Fault tolerant control system for Hall Effect Position sensors failure of BLDC Motor

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Abstract- *Brushless DC (BLDC) motors are vastly used nowadays in applications that require high reliability, high efficiency, and high power-to-volume ratio. Theses motors follow a unique sequencing and switching mechanism and hence must be electronically commutated. A BLDC motor is hence highly reliable because it does not have any brushes that can wear out decreasing the longevity of motor. Whenever a motor breaks down or needs to be replaced, the project, or a part of it must be shut down. Hence there is a trade off between time and cost. BLDC motors may be with or without Hall Effect sensors. Hence the classification Sensor based BLDC and Sensor less BLDC motors. Sensor less BLDC motors are electronically commutated and use three main types of commutation techniques depending on the detection of Back EMF (Electro-motive force): trapezoidal commutation, sinusoidal commutation and vectorial commutator .The brushes and commutator have been eliminated and the windings are connected to the electronics. The control Electronics replace the function of commutator and energize the proper windings. The motor has less inertia, therefore easy to start and stop. BLDC motors are permanently cleaner, faster, more efficient, less noisy and more reliable. The brushless DC motor is driven by rectangular or trapezoidal voltage strokes coupled with rotor position. The voltage strokes must be properly aligned, between the phase a, so that the angle between the stator flux and rotor flux is kept close to 90 degree, to get maximum developed torque. BLDC Motor considered in these models is star connected with neutral grounding, but several applications require isolated neutral. Keeping merits of these developments in view, in this paper the motor with windings placed in the slots that are axially cut along the inner periphery or around stator salient poles. In the brushless DC motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Although dc motors possess good control characteristics and ruggedness, their performance and application in wider areas is inhibited due to sparking and commutation problems. The permanent magnet machines have the features of high torque to size ratio and possess very good dynamic characteristics due to low inertia in the permanent magnet rotor and better power factor and better output power per unit mass & volume without sacrificing the reliability. A brush less dc motor is defined as a permanent synchronous machine with rotor position feedback. The brushless motors are generally controlled using a three phase power semiconductor bridge. The motor requires a rotor position sensor for starting and for providing proper commutation sequence to turn on the power devices in the inverter bridge. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. Instead of commutating the armature current using brushes, electronic commutation is used for this reason it is an electronic motor. This eliminates the problems associated with the brush and the commutator arrangement. In this paper the four quadrant operation and regenerative braking achieves of a three phase (star connection) permanent magnet BLDC motor with the inbuilt Hall Effect sensor are explained.*

Keywords- BLDC Motor. Hall Effect. Sensors and dsPIC30F2010/

I. INTRODUCTION

BLDC MOTOR

Figure 1 is a simplified illustration of BLDC motor construction. A brushless motor is constructed with a permanent magnet rotor and wire wound stator poles. Electrical energy is converted to mechanical energy by the magnetic attractive forces between the permanent magnet rotor and a rotating magnetic field induced in the wound stator poles.

