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Fault-Tolerant Brushless DC Motor Drive for Aerospace Applications

Harminder Singh Johar,[#,*] Abhijit Bhattacharyya[$] and Srinivasa Rao S.[!]

[#]*DRDO–Research Centre Imarat, Hyderabad - 500 069, India*

[$]*DRDO–Defence Research and Development Laboratory, Hyderabad - 500 058, India*

[!]*Electrical Engg. Deptt. NIT, Warangal, Telangana – 506 004, India*

[*]*E-mail: hsjohar.rci@gov.in*

ABSTRACT

This article brings out a Fault-tolerant BLDC motor drive for aerospace applications using the redundancy concept. In a way, it brings out a fault-tolerant strategy that can be used to continue the regular operation of a BLDC motor drive even after the occurrence of faults. As BLDC motors are used in critical and dangerous control areas like military services and space vehicles, a fault-tolerant drive is essential to maintain drive operation and provide desirable output. This article compares fault simulation results in the software model of a BLDC motor drive to those of fault simulation results in hardware for three main types of faults. Fault simulation is carried out for three types of faults, viz. inverter device open circuit fault, motor winding open circuit fault, and rotor position sensor (hall sensor) open-circuited fault. Fault tolerance is ensured by introducing a redundant drive (drive-2), which operates the complete drive at the advent of any of the faults mentioned above in the main (healthy) drive-1. A fault-tolerant (redundant) hardware comprising dual stator BLDC motor and redundant controllers is realized and operationalized. Fault simulation is carried out in this hardware, and these results are validated with the results of fault simulation in the MATLAB SIMULINK model. Software and hardware results are comparable and form a basis for developing fault-tolerant electro-mechanical actuation systems for high-reliability, high-cost applications, mainly aerospace.

Keywords: BLDC motor drive; Fault simulation; Fault analysis; Dual stator BLDC motor

NOMENCLATURE

E_a	: Back EMF (a phase), volts
E_b	: Back EMF (b phase), volts
E_c	: Back EMF (c phase), volts
I_a	: Current (a phase), Amps
I_b	: Current (b phase), Amps
I_c	: Current (c phase), Amps
T_e	: Torque, N-m
ω	: Speed, rad/sec

1. INTRODUCTION

Brushless DC Motor (BLDC) motors have become more popular nowadays. A BLDC motor consists of a rotor with rare earth magnets and a stator. Brushless DC Motors are considered an “inside-out” version of a Brushed DC Motor; the commutator and brushes are non-existent, and the windings are located externally, connected to the controller[1-2]. BLDC motors are electronically commutated motors with several advantages over ordinary brushed DC motors[1]. These motors are generally reliable and efficient. These motors have a noiseless operation, good dynamic response, long life, and are less affected by adverse climatic conditions. Also, their high torque-to-size ratio makes them applicable where space and weight are critical factors. Comparisons between Brushless DC motors, Brushed DC motors, and induction motors are discussed in detail in literature[2]. Due to various advantages, BLDC motors are mainly used in automotive industries, aerospace, military and robotic applications[3].

Since these motors are mostly used in high-risk areas like military services, robotics, aerospace[3], etc., continuous operation is required every time. In aerospace applications, these motors are used in electro-mechanical actuation systems[4]. The occurrence of faults should not affect the normal working of these actuation systems. Since aerospace applications require high reliability and strong fault tolerance[5,7], there is a need to develop innovative redundancy and fault-tolerant schemes applicable to motor drives[6-7]. Innovative system architecture with fault-tolerant schemes to improve the system reliability even by accepting degraded performance is under development[7-8]. For aerospace applications where BLDC motor drives are used mainly in electro-mechanical actuation systems, 100 per cent reliability is anticipated to avoid mission failures, which prove fatal as well as costly. Advanced monitoring systems for fault diagnosis and detection are required for electro-mechanical actuators to make them fault-free[4]. Despite the availability of a rich repertoire of fault-diagnosis methods and post-fault drive configuration strategies in the area of induction motor drives, they do not apply to BLDC motor drives due to the discontinuous current and trapezoidal back EMF of the BLDC motors[17].

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2. BLDC DRIVE SYSTEM

Generally, a BLDC motor drive system combines a BLDC motor and a 3-phase bridge inverter comprising power semiconductor devices such as MOSFETs, IGBTs, etc. A BLDC motor drive system can be modeled as an electrical equivalent circuit that consists of resistance, inductance, and Back-EMF per phase[3]. The electrical equivalent circuit and drive performance of this system[3] are shown in Fig. 1. Waveforms of Back-EMFs, Phase currents, and Torque[3] are shown in Fig. 2.

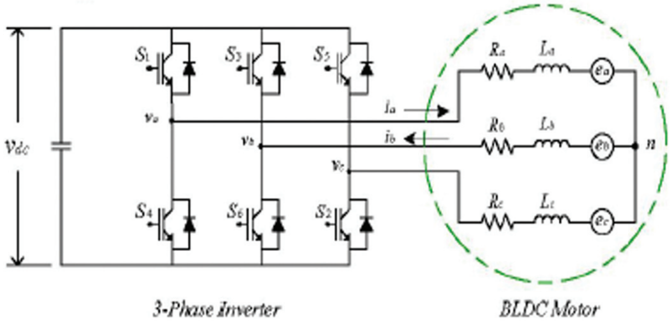

Figure 1. Electrical equivalent circuit of a BLDC drive system.

