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Buck Converter with Fault Tolerant Inverter Combination for BLDC Motors in Aerospace Applications

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ABSTRACT

Considering the aerospace applications, different types of motors can be used in the control moment gyroscope. Control moment gyro is an attitude control device used in the attitude control system. Due to the different advantages of brushless dc (BLDC) motors like high power density, higher efficiency, high dynamic response, linear speed torque characteristics and long life it is more preferred than all other motors in aerospace applications. As this paper deals with a critical application like spacecraft, reliability of the system is the first concern. Therefore a fault tolerant topology is required to drive the BLDC motor, which further increases the reliability and operational safety of the system. The first part of the paper introduces a fault tolerant topology which consists of a redundant switch for each faulty switch in both converter side and inverter side. Based on the investigation of current through the defective switch, the fault detection and reconfiguration is possible. Second part of the paper discusses about a novel speed measurement technique. This technique depends on the analysis of zero crossing points of the back EMF signals. The third part of the paper deals with the sensor-less regulation of the brushless dc (BLDC) motor. Sensor-less control is also based on the zero crossing points of the back EMF signals. Therefore the proposed topology increases the reliability of the system and ensures safe and continuous operation. The simulation results validate the consistency and feasibility of the proposed topology.

Keywords: *Brushless dc (BLDC) motors, buck converter, fault tolerant topology, system reconfiguration.*

1. INTRODUCTION

Aerospace is defined as the effort of human being in the field of science, engineering and business to fly in the earth's atmosphere and surrounding space. Considering the aerospace application, the attitude control of the spacecraft is achieved using the magnetically suspended control moment gyroscope. It has a number of advantages like long life, high precision and large moment which leads to zero friction and enhanced damping of a high speed rotor. Based on various motor selection factors like the application of the motor, the environment it has to work, the commutation method, no- load speed, torque ripples , power source etc. different motors can used in the control moment gyro for attitude control. Few motors used for the attitude control purpose are AC induction motors, Brushed DC motors, Brushless DC motors, Stepper motors etc. As a critical part of magnetically suspended control moment gyroscope for aerospace application in vacuum, the immense speed rotor drive system requires small power loss and high operating speed [1]. Therefore a brushless dc (BLDC) motors with slot- less and ironless stators are always preferred in spacecraft.

Safety is considered as the key angle while structuring or actualizing new innovations. Aerospace application involves highly reliable and critical systems, which should ensure continuous and high performance operation even in faulty situation. The defects that can arise in the electrical part of the system are now and again exceptionally problematic and may make extensive damages to the system. Hence by commissioning appropriate fault tolerant circuits the consistency as well as the safety can be improved. Looking at the motor drive system, around 38% of the system breakdowns are detected in the power converter section and majority of the faults are recognized in the power semiconductor switches [4]. Consequently, the fault tolerant control is very essential in critical aerospace application as a result of its delicate semiconductor switches. For the fault tolerant control topologies of the brushless dc (BLDC) motor drive systems, there are predominantly two capacities: 1) Fault interpretation and 2) system reconfiguration to get back from the fault. There have been various researches carried out in the field of fault detection of inverters in the three phase BLDC motor drive systems [7]. A mandatory case of the fault tolerant control of the three phase inverter is the topology which has the fault tolerant competence. In this way, the system reconfiguration techniques have redundant hardware topologies that have the benefits of high dependability and wellbeing which have pulled in numerous analysts in the ongoing decades [8]. The restrictions of Hall Effect sensors such as sensitive to temperature, unavoidable lead wires etc.[9] makes it difficult to be used in harsh environment. Considering the system authenticity, various sensor-less regulation strategies have been examined for a couple of decades [12]-[14]. Thus, the target of this work is to propose a corrective technique which includes software reconfiguration and the architecture of hardware topology.

The concepts proposed in this paper focuses to share a unique highly dependable and highly efficient inverter topology with sensor-less control strategy for BLDC motor drive of a magnetically suspended control moment gyroscope. The proposed system will enhance the system reliability and decreases the power losses. The framework of the paper is as follows. Section 1 recommends various conventional fault tolerant topologies and the need of the proposed system. Section 2 deals with proposed fault tolerant topology and its advantages. Section 3 deals with the design of the proposed buck converter. Section 4 deals with novel speed measurement technique employed in the system. Section 5 deals with the sensor-less control of BLDC motor drive and about the control strategy. Section 6 gives the simulation analysis of the proposed topology and section 7 outlines some significant ends.