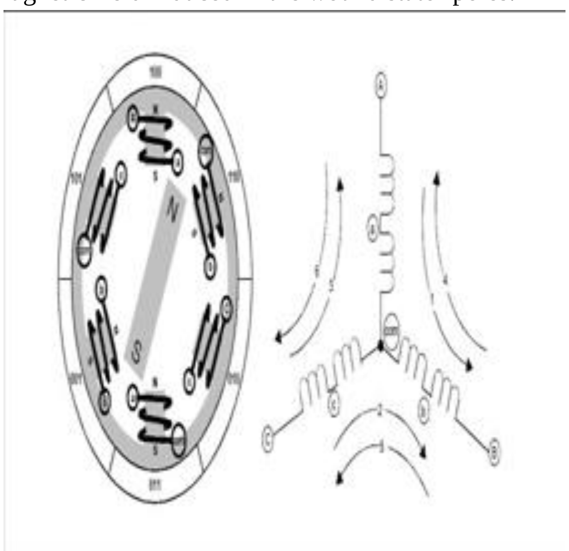

Figure 1- BLDC motor construction

The key to BLDC commutation is to sense the rotor position, then energize the phases that will produce the most amount of torque. The rotor travels 60 electrical degrees per commutation step. The appropriate stator current path is activated when the rotor is 120 degrees from alignment with the corresponding stator magnetic field, and then deactivated when the rotor is 60 degrees from alignment, at which time the next circuit is activated and the process repeats. Commutation for the rotor position, shown in Figure 1, would be at the completion of current path 2 and the beginning of current path 3 for clockwise rotation. Commutating the electrical connections through the six possible combinations, numbered 1 through 6, at precisely the right moments will pull the rotor through one electrical revolution. In the simplified motor of Figure 1, one electrical revolution is the same as one mechanical revolution. In actual practice, BLDC motors have more than one of the electrical circuits shown, wired in parallel to each other, and a corresponding multi-pole permanent magnetic rotor. For two circuits there are two electrical revolutions per mechanical revolution, so for a two circuit motor, each electrical commutation phase would cover 30 degrees of mechanical rotation

BLOCK DIAGRAM

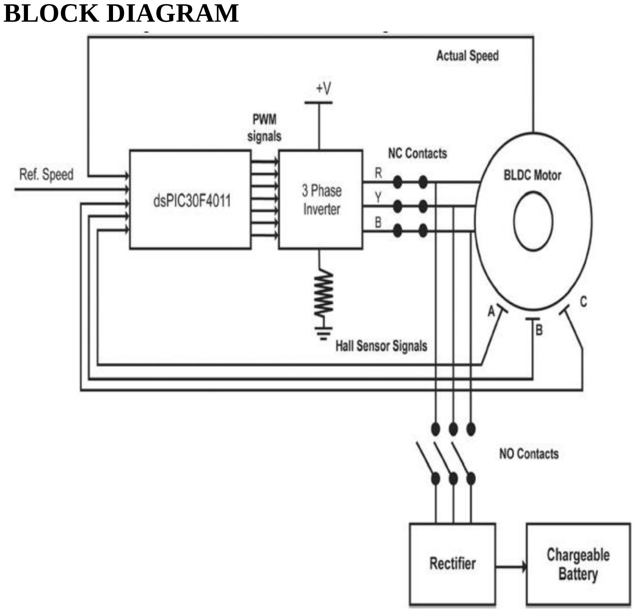

Figure 2- Block diagram of control

The in runner configuration consists of three stator windings located around the rotor, with permanent magnets as a part of the rotor. The out runner has a reversed relationship between the magnets and the coils. The permanent magnets rotate inside a suspended rotor surrounding the core of the Brushless DC Motor. Internally, a 3-phase motor can be configured to a "Wye" or "Delta" configuration. The primary advantage to the "Wye" configuration, also known as the Star configuration, is that the phase-to-neutral voltage is equal in all three legs. The arrangement is a parallel circuit in a shape of the letter Y, where all windings are connected at a central point, and power is applied to the remaining windings.

The dspic30F2010 digital controller is used for control and determines the motor operation for different quadrant and regenerative braking. When the regenerative braking is applied normally closed (NC) contacts opens and normally open contacts (NO) contacts closes, hence wasting kinetic heat energy wasted in the motor the back EMF voltage utilized by three phase rectifier circuit to charge the battery. In fact the wasted energy is conserved and saving in regenerative braking operation. The arrangement of schematic diagram as shown in the figure.

II. HARDWARE DESCRIPTION

The BLDC motor is driven using a dsPIC30F2010 the six MCPWM outputs are connected to three MOSFET driver pairs (IR2101S), which in turn are connected to six MOSFETs (IRFR2407). These MOSFETs are connected in a three-phase bridge format to the three BLDC motor windings. In the current implementation, the maximum MOSFET voltage is 70 Volts, and the maximum MOSFET current is 18 Amps. It is important to note that adequate heat dissipation must be provided if the maximum capabilities are being used. MOSFET drivers also require a higher voltage (15V) to operate, so this voltage level needs to be provided. The motor is a 24V BLDC motor so the DC+ to DC- bus voltage is 24V. A regulated 5V is provided to drive the dsPIC30F2010. The three Hall effect sensor inputs are connected to input pins that have Change Notification circuits associated with them. These inputs are enabled along with their interrupt. If a change occurs on any of these three pins, an interrupt is generated.To provide a speed demand, a potentiometer isconnected to an ADC input (RB2). To start and stop the motor, a push button switch is provided at RC14. To provide some current feedback to the motor, a low value resistor (25 milliohms) is connected between the DC- bus voltage and ground or Vss. The voltage generated by this resistor is amplified by an external opamp(MCP6002) and fed to an ADC input (RB1).