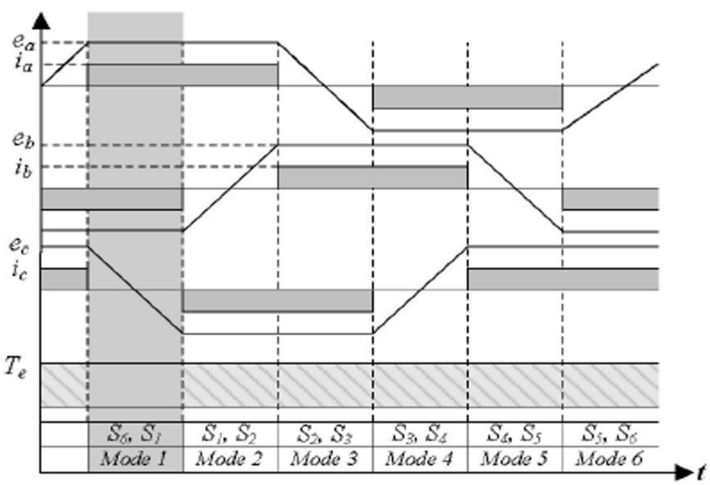

Figure 2. Waveforms of Back-EMFs, phase currents and torque.

As shown in Fig. 2, the BLDC motor has a trapezoid-shaped Back-EMF. Therefore, when Back-EMF is constant, a square wave current is injected. BLDC motor drive system is operated by exciting two phases among the three. Only two switches are operated in one mode. Assuming that self and mutual inductances are constant, the voltage equation of three phases is given by[3]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The torque equation is given by:

$$T_e = \frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_m} \quad (2)$$

where,

v_a, v_b, v_c, are phase voltages,
R_a, R_b, *and* R_c are phase resistances,
i_a, i_b, i_c, are phase currents,
L_a, L_b, *and* L_c are phase inductances,
e_a, e_b, e_c, are phase Back-EMFs,
ω_m is rotor speed.

3. DESIGN CONSIDERATIONS IN BLDC DRIVE SYSTEM FOR MILITARY & AEROSPACE APPLICATIONS

BLDC motors are used in electro-mechanical actuation (EMA) systems[4] for military and aerospace applications. An EMA system must address design considerations such as stall force, operating load, stroke length, maximum deflection, hinge moment, bandwidth, non-linearity, backlash, linear speed, position accuracy at full load, null offset at no load, etc. All these parameters, in turn, lead to the finalization of specifications for a BLDC motor drive system comprising a BLDC motor and its controller (power inverter) for EMA systems. BLDC motor and controller for one such requirement is brought out in Table 1 and Table 2. This BLDC motor and controller combination, referred to as a Fault-tolerant BLDC motor drive, is used in the hardware realized for fault simulations and is subsequently presented in this article. Figure 3 shows a block diagram of an FPGA-based electro-mechanical actuation system with all sensors, drives, and actuator components.

Table 1. DS BLDC motor specifications

Voltage	50 V
Current	40 A
Power	2 Kw
Speed	3000 RPM
Torque	6.5 N-m
Resistance	0.3 Ω
Inductance	115 mH
No. of poles	12
No. of slots	36
Slots per pole	3
Turns per slot	12

Table 2. Controller specifications

MOSFET	**International rectifier part no.**	**IRFS4115PbF**
	V_{DSS}	150 V
	I_D	100 A
	$R_{DS\,(ON)}$ typ.	10.3 mΩ
	$R_{DS\,(ON)}$ max.	12.1 mΩ
	V_{GS}	± 20 V
	T_J & T_{STG}	-55 to 175 °C
Gate driver	**Texas instruments part no. DRV8350**	
	V_{VM}	9 – 75 V
	V_{VDRAIN}	7 – 100 V
	f_{PWM}	0 – 200 kHz
	I_{GATE}	0 – 25 mA
	T_A	-40 to 125 °C
	T_J	-40 to 150 °C

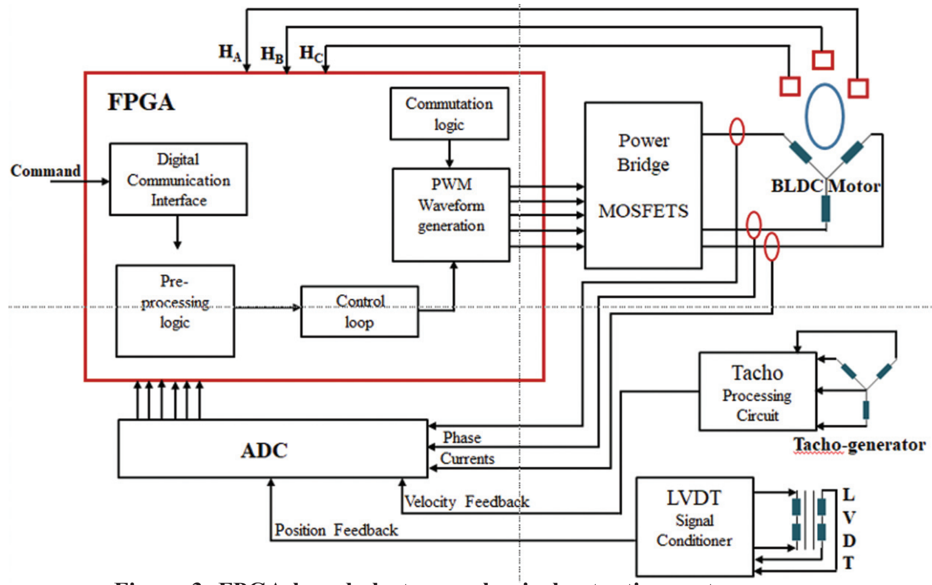

Figure 3. FPGA-based electro-mechanical actuation system.