2. PROPOSED BUCK CONVERTER BASED FAULT TOLERANT TOPOLOGY

A novel buck converter based three phase H-bridge fault tolerant inverter topology of brushless dc (BLDC) motor drive is recommended as shown in Figure 1. The buck converter is used in the proposed topology to monitor the current and the three – phase inverter is regulated by the commutation logic without pulse width modulation (PWM). The proposed inverter topology has the fault tolerant ability to overcome the power converter switches failure, and grant the BLDC drive system to maintain its operation. This is very decisive in critical applications like aerospace.

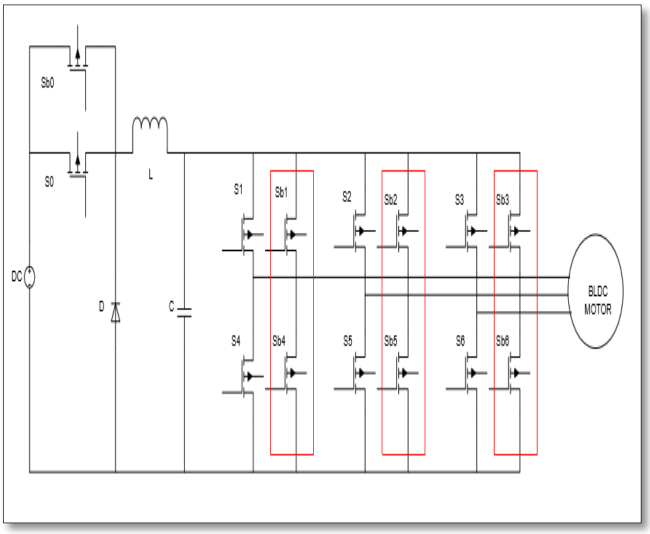

Figure 24 : Circuit diagram of the proposed buck converter based fault tolerant inverter topology.

The proposed topology consist of a buck converter followed by a voltage source inverter to drive the brushless dc (BLDC) motor which is used in magnetically suspended control moment gyroscope. As critical aerospace application is considered, fault tolerance is the primary concern as discussed before. This paper only deals with the fault tolerance and system reconfiguration of the power semiconductor switch failures. Here each switch in both converter side and inverter side can be replaced by a redundant switch whenever a failure is noted in any one of the switches.

Here all the six switches of the three phase full bridge inverter are regulated by the commutation logic of the brushless dc (BLDC) motor drive. So as to accomplish low power consumption, a pulse width modulation (PWM) controlled buck type DC – DC converter is utilized before the three phase H bridge inverter for BLDC motor drive of magnetically suspended control moment gyroscope. This converter transforms the attributes of the three phase inverter and expands the complications of its fault tolerant control.

Whenever any one of the switch fails to operate and discontinues the operation, as a critical application is considered the defective switch is being restored by a redundant switch. So as to locate the defective switch out of the six switches of the inverter, the current through all the switches are continuously evaluated. If any abnormalities are noted, then the corresponding switch is restored by the redundant switch and the system continuous its operation and the reliability of the system are maintained.

3. DESIGN OF THE PROPOSED BUCK CONVERTER

Here in the above discussed proposed topology, a buck converter with 24V input and 12V output is required. The proposed topology is having the switching frequency of 20 kHz. In order to design a 24\12V buck converter, assume that

$$Vin = 24V$$
$$Vout = 12V$$

Therefore, the duty ratio D is given by the equation:

$$D = \frac{Vout}{Vin} \tag{1}$$

$$D = \frac{12}{24} = 0.5$$

Inductor ripple current, Δ IL is given by:

$$\Delta\ IL = \frac{(Vin - Vout)D}{fs * L} \tag{2}$$

Where fs is the switching frequency, and also assume that ripple current Δ IL=0.33

Therefore, buck converter inductance, L is given by the expression:

$$L = \frac{Vout\ (Vin - Vout)}{IL * fs * Vin} \tag{3}$$

On calculation inductance L = 1mH.

Also the buck converter capacitance is given by the expression:

$$C = \frac{IL}{8 * fs * Vout} \tag{4}$$

On calculation capacitance C =100µF.

4.NOVEL SPEED ESTIMATION TECHNIQUE

The torque preciseness of the magnetically suspended control moment gyroscope is mainly dependent on the stabilization and accuracy of speed of the motor drive system. Efficient speed control comprises high precision and frequency speed estimation. Moreover, accurate and fast speed estimation is vital for delaying the commutation instants. The establishment mistake and misalignment of stator phase windings and poles may cause the duty factor of the zero intersections point's signals contrast from each other, which may reach up to half. Subsequently, the estimated speed values will oscillate around its actual values when the position pulses are used by the conventional method.