III. FIRMWARE DESCRIPTION

Two firmware programs are included in Appendix A and Appendix B to illustrate the methods described in the Application Note. One program uses open-loop speed control. The other uses proportional and integral feedback for closed loop speed control. The open-loop method is generally not practical for actual applications. It is included here primarily to illustrate the BLDC motor drive methodology. Open-Loop Control In open-loop control, the MCPWM directly controls motor speed based on the voltage input from the Speed Pot. After initializing the MCPWM, ADC, Ports and the Change Notification inputs, the program waits for an activation signal (e.g., a key press) to indicate a start (see Figure 7). When the key is pressed, the Hall sensors are read. Based on their value, a corresponding value is retrieved from the table and written to the OVDCON. At this point the motor starts spinning. The Hall effect sensors are connected to the Change Notification Pin. The CN interrupt is enabled. As the rotor spins, the position of the rotor magnet changes, and the rotor enters a different sector. Each new position is signalled by a CN Interrupt. In the CN Interrupt routine, which is shown in Figure 9, the Hall effect sensors are read and based on the value, a table lookup value is got and written to the OVDCON register. This action will insure that the correct windings are excited in the right sector and the motor will continue to spin.

IV. WORKING

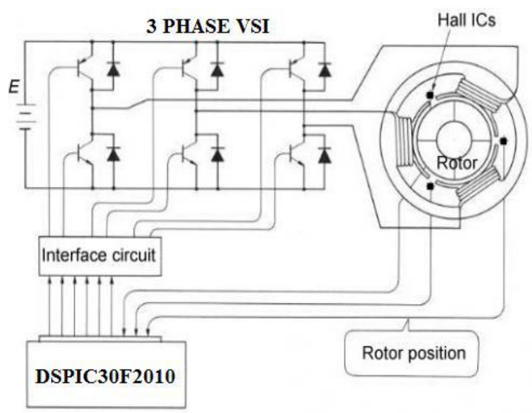

Figure 3- working model of BLDC motor

BLDC motors are controlled either using inverters or switching power supply, which results in an AC electric signal to drive the motor. Here AC (alternating current), doesn't refer to a sinusoidal waveform, but is rather a bi-directional current with no restriction on the waveform. In the proposed design a Half Effect sensors based BLDC motor is used. The motor comes with 120 degree phase differences to detect rotor position. The Output of each sensor is high i.e logic „1" for first 180 electrical degree and is low i.e logic „0" for the next 180 degree with respect to rotor position. Here the failure of Hall Effect sensors is detected when the sensor value becomes high while the motor is rotating continuously The proposed fault tolerant control system should be capable of doing the following tasks i.e. fault detection, fault identification and remedial strategies. In this paper position sensor failure of a three phase (star connection) permanent magnet BLDC motor with the inbuilt Hall Effect sensors is discussed. There are a few research works on Hall Effect sensor failure of BLDC motor specifically for electric vehicle applications. Jeong et al. have presented a control strategy that provides fault tolerance to the major sensor faults which may occur in an interior-permanent-magnet-motor (IPMM)-based electric vehicle propulsion drive system. Position sensors fault is detected through difference between the estimated rotor angle and the actual measured one through a sensor less algorithm based on extended EMF in rotating reference frame. In this approach reconfiguration to sensor less control scheme is introduced to rectify the fault and maintain the proper operation of the motor after fault occurrence is detected. Complexities of sensorless control scheme and transition Algorithm to senseless control is the main drawbacks of the proposed method. A three phase low voltage BLDC motor is used as a practical test motor to validate simulation results. BLDC motor is simulated in Simulink using Simpower Systems library. The three phase variable source inverter drive of BLDC motor is simulated using MOSFET switches. The source to the BLDC motor is AC supply which is converted to DC through VSI. Here six switch 3 legs inverter is used. MOSFET is used as switch in order to control the speed of the motor .The speed of the motor is controlled through pot speed controller which is interfaced to DSP.Starting of motor and controlling the direction of rotation of motor is controlled using motor start key and direction control key. The output of hall sensors is indicated through LED"s interfaced to controller. BLDC motor is connected to the controller through BLDC motor driver i.e. voltage source inverter. The controller used here is DSPIC30F2010, which is an 28 pin IC. A very good quality of this controller compared to the other controller is, it has in build 10 bit ADC with six input channels. Also it has 6 in built PWM channels. PWM signals are generated by the controller in order to operate the switches in particular sequence. Hall sensor signals are given to the controller through cut-off switches. The hall sensor signals are indicated through LED"s interfaced to controller. If the hall sensor fails the cut-off switch will disconnect the particular signal from sensor.