FPGA control board mainly consists of (1) Power supply, front-end EMI/EMC filter, and DC-DC converters, and (2) Signal processing and FPGA section for control algorithm implementations. The FPGA section gets feedback signals related to actuator position, motor speed, and motor current from respective sensors and generates control outputs for the actuator. Logic blocks inside the FPGA implement the servo loop to control the actuator. The output of the control loop algorithm would be converted to equivalent PWM outputs to drive an external MOSFET bridge which drives the motor. Desired position command is sent via any digital communication interface by the main processing unit of an aerospace vehicle. Based on this input and the current position of the actuator, the servo loop then produces the output to move the actuator to a desired position. The position loop gets a feedback signal as LVDT analog output as a digital command, converted by the ADC. Similarly, the velocity loop gets a feedback signal as tacho-generator output as a digital command converted by the ADC. Motor current information is obtained from the corresponding ADC channel and is used for limiting the current to a safe pre-determined value. Design considerations for BLDC motors to be used in military and aerospace electro-mechanical actuation systems are mainly voltage, current, power, torque, and speed, which are derived from the requirements of an EMA system, as mentioned earlier.

4. FAULT-TOLERANT BLDC DRIVE

BLDC drive failure may occur for various reasons, including mechanical or electrical. Mechanical breakdown (e.g., bearings) causes approximately 40 per cent - 50 per cent of motor failures, while electrical issues (e.g., stator windings) also account for 40 per cent of motor failure[16]. Drive failure may also occur due to faults in power semiconductor devices, which account for 38 per cent of total faults occurring in motor drive configurations[15,17]. Faults in power semiconductor devices may be of two types 1) Open circuit (OC) and 2) Short circuit (SC) faults[15,17]. Another critical fault in BLDC drive configuration is the position (hall) sensor fault, which contributes significantly to drive failure[6,10,11,14]. Hall sensor fault may be either stuck high or low, where the sensor output gets stuck to one (stuck high) or zero (stuck low). This article considers all the abovementioned faults (mainly open circuit faults).

A redundant fault-tolerant BLDC motor drive is presented, and simulations of three main types of faults in BLDC motor drive are carried out in the software model and hardware. BLDC motor drive system hardware is realized using a Dual Stator BLDC Motor[7] (DS BLDCM), with each stator winding energized from a separate power inverter. For fault simulation in the software model, two drives are chosen, one as drive-1 (main drive) and the second as drive-2 (redundant drive). Faults are induced in drive-1, i.e., the main drive (both in the software model and in the hardware). Immediately after the occurrence of a fault, it is ensured that drive-2, i.e., the redundant drive performs the overall drive operation. This redundant drive operation[13] is achieved with the help of logic circuits for sensing faults in the main drive and energizing the redundant drive after a fault.

Based on the results of software simulation and hardware, it can be inferred that even after the occurrence of a fault, the complete drive (with redundant drive operational) can cater to regular operation without coming to a standstill.

Three major types of open circuit faults are expected in a BLDC motor drive as follows:

- Inverter device open circuit fault[3,5]
- BLDC motor winding open circuit fault[5]
- Hall sensor open circuit fault[6,9,11,12,14].

All three types of faults are simulated in software models and hardware, and their simulation results are presented in this article. Both software and hardware results are comparable and form a basis for the development of a fault-tolerant electro-mechanical actuation system which is the main emphasis of this article.

Modeling of BLDC motor drive[10], fault simulation of each of the abovementioned faults in MATLAB SIMULINK, hardware realization, fault simulation of each of the abovementioned faults in hardware, results of these simulations and their analysis, and comparison of software and hardware fault simulation results are presented in the subsequent sections of this article.

5. FAULT SIMULATION AND ANALYSIS

Modeling[10] of the fault-tolerant drive is carried out in MATLAB SIMULINK. An additional (redundant) drive[13] is provided for fault tolerance, which performs drive operation after fault in the main drive and operates the load. Suitable logic is implemented to ensure that a redundant drive performs drive operation in case of any fault in the main drive. Three major types of open circuit faults are expected in a BLDC motor drive and are simulated in the MATLAB SIMULINK model[10] as follows:

- **Inverter Device Open Circuit Fault**

Inverter device open circuit fault is simulated by withdrawing gate pulse to one of the inverter devices (top or bottom) in one of the legs of the inverter.

- **BLDC Motor Winding Open Circuit Fault**

This fault is simulated by opening a switch placed in series of one of the windings of the BLDC motor.

- **Hall Sensor Open Circuit Fault**

This fault is simulated by opening a switch placed in series of the output of one of the rotor position (hall) sensors.