The speed variances brought about by the uncertain assembly can be eliminated through estimation of the zero crossing point's signals. It is possible to get the speed value with a double frequency by individually estimating the high and low state span of the zero crossing points signals. Although the speed measured is different during high and low state due to uncertain assembly, the correct value can be obtained by computing the 2 x P successive estimations of the half electrical cycle of the zero crossing point's signals. Hence, it is possible to obtain appropriate speed without vibration with 2 x P repetitions (Where P specifies the number of pole pairs).

Consider the position signals achieved from the zero intersection points of the back – EMF be S_1, S_2, and S_3 respectively. During each difference in condition of the position signals the pulse Sp is generated. The detection and analysis procedure of the three position signals are autonomous of one another. The three counters C_1, C_2 and C_3 are utilized to check a steady high frequency clock pulses and furthermore to decide the span of the present condition of the position signals.

When the condition of the position signals is changed, the results of the respective counter is duplicated to any one of the registers $m_1(k)$, $m_2(k)$ and $m_3(k)$ and the counter resets and starts counting again. Where k is an integer value which ranges from 0 to 2P. Here C_m represents the maximal value assigned to counter C_1.The improved mechanical speed of the motor is determined by:

$$wm = \frac{60*f}{T_1} \tag{5}$$

Where f represents the frequency of the system clock, Wm represents the mechanical speed of the motor and T_1 denotes the time period of the position signals. Taking phase A for instance, a flowchart of the novel speed estimation calculation is demonstrated in Figure 2. The flowchart can be simultaneously executed for the three phases of the motor.

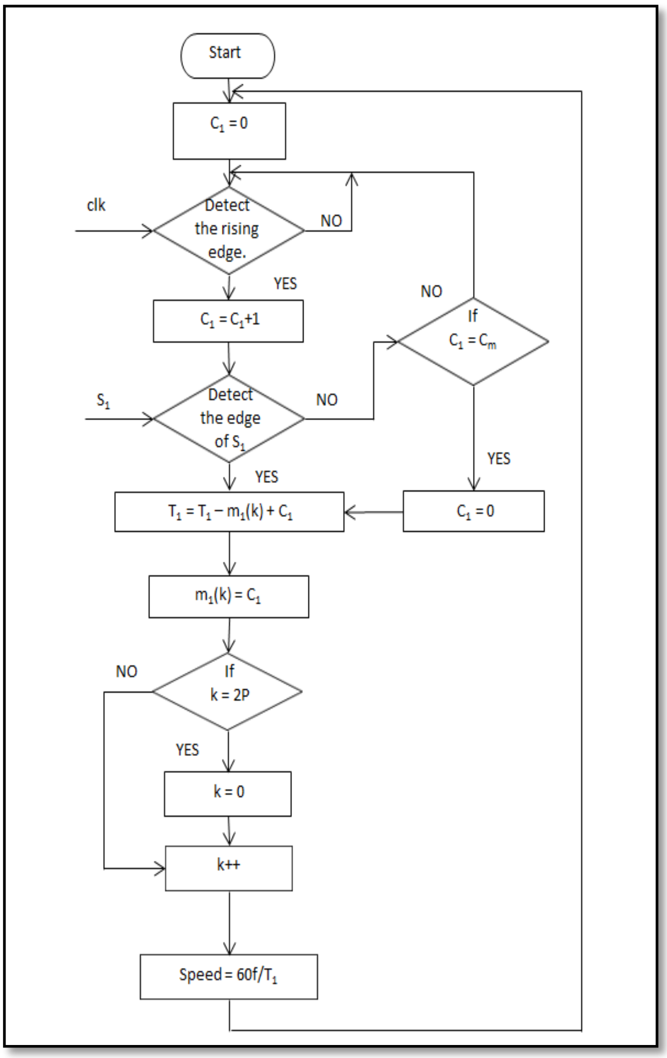

Figure 2: Flowchart of the proposed speed estimation technique.

5. CONTROL METHODOLOGY

The control methodology of the proposed fault tolerant inverter used for magnetically suspended control moment gyroscope of aerospace application is discussed below. Information on the rotor position is required when a BLDC engine is driven by an inverter. Normally, the commutation logic for the inverter switches are contributed by the sensors like hall sensors, encoders, resolvers etc. the accurate placement is tough to assure, it will prompt to unstable operation which further expands the power of the system. Due to all these limitations, sensor-less regulation of brushless dc (BLDC) motor is preferred in critical application where the environment is very harsh. Figure 3 displays the detailed block diagram of the control system.