BLDC motor control:

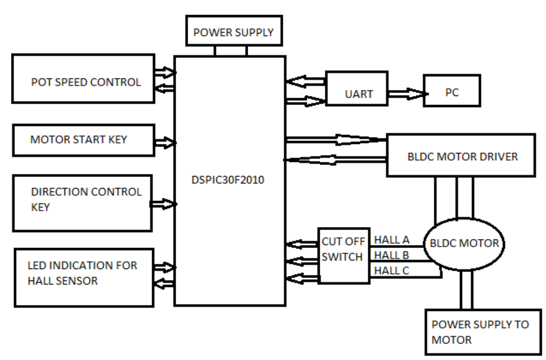

Figure 4- BLDC motor control

An electronic Brushless DC Controller (also known as a basically it is an electronic motor and requires a three-phaseinverter in the front end as shown in Fig. 2. In self-control mode the inverter acts like an electronic commutator thatreceives the switching logical pulse from the absolute position sensors. The drive is also known as an electronic commutated motor. Basically the inverter can operate in the following two modest they are 1200 angle switch-on mode and Voltage and current control PWM mode

V. FOURQUADRANT OPERATION

There are four possible modes or quadrants of operation using a three phase Brushless DC (BLDC) Motor. In 1stQuadrant positive speed and The torque is positive hence the motor rotates in the forward direction. . In 2nd Quadrantmotor is rotating in the forward direction, but torque is being applied in reverse. Reverse Torque is applied to “brake”the motor, and the motor is now generating power. In 3rd Quadrant negative speed and negative torque. In thiscondition the motor is rotating in reverse direction. in 4th Quadrant exactly the opposite. The motor is rotates in thereverse direction, but the torque is being applied in the forward direction. Again, torque is being applied to attempt toslow the motor and change its direction to forward again. Once again, power is being generated by the motor.The three phase brushless DC (BLDC) motor is initially made to rotate in forward direction, but when the speed command is given reverse, the control goes into the forward braking mode hence current flows from motor to battery , in this case the rotor comes to the standstill position is term named as forward braking or regenerative braking. Instead of waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Similarly for when the motor rotates in the reverse direction, but when the speed command is given positive, the controller goes into reverse regeneration mode, in this case the current is flows from motor to source.

