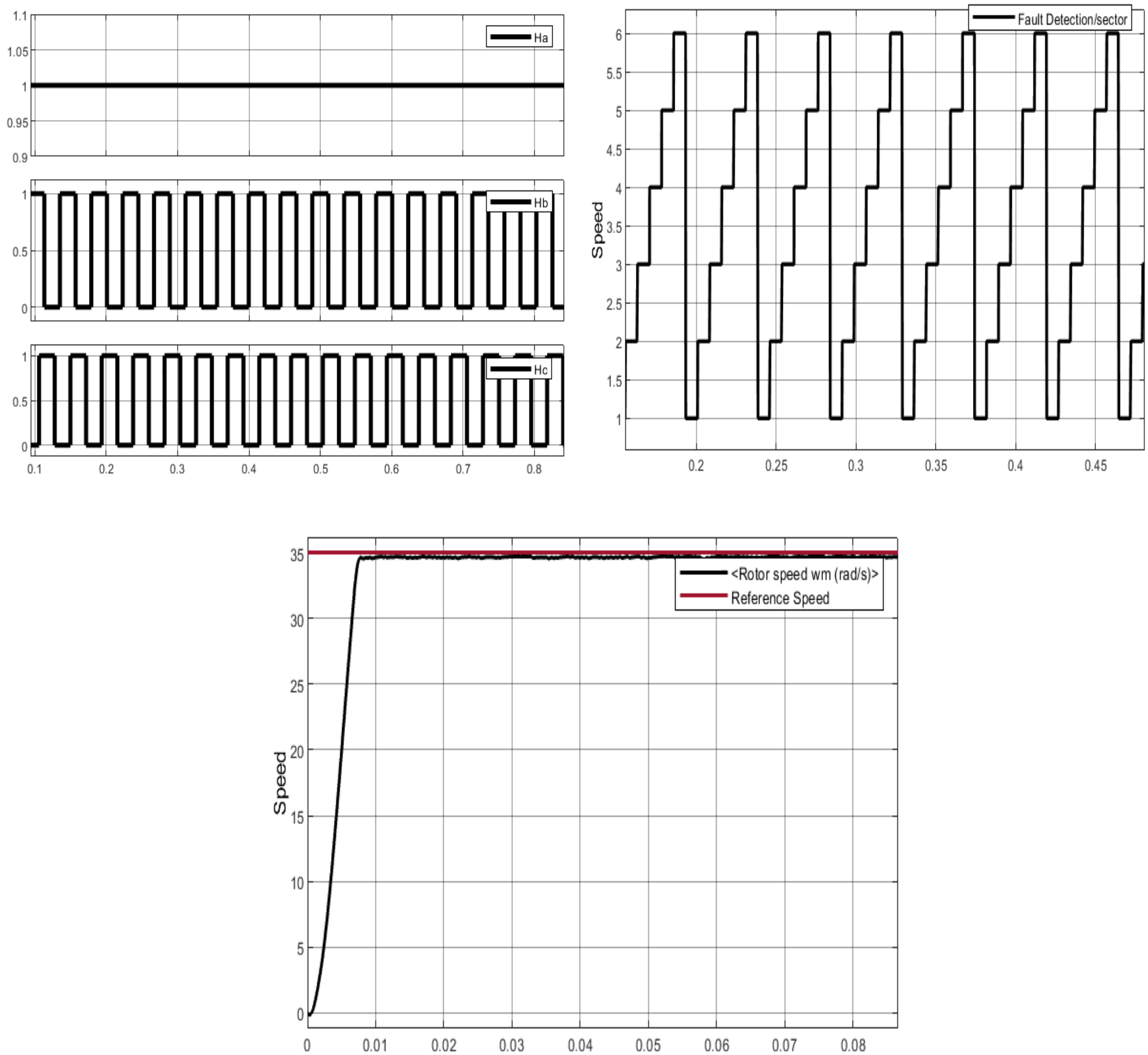

Figure 4.3:Matlab Simulation Results: Hall Sensor Ha, Hb, Hc as Inputs, Sector Count Value, Actual Speed, and Reference Speed with respect to time when Ha=1 fault introduced.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The hall sensors play a major role in running the BLDC motor continuously. As per the novelty of the paper, our Matlab simulation works fine even when the sensor fails and also the motor maintains the same speed as that of the pre-fault speed which also eliminates the need for sensors that increases the reliability of the system.

5.2 Future Work

As we are all aware of that, while designing any particular system there will be certain parameters that need to be taken care of that may be efficiency, reliability, or performance of the system. In our project, we have designed the fault detection system, but the speed of the motor is not the same as the reference speed to its full extent as we can observe a little amount of ripple in the speed graph. So, this ripple in the speed can be removed by implementing an algorithm that adjusts the commutation logic so that it helps in achieving the exact desired speed and thereby the efficiency of the system can be improved. For the fault analysis and correction, we have used a repeating sequence(which is not 100% efficient), instead, there might be a block placed in which the fault detection and correction algorithm(like machine learning algorithms) can be implemented efficiently so that the block can be directly connected to our system. The machine learning algorithms can provide early warnings and thus enable corrective time actions to diagnose the faults. Not only this, our fault system can be extended for predictive maintenance capabilities which involves predicting the motor performance data which tells us when the maintenance will be needed and scheduling will be required so that the faults can be prevented.

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