From the below block diagram it is clear that the switching logic for the three phase fault tolerant inverter is provided by the position signals obtained from the sensor-less control of the brushless dc (BLDC) motor.

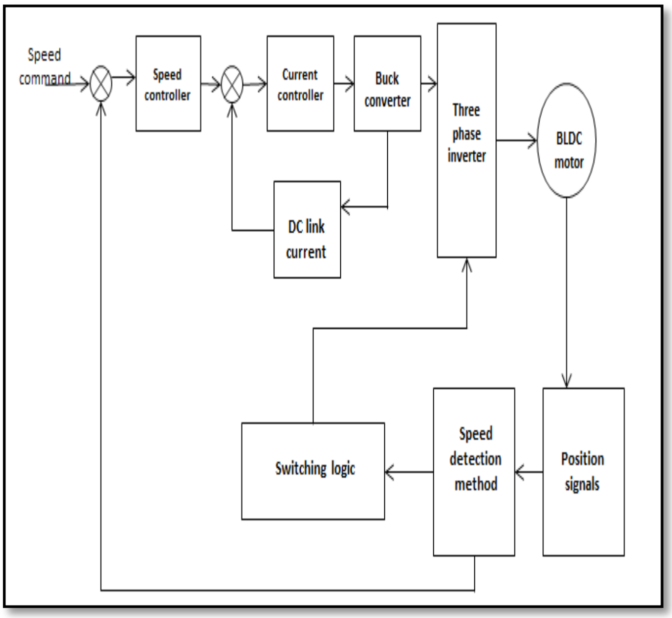

Figure 3: Detailed block diagram of the proposed control methodology.

Also the switching logic of the buck converter is provided by the closed loop control logic of the system using both the speed and current controller. Here PI controller is used as the speed and current controller, where P value is first fixed and integral value is varied by manual tuning process to achieve the required response and also to minimize the steady state error. The following table describes about the parameters of the control system.

Table I: Specifications of the proposed control system.

Parameters	Value
Buck converter inductance	1 mH
Buck converter capacitance	100µF
Current proportional coefficient	1
Current integral coefficient	5
Speed proportional coefficient	0.1
Speed integral coefficient	0.5

6. SIMULATION ANALYSIS AND RESULTS OF THE PROPOSED TOPOLOGY

The proposed buck converter based fault tolerant topology is simulated utilizing MATLAB/SIMULINK in order to confirm the working of the proposed topology and the post fault reconfiguration and different parameters. Figure 4 represented the Simulink model of the proposed system.

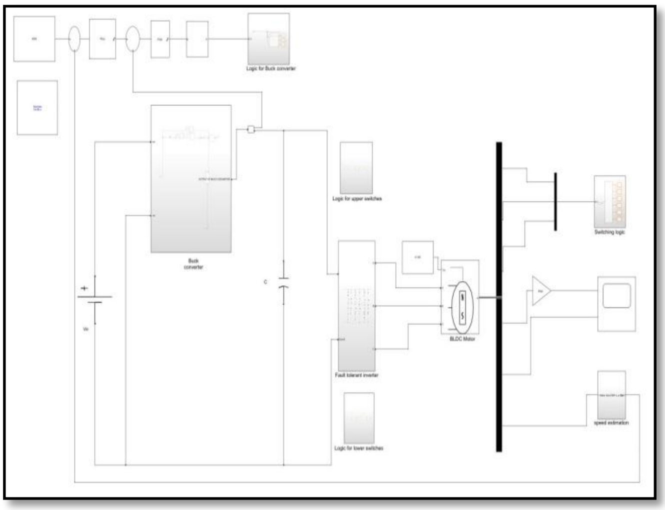

Figure 4: Simulink model of the proposed fault tolerant topology.

Figure 5 represents the logic developed to generate the error signal by which the pulses are transferred from the faulty switches to the backup switches.