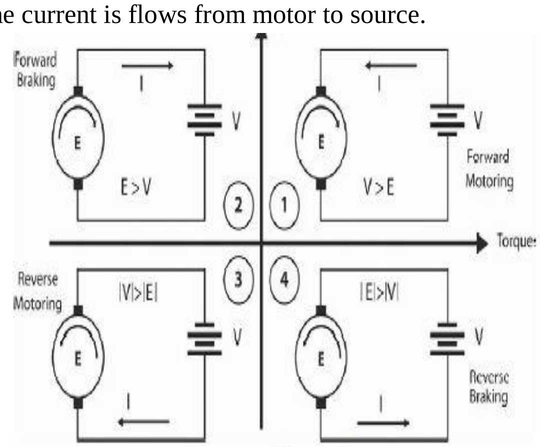

Figure 5- Four quadrant operation

VI. HALL EFFECT SENSORS

To move the rotor in the commanded direction, the drive will send current through two of the motor’s stator coils. This current produces electromagnetic fields that develop a torque on the rotor, and the rotor turns. The rotor will stop if it can reach a position where its permanent magnets are next to the magnetic fields that attract them. Before the rotor can get to this position, though, the drive switches the current to a new combination of stator coils, and creates a new set of electromagnetic fields that cause the rotor to continue its movement. The process of continually switching current to different motor coils to produce torque on the rotor is called commutation. If the drive knows the position of the rotor’s permanent magnets, it can set up magnetic fields in the stator that have the correct location and polarity to cause the rotor to turn. How can the drive know rotor position? Three Hall Effect sensors located in the motor are affected by the rotor’s permanent magnets. The three sensors transmit a unique pattern of signals for each rotor position. The drive uses these signals to determine the position of the rotor. There are three Hall Effect sensors inside of a motor. The next figure shows a conceptual drawing of the inside of the motor, and the three sensors. For clarity, the stator is depicted in simplified form, without its coil windings. The Hall effect sensors are located at one end of the stator, near the pole faces of the rotor. They are positioned approximately as shown in the figure. Five wires are shown for making connections to the Hall sensors. Three wires are for individual outputs. The fourth and fifth wires are for +5VDC and Ground, which are internally connected to all three sensors. Note that Hall #3 is positioned between Hall #1 and Hall #2.Most servo motors do not use Hall effect sensors. Instead, the motor's encoder has an extra commutation track, with three outputs. These outputs mimic signals that would be obtained from Hall sensors; in fact, the outputs are called Hall outputs.

TIMER: A 16-bit timer has the ability to generate an interrupt on period match. When the timer count matches the period register, the T1IF bit is asserted and an interrupt will be generated, if enabled. The T1IF bit must be cleared in software. The timer interrupt flag T1IF is located in the IFS0 control register in the Interrupt Controller. When the Gated Time Accumulation mode is enabled, an interrupt will also be generated on the falling edge of the gate signal (at the end of the accumulation cycle).Enabling an interrupt is accomplished via the respective timer interrupt enable bit, T1IE. The timer interrupt enable bit is located in the IEC0 control register in the Interrupt Controller.9.5 Real-Time ClockTimer1, when operating in Real-Time Clock (RTC) mode, provides time-ofday and event time stamping capabilities. Key operational features of the RTC are:

- Operation from 32 kHz LP oscillator
- 8-bit prescaler
- Low power
- Real-Time Clock Interrupts
- These Operating modes are determined by setting the appropriate bit(s) in the T1CON Control register

Simulink Model

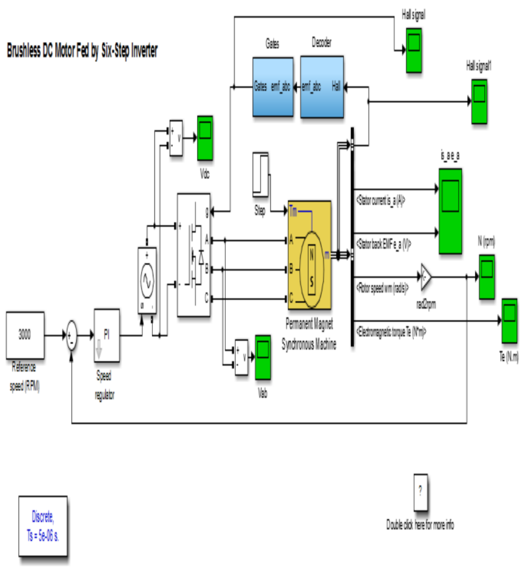

Figure 6: simulink model

The addition of Hall signals introduced by (1) is a fault signature for Hall Effect sensors breakdown. Maximum possible value of Hf is 2, where the minimum possible value is 1 (value of Hf should be 1 or 2) for each specific electrical angle section. If Hf value goes over of these limits Hall Effect sensor failure is detected. Hall Effect sensors Fault Flag (HFF) is introduced for sensor fault detection. HFF is set to "1" if Hf value is more than 2 (it means that one of the position sensor signals is constant one), HFF is set to "-1" if Hf value is less than 1 (it means that one of the position sensor signals is constant zero) and HFF is "0" in case of no fault. Maximum fault detection time is the time of on electrical rotation of rotor which is quite fast. HF=HA+HB+HC

Case 1: Hall Effect Signal is Constant Zero

BLDC motor is tested for the case 1 where the hall signal output is constant 0. Hall Effect sensor fault of phase A (HA=0) is applied to BLDC motor running at 3000 RPM speed. Hall Signal at constant 0 is shown