5.1 Inverter Device Open Circuit Fault

5.1.1 Fault Simulation

Inverter device open circuit fault[3,5] is simulated using a switch. This switch withdraws the gate drive to one inverter device (MOSFET) at an instant of 0.2 seconds after the start in a particular phase (Phase-a). The logic implemented for fault detection is based on the voltage across the MOSFET, which is sensed. When it is greater than or equal to 1 (which indicates MOSFET is open), a command is given to the redundant drive to take over. This way, an open circuit fault across the inverter device is simulated.

5.1.2 Analysis of Results

Plots of Back EMFs, Currents, Torque, and Speed (E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω) for the healthy as well as faulty drives are shown in Fig. 4 & Fig. 5, respectively. Figure 4 shows plots for a healthy drive, wherein the main drive operates. Figure 5 shows plots for the faulty drive, wherein the redundant drive operates. It is evident from the plots that at

the instant of occurrence of a fault (at 0.2 sec.) main drive (drive-1) stops operating, and the redundant drive (drive-2) performs regular drive operation. The same behavior of the drive is confirmed for all phases by inducing the same fault in one of the devices of another phase (another leg) of the same inverter. Simulation results are validated for various phases (a, b, c).

5.2 Motor Winding Open Circuit Fault

5.2.1 Fault Simulation

Motor winding open circuit fault[5] is simulated using a normally closed switch for healthy drive operation. To simulate this fault, an open (OFF) command is issued to the switch at 0.2 seconds in a particular phase (phase-a). Before the induction of this fault, drive-1 (main drive) operates; after that, drive-2 (redundant drive) performs regular drive operation.

5.2.2 Analysis of Results

Plots of Back EMFs, Currents, Torque, and Speed are shown in Fig. 6 and Fig. 7 for healthy and faulty drives, respectively. Plots indicate that before the fault, drive-1 (main drive) operates; after that, drive-2 (redundant drive) performs