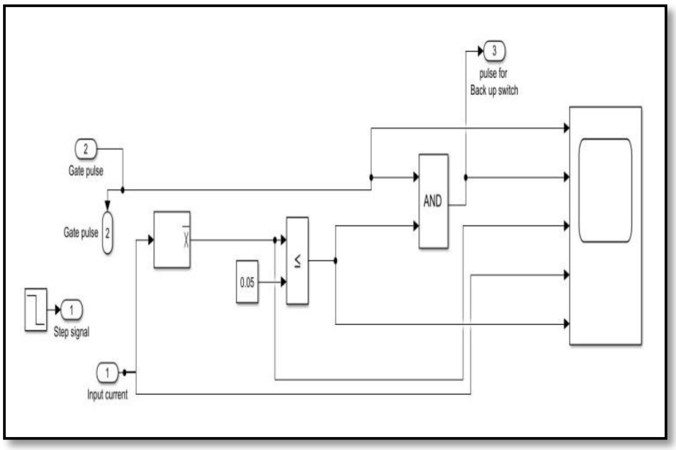

Figure 5: Logic for error signal generation.

The simulation results of the above mentioned buck converter based fault tolerant inverter is analyzed in both cases, that is with fault and without fault condition.

Case 1: when the proposed buck converter based fault tolerant topology is considered without any fault.

In this case the proposed system is healthy, that is all the switches are working normally. Figure 6 displays the simulation results of the proposed buck converter based fault tolerant inverter without any fault. That is all the switches are healthy, so that the converter and the inverter operates normally and the BLDC motor attains its required speed. The electromagnetic torque shown above has some ripples which can be reduced further for smooth operation of the motor.

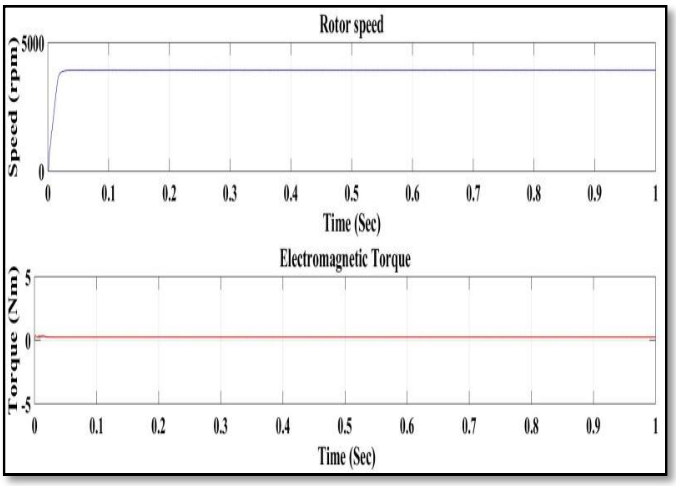

Figure 6: waveform of speed and torque of the motor without fault.

Case 2: when the proposed buck converter based fault tolerant topology is considered with fault.

As discussed earlier when fault is applied to the converter switches or inverter switches, fault detection and system reconfiguration is done immediately. It is clear that there is a small decrease in the motor speed when fault occurs which lasts for few milliseconds and the system is reconfigured immediately. The system reconfiguration is possible by switching the action of the faulty switch to its redundant switch, so that the motor speed is regained to its required value and the operation is continued. Figure 7 shows the current waveform of the faulty switch, the error signal and also the current through the back up switch.

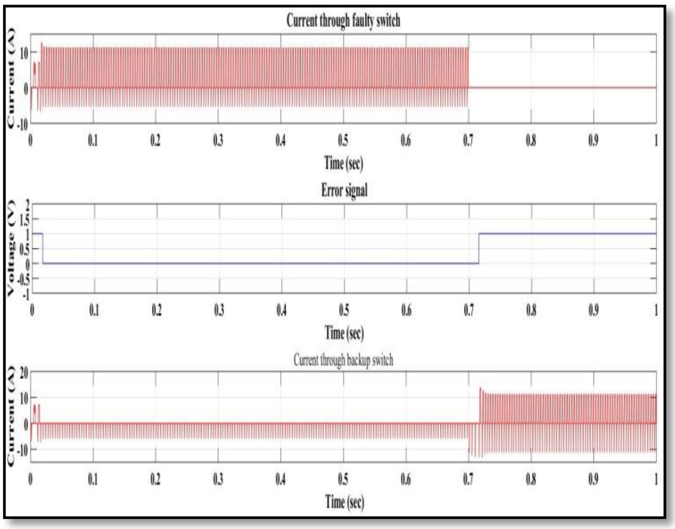

Figure 7: Waveform of current through faulty switch and error signal generated.

Figure 8 is the simulation result of the suggested fault tolerant inverter with fault at any switches either in buck converter or in the three phase inverter.