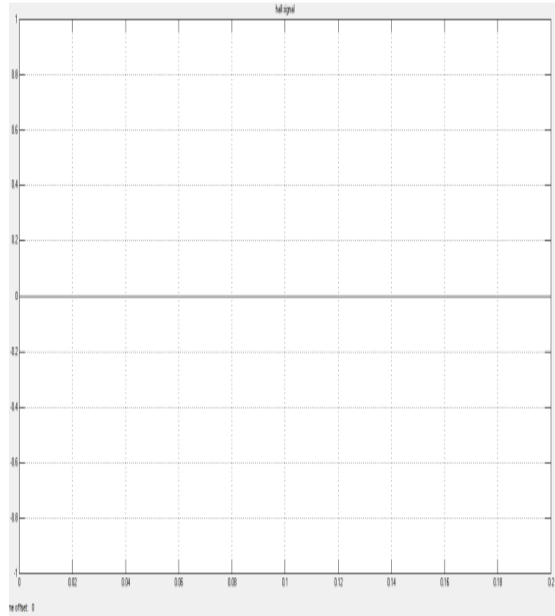

Figure 7**:** Hall Effect Signal is Constant Zero

The controller designed in this paper detects the fault in sensor, and then it is capable of generating the signal corresponding to the particular hall sensor as we have taken Hall sensor of Phase A (Hall A).After the signal generated by controller, the hall signal is shown above

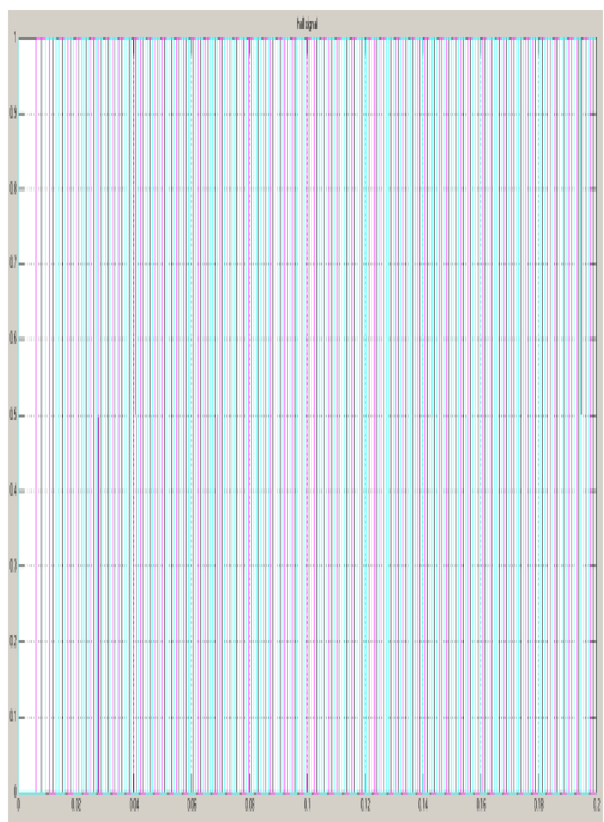

Figure 8- Hall sensor signal after fault is corrected

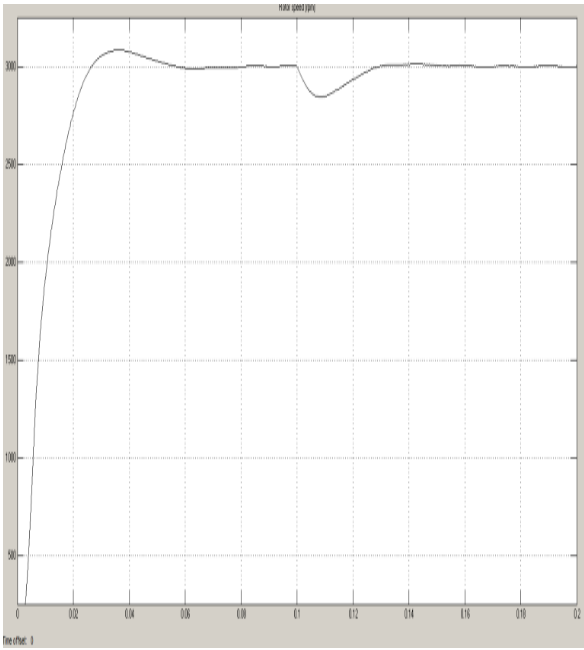

Figure 9- Speed and Torque characteristics (HA=0)