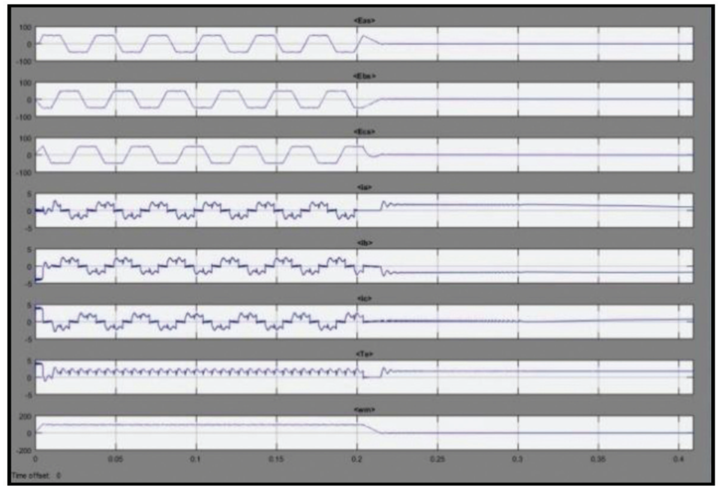

Figure 4. Drive-1 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

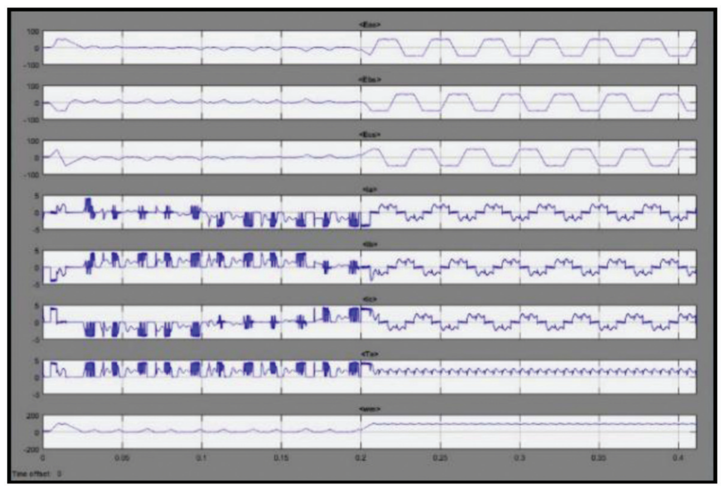

Figure 5. Drive-2 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

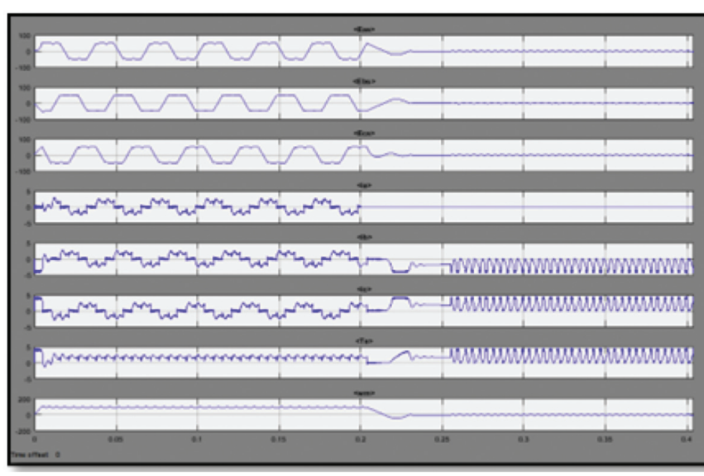

Figure 6. Drive-1 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

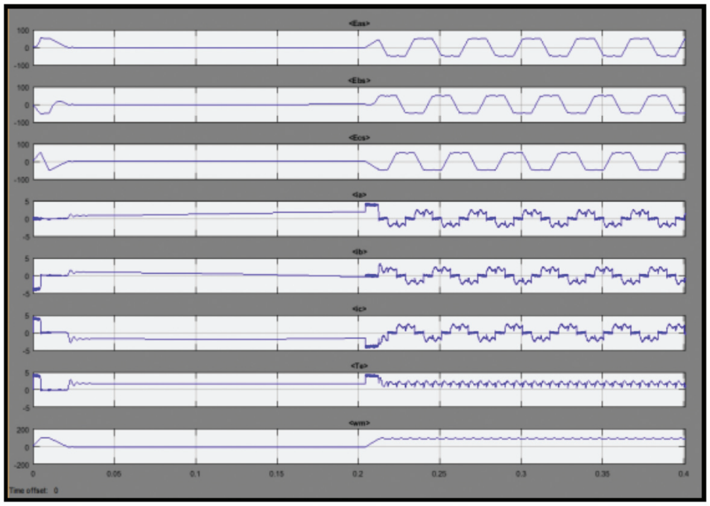

Figure 7. Drive-2 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

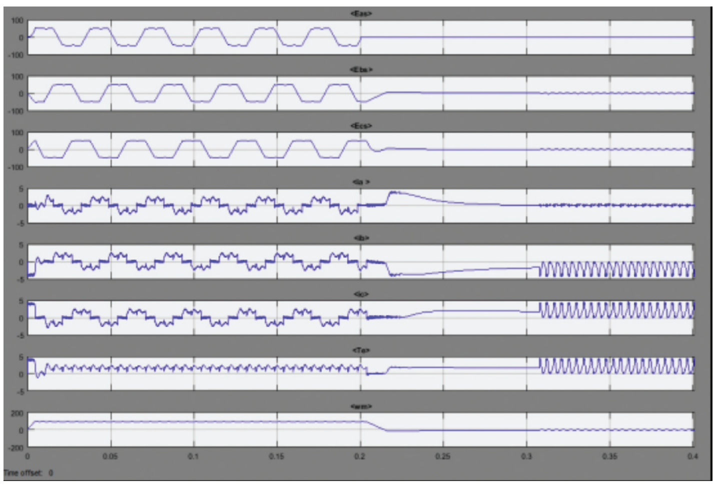

Figure 8. Drive-1 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

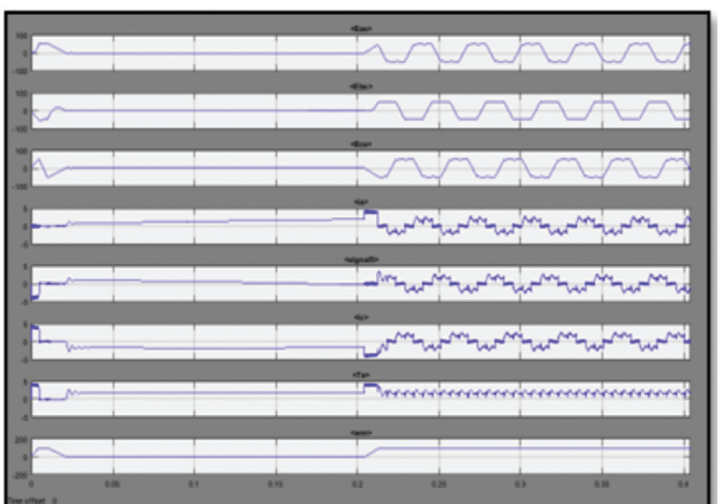

Figure 9. Drive-2 Plots of E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω.

regular drive operation. In Fig. 6, plots for the healthy drive are shown where the primary drive operates. Figure 7 shows plots for the faulty drive, wherein the redundant drive operates. Simple logic is implemented to detect the fault in the main drive such that the redundant drive takes over as soon as the current drawn exceeds the rated value. It is evident from the plots that at the instant of fault occurrence, the main drive (drive-1) stops, and the redundant drive (drive-2) performs drive operation, ensuring fault-tolerant operation.

5.3 Hall Sensor Fault

5.3.1 Fault Simulation

Rotor Position Sensor (Hall Sensor) fault[6,10,11,14] simulations are done using a switch that withdraws the output of a hall sensor to the drive in a particular (phase-a) after 0.2 seconds. Before the induction of this fault, drive-1 (main drive) operates; after that, drive-2 (redundant drive) performs regular drive operation.

5.3.1 Analysis of Results

Plots of Back EMFs, Currents, Torque, and Speed (E_a, E_b, E_c, I_a, I_b, I_c, T_e, ω) for healthy and faulty drives are shown in Fig. 8 & Fig. 9, respectively. In Fig. 8, plots for the healthy drive are shown where the primary drive operates. Figure 9 shows plots for the faulty drive, wherein the redundant drive operates. It is evident from the plots that at the instant of fault occurrence, the main drive (drive-1) stops, and the redundant drive (drive-2) operates, thereby ensuring fault-tolerant operation.