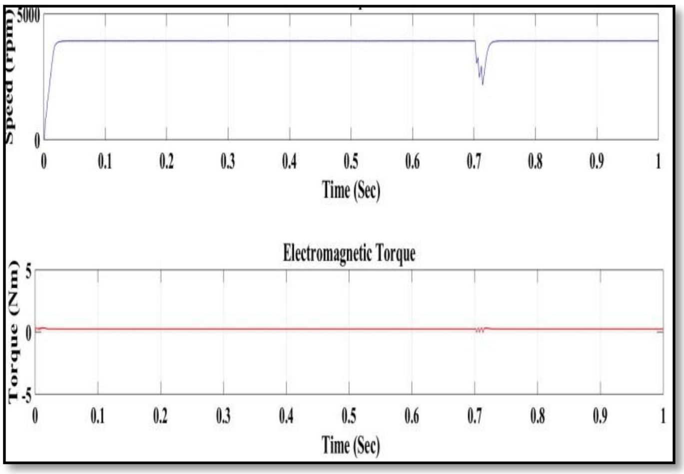

Figure 8: waveform of speed and torque of the motor with fault.

Figure 9 shows the unbalance in back emf generated when the proposed topology is under fault condition.

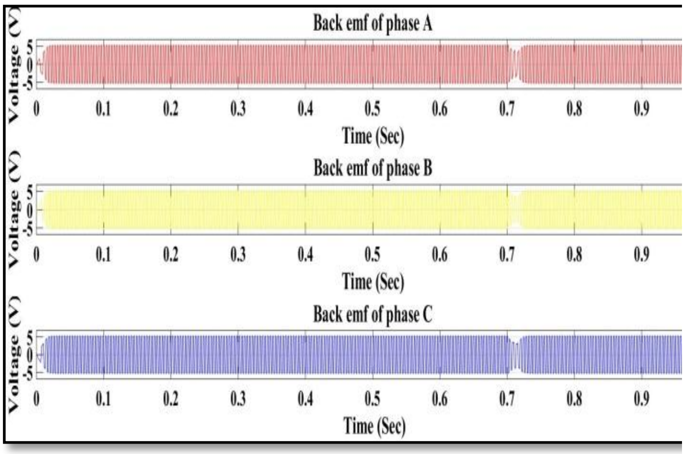

Figure 9: waveform of back emf under fault condition.

Fault disconnection and reconfiguration of fault in the three phase inverter is checked by presenting open circuit faults in the system. The shortcomings were applied anytime of the simulation time as in the previous case. By the simulation of these circumstances the complete segregation time and reconfiguration time can be resolved and evaluated. Therefore the simulation validates that the proposed topology increases the reliability of the system and ensures safe and continuous operation.

As discussed before a buck converter based fault tolerant inverter topology is suggested. So here a 24 volt input, 4000 rpm brushless dc (BLDC) motor is been used. The 24 volt input is supplied to the buck converter, the converter step downs the voltage to the required level according to the switching logic. This output is fed as the input of the three phase inverter which is utilized to drive the brushless dc (BLDC) motor. Switching logic for the inverter is provided by the signals generated by the sensor -less control of the brushless dc (BLDC) motor. The specifications of the brushless dc (BLDC) motor are indexed below.

Table II: Parameters of the brushless dc (BLDC) motor.

Parameters	Value	Units
Rated speed	4000	rpm
Pole pairs	4	-
Number of phases	3	-
Voltage	24	V
Torque	0.125	Nm
Torque constant	0.036	Nm / A
Resistance	0.72	Ω
Inductance	1.2	mH
Peak current	10.6	A
Rotor inertia	48	Kg / cm^2

7. CONCLUSION

In this paper, a buck converter based fault detection and remedial topology for brushless dc (BLDC) motors for aerospace applications is suggested. This proposed topology aids in fault detection and system reconfiguration more accurately and safety of the system is assured. The buck converter at the front end makes the topology increasingly important. The buck converter helps to weaken the induced current and torque ripples as the torque ripples will induce acoustic noise, speed fluctuations and mechanical vibrations. In the proposed topology each faulty switch is replaced by a redundant switch. This ensures safe operation and maintains the reliability of the system in critical applications. The sensor-less position detection of the brushless dc (BLDC) motors are analyzed to maintain the accuracy of the system. The system reconfiguration can be actualized quickly and successfully after the open circuit switch shortcoming happens by the proposed technique. Simulation examination and results confirm the effectiveness of the proposed fault estimation and rectification technique.

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