Hall Effect sensor failure causes change of the switching signals of VSI and effect directly on the applied line voltage. Effect of various Hall Effect sensors fault on the switching signals of VSI is given in Table II. Switching signals S1 and S6 are constant zero (switches S1 and S6 remain open circuit) for HA = 0 fault

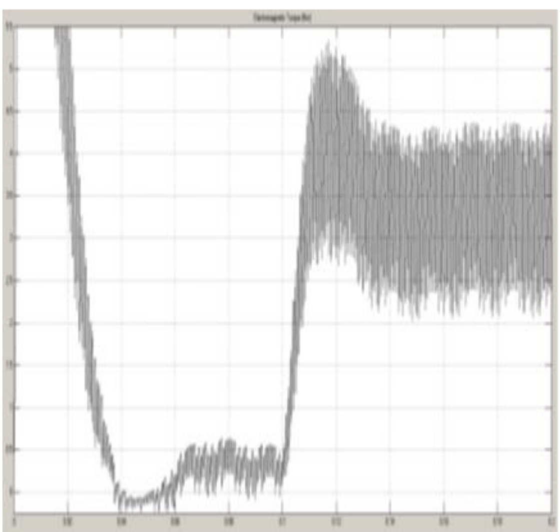

Figure 10-

condition. Change of applied voltages cause variation of the stator phase currents of the
BLDC motor that effects directly on electrical torque of motor and increases torque ripple.

Case 2: Hall Effect Signal is Constant One

BLDC motor is tested for the case 2 where the hall signal output is constant 1. Hall Effect sensor fault of phase A (HA=1) is applied to BLDC motor running at 3000 RPM speed.

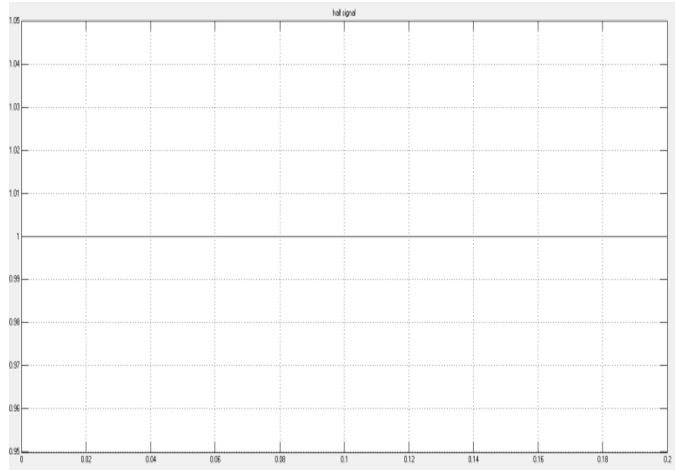

Figure 11- Hall Signal at constant 1

It can be seen that speed and torque responses of BLDC motor for HA = 1 are quite similar to the ones for HA = 0 fault condition. However by checking switching signals of VSI, it can be observed that switches S2 and S5 are constant zero (switches S2 and S5 remain open circuit) after fault occurrence which are not the same as previous fault condition. Therefore applied voltages to the motor are completely different for HA = 1 fault condition.