The above simulation results and their analysis show that during healthy drive operation, the main drive (drive-1) operates, and post-fault, the redundant drive (drive-2) operates. Similar results are obtained from fault simulation in hardware and are presented in subsequent sections of this article.

6. HARDWARE AND RESULTS

A fault-tolerant BLDC motor drive for use in electro-mechanical actuation systems is proposed in this article. A fault-tolerant drive comprising a primary drive (drive-1) and a redundant drive (drive-2) is realized using a dual stator BLDC motor[7,13]. A DS BLDC motor is a novel fault-tolerant BLDC drive configuration that addresses motor winding faults. This motor comprises two stators & one rotor mounted with permanent magnets. These two stators employed with winding can be controlled independently or simultaneously as per requirement. The simultaneous functioning of both stators provides high torque. These two stators can be used independently & switched based on requirements for fault tolerance. If a fault (maybe an open circuit or a short circuit fault) occurs in any one stator winding[3,5], the second (redundant) winding can be switched into the circuit and continue motor operation[13]. Each stator winding is connected to a separate controller (power inverter). Specifications (ratings) for the DS BLDC motor are shown in Table 1, and for the controllers are shown in Table 2.

Separate controllers are used for realizing a fault-tolerant system for any power inverter faults[5]. If faults occur in one controller, drive operation can be continued with the redundant controller. Generally, direct redundant hall sensors comprising a set of primary and secondary sensors are employed for fault-tolerant (redundant) operation[11, 12, 13]. In hardware realized using DS BLDC, only one set of hall sensors is built into the motor for position feedback. An extra set of hall sensors can be provided in the DS BLDC motor, which can serve as redundant sensors. Hall sensor fault simulation is carried out by withdrawing the hall sensor output to one primary controller and subsequently switching ON the secondary controller.

A fault simulator unit is realized to simulate each type of fault by routing the inverter bridge lines, motor winding lines, and hall sensor output lines through this simulator unit. These faults can be simulated with the help of toggle switches provided on the fault simulator unit as follows: For simulating inverter faults, both device open circuit faults and device short circuit faults, toggle switches are provided. There are six toggle switches for simulating each device short circuit fault in all three phase bridge lines. For simulating inverter device open circuit faults, there are another three two-way toggle switches in series with the gate drive (one each for the upper device and lower device) of a particular leg. Similarly, for simulating motor winding faults in all three phases[3,5] there are three two-way toggle switches for each phase. Switching a two-way toggle switch on one side (in a particular phase) simulates a motor winding short circuit fault, while switching the same on the other side simulates a motor winding open circuit fault (in that phase). For simulating hall sensor faults, there are three additional toggle switches. These switches are located at the output of the hall sensors routed to the inverter drive to simulate the hall sensor stuck low (open circuit) fault.

All three types of faults, viz. inverter device open circuit fault, motor winding open circuit fault, and rotor position sensor (hall sensor) open-circuited fault, are simulated in the MATLAB SIMULINK model and practically simulated in hardware. These faults are simulated using toggle switches in the fault simulator unit. The hardware setup is shown in Fig. 10. This setup includes a DS BLDC motor, main controller (power inverter), fault simulator unit, and power supply. Each fault is simulated using toggle switches on the fault simulator unit, and plots for speed and current are recorded.

Figure 11, Fig. 12 and Fig. 13 show plots of motor speed in RPM and current in Amperes for inverter device open circuit fault, motor winding open circuit fault, and hall sensor open circuit fault, respectively. Plots are shown for motor speeds of 100 RPM and 500 RPM for each type of fault. Each fault is induced after a few sec. of normal (healthy) drive operation,

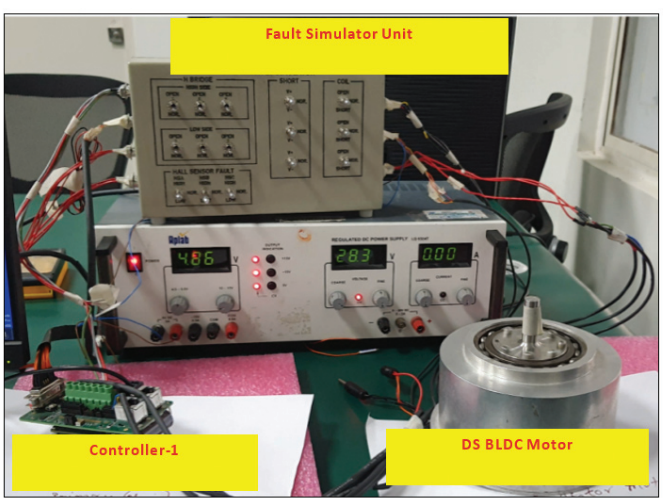

Figure 10. Hardware fault simulation setup.