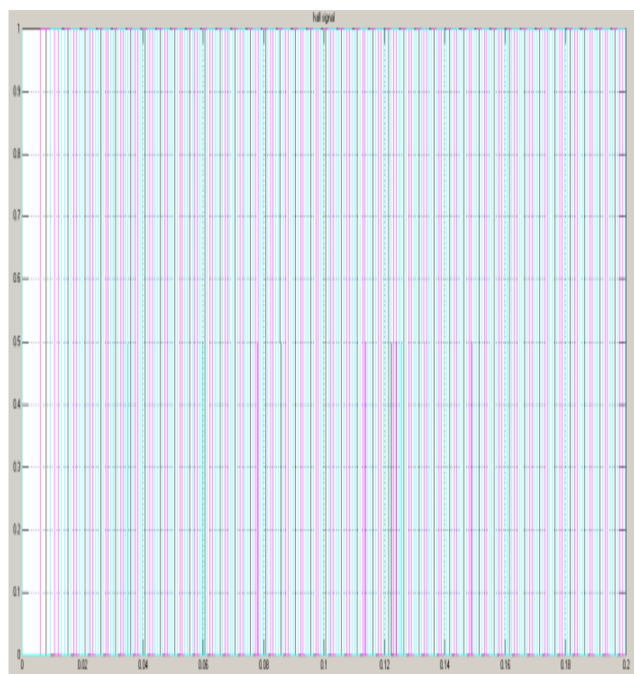

Figure 12- Hall sensor signal after fault is detected

The speed and torque curve for case 2 is shown in the below figure

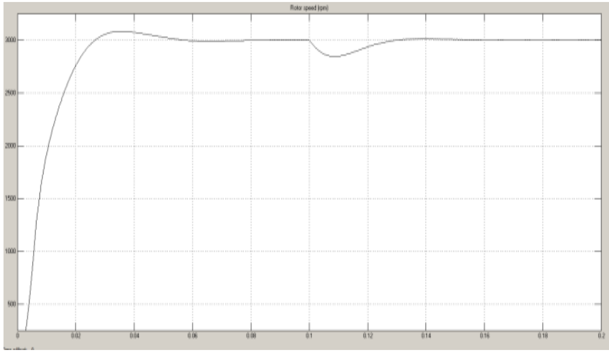

Figure 13-Speed and torque characteristics (HA=1)

FAULT DIAGNOSIS:

A three phase low voltage BLDC motor is used as a practical test motor to validate simulation results. BLDC motor is simulated in Simulink using SimPower Systems Library. If the position sensor fails, it causes the output signal either to be constant high (logic 1) or constant low (logic 0). The output of the position sensor does not change according to the change in the rotor position. Therefore simulation is carried out for both the cases i.e. for both logic 0 and logic 1. Here simulation is done for the failure of Hall Effect position sensor of phase A. The simulink model is shown in Fig.3.A three phase low voltage BLDC motor is used as a practical test motor to validate simulation results. BLDC motor is simulated in Simulink using SimPower Systems Library. If the position sensor fails, it causes the output signal either to be constant high (logic 1) or constant low (logic 0). The output of the position sensor does not change according to the change in the rotor position. Therefore simulation is carried out for both the cases i.e. for both logic 0 and logic 1. Here simulation is done for the failure of Hall Effect position sensor of phase A. The simulink model is shown in Fig.3 Electronic commutation is done by decoding the position sensor signals. Decoding rules of Hall Effect signals to choose a proper switching vector of VSI are shown in Table 1.

Table-1: Decoding rules of Hall Effect signal

ROTORANGLE (ELECTRICAL DEGREE)	HALL A	HALL B	HALL C	COND SWITCHES
30-60	1	0	1	S1,S4
90-150	1	0	0	S1,S6
150-210	1	1	0	S3,S6
210-270	0	1	0	S3,S2
270-330	0	1	1	S5,S2
330-30	0	0	1	S5,S4

VII. CONCLUSIONS

Fault tolerant control system for Hall Effect position sensors failure of BLDC motor is discussed in this paper. Behavior of BLDC motor is studied for position sensor failure situations. BLDC motor is implemented on the verified simulation model. A knowledge based table is developed to identify the faulty sensor by analyzing the simulation results. As BLDC motor runs according to the signal generated from hall sensors. If any of the one sensor fails then it directly effects on the performance of the motor. As BLDC motor runs according to the signal generated from hall sensors. If any of the one sensors fails then it directly effects on the performance of the motor. The controller in this project detects, identifies the fault in hall sensors. After identifying the fault, controller will generate the signal corresponding to the faulty sensor output so that it won't affect the performance of the motor. In real time applications, there will be chances of failure of hall sensors so that motor can stop immediately which will create problems. There will be particular sequence in which the switches should operate, so the particular hall signal is generated by controller which will make the motor to run in same speed continuously even if the hall sensor fails and will match the sequence of switches operation.

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