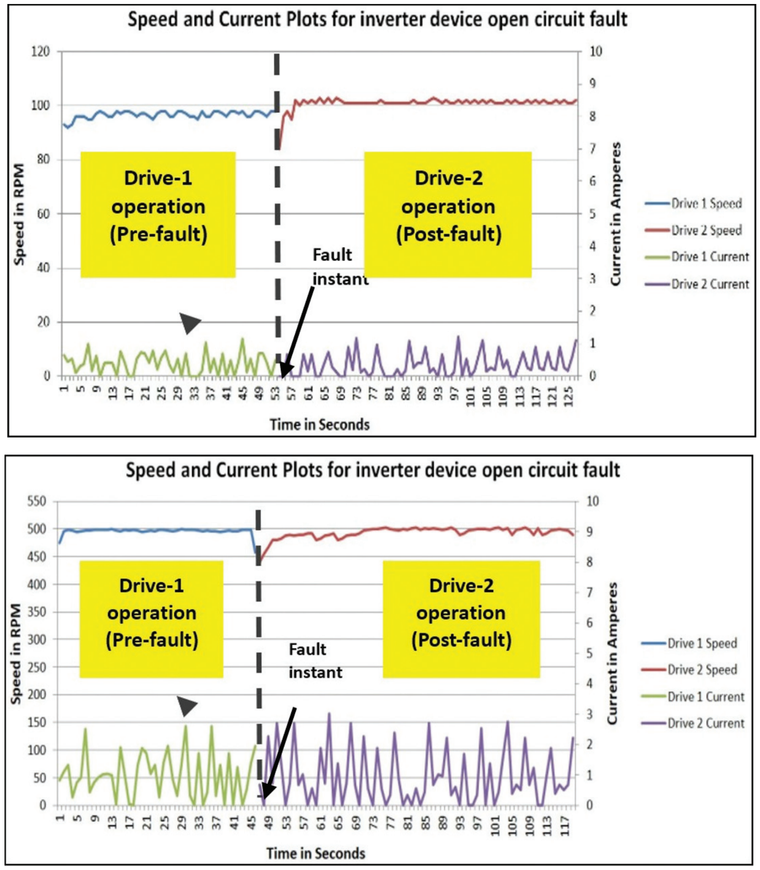

Figure 11. Speed and current plots for inverter device open circuit fault simulated in hardware.

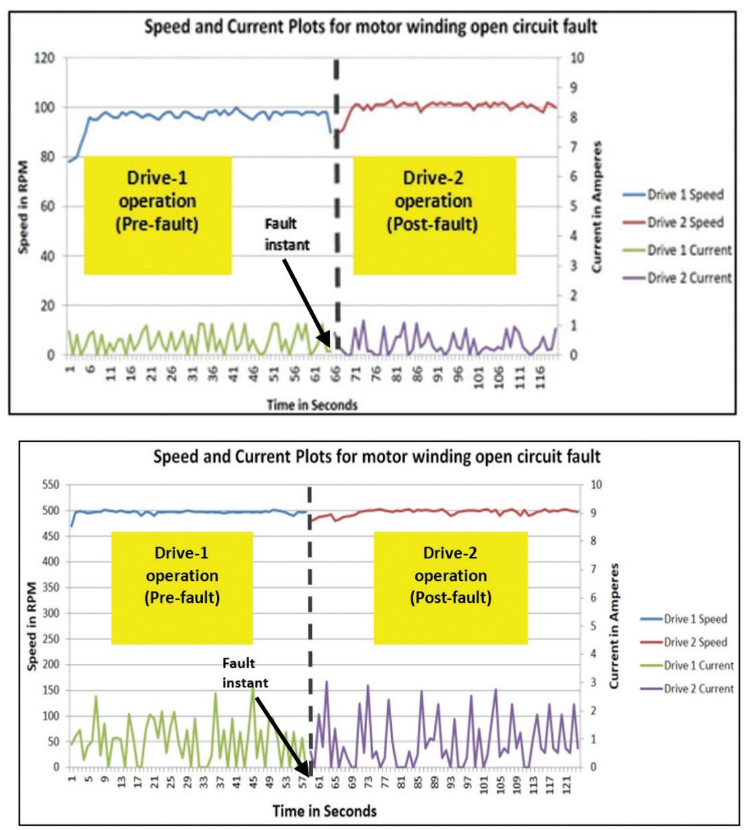

Figure 12. Speed and current plots for motor winding open circuit fault simulated in hardware.

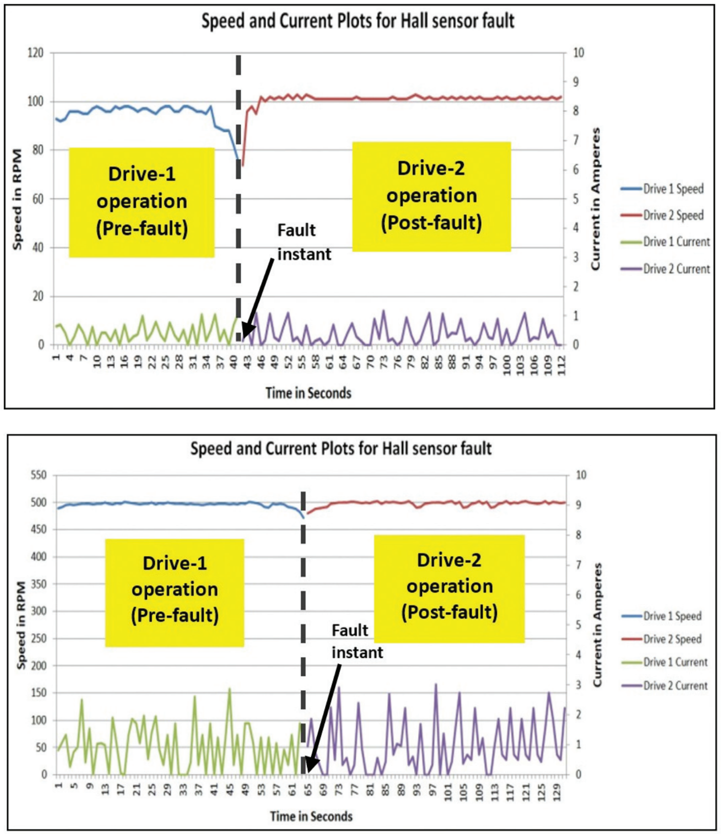

Figure 13. Speed and current plots for hall sensor fault simulated in hardware.

wherein the main drive (drive-1) operates. The logic circuit immediately senses this fault; drive-1 (main drive) is switched OFF, and drive-2 (redundant drive) is switched ON, which indicates fault-tolerant drive operation. The motor is operated at no load and lower speeds, i.e., at 100 RPM and 500 RPM. Prior to inducing fault, drive-1 is operating at 100 RPM and 500 RPM, and post-fault drive-2 delivers output at the same speed, i.e., at 100 RPM and 500 RPM, respectively.

Currents drawn by the motor before and after the fault are also comparable and of the order of 0.5 A (average) for 100 RPM and 1.5 A (average) for 500 RPM. Results are comparable for both 100 RPM and 500 RPM motor operations, wherein after fault is simulated, drive-1 (main drive) switches OFF, and drive-2 (redundant drive) switches ON, which indicates fault-tolerant drive operation. Software simulation results are validated with hardware results, which give confidence in realizing a fault-tolerant drive for high-reliability, high-cost applications, mainly military and aerospace. Results for all three types of faults simulated in hardware setup are presented, which form a basis for developing a fault-tolerant electro-mechanical actuation system.

7. CONCLUSION

Fault-tolerant BLDC motor drive has been modeled[10] in MATLAB SIMULINK, in which a redundant drive (drive-2) is provided in addition to the main drive (drive-1). Three main types of faults have been simulated, viz. inverter device open circuit fault, motor winding open circuit fault, and rotor position sensor (hall sensor) open circuit fault[3,5-6]. Logics are implemented such that a redundant drive operates the complete drive when faults occur in the main drive. Faults have been introduced in healthy drive, and simulations have been carried out. A fault-tolerant BLDC drive comprising a dual stator BLDC motor[7] with each stator winding connected to a separate power inverter (controller) and a fault simulator unit was realised.

Faults simulated in the software model were also simulated in this hardware using the fault simulator unit, and results are presented for three main types of fault. Hardware results are comparable to software simulation results. From these results, confidence is achieved that a fault-tolerant redundancy-based drive can be developed which can operate continuously without coming to stand still, thereby improving the overall reliability of the system[7-8]. However, optimization in size would be a significant challenge in realizing a fault-tolerant BLDC drive for aerospace applications. The design of FTCS[11-12] (Fault-tolerant Control system), for minimizing switch over time from one drive to the other, employing fault detection and control techniques[6] needs further study and implementation.

Methods using additional voltage sensors that can identify faults faster than the existing method can maintain the control performance of the system[3]. Extra protection circuitry involving fast-blowing fuses[3] and power devices must be designed to cater to short circuit faults and can be of research interest in the future. Multiphase motors are being proposed to improve the reliability[16] of a BLDC drive system, wherein an alternative phase is introduced after an open circuit fault is detected. In this fault tolerance method, the output torque exhibits a relatively large pulsation, which needs to be mitigated and requires a complex fault tolerant control (FTC) circuit[16]. However, if optimization in space and control circuits is achieved, a redundant drive system can be a good option for developing fault-tolerant BLDC drives for aerospace applications.

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CONTRIBUTORS

Mr Harminder Singh Johar obtained his MTech in Power Electronics and Power Systems from the IIT, Bombay. He is working as a Scientist at DRDO-RCI, Hyderabad. His areas of specialisations include: Electrical integration and checkout of air launched and air defense missile systems, design and realisation of electrical interfaces for on-board avionic sub-systems, and performing functional and environmental testing of these avionic sub-systems. He has carried out conceptualisation of the problem, carried out modelling and hardware realisation of the fault-tolerant BLDC motor drive, hardware realisation and simulation studies.
He has carried out the analysis and comparison of software and hardware fault simulation results.

Dr Abhijit Bhattacharyya obtained his PhD from IIT, Madras, in Control Systems. He works as a Project Director at DRDO-DRDL, Hyderabad. His areas of interest include: Missile guidance, control, estimation, and modeling of seekers and also in Advanced guidance, control, and estimation design for aerospace applications.
In the present work, he has guided in preparing the MATLAB SIMULINK model of a fault-tolerant BLDC motor drive system and the simulation of faults in this model. Also, he has guided in carrying out fault simulations in the hardware and analysis of software and hardware fault simulation results.

Prof. Srinivasa Rao S. obtained his PhD from the NIT, Warangal and working as a faculty member at NIT, Warangal, India. His research interests include: Power electronic drives, switch mode power converters, DSP-controlled drives, and renewable energy systems.
In the present work, he has guided the conceptualisation of the problem, guided in carrying out simulation studies, hardware realisation, analysis, and comparison of software and hardware fault simulation results.