Inverter Switch Fault Diagnosis System for BLDC Motor Drives

A. Tashakori and M. Ektesabi

***Abstract*—Safe operation of electric motor drives is of prime research interest in various industrial applications. This paper presents a new fault diagnosis system for open circuit switch faults in three phases Voltage Source Inverter (VSI) drive of the permanent magnet Brushless DC (BLDC) motors. The proposed fault diagnosis system is capable of detecting as well as identifying the faulty switch in the voltage source inverters. Faults diagnosis is based on Discrete Fourier Transform (DFT) analysis of the BLDC motor line voltages. Behaviour of the BLDC motor is analysed under open circuit faults of inverter switches through a validated simulation model. A knowledge based table is developed to identify the faulty switch by analysing the simulation results under various fault conditions. Performance of the BLDC motor is also investigated under open circuit faults of VSI switches through the experimental test rig. Experiment results validate the proposed inverter switch fault diagnosis algorithm for the BLDC motor drives.**

***Index Terms*—BLDC motors, Inverter switch faults, Fault diagnosis systems, Fault tolerant control systems.**

I. INTRODUCTION

PERMANENT magnet brushless DC motors have been popular in industrial applications since 1970s. It is a type of conventional DC motors that has no brushes; thus commutation is done electronically according to the permanent magnet rotor position. Techniques to detect the BLDC motor rotor position are based on either use of sensors, Hall Effect sensors for low resolution application and optical encoders for high resolution applications, or through sensorless algorithms [1]. In this study, inbuilt Hall Effect sensors are used for rotor positioning in BLDC motor experimental set-up and simulation model; however the proposed fault diagnosis systems is also applicable to the sensorless BLDC motor drives. Schematic diagram of a three phases, star connected BLDC motor drive is shown in Fig. 1.

Safety is the most significant issue in industrial applications that involves direct human interaction. BLDC motors have been widely used in traction applications such as hybrid electric vehicle (HEV) and pure EV. Any drive train failures or malfunction in an EV application may result in a fatal accident. Therefore in such applications implementing of Fault Tolerant Control Systems (FTCS) is necessary to improve safety and reliability of the overall system [2]. A FTCS generally performs the following tasks,

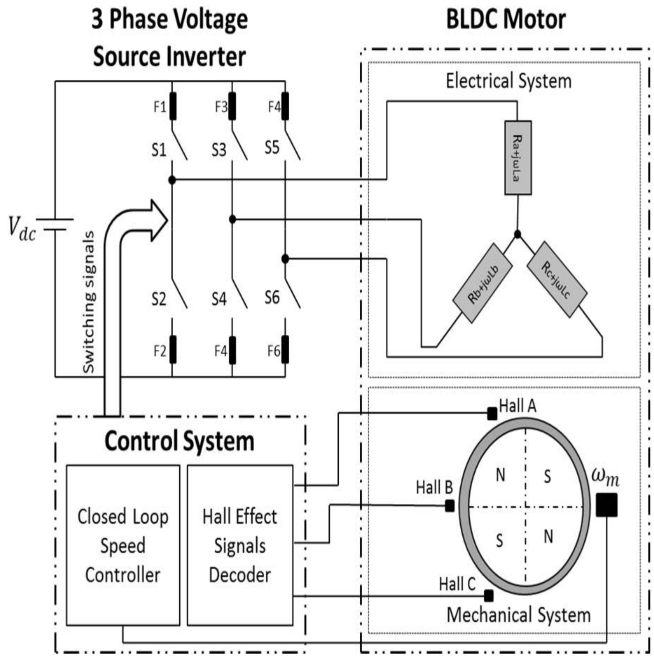

Fig. 1. Schematic diagram of a 3 phases, star connected BLDC motor drive

1) Fault detection;
2) Fault identification;
3) Fault isolation;
4) Remedial strategies.

Various faults may occur at stator, rotor, position sensors or voltage source inverter in a BLDC motor drive. Some of the possible faults of the BLDC motor drive are summarized in Table I. Each fault has specific effects on the BLDC motor; some degrade the motor performance and may cause a serious failure if they last longer and some others cause motor stop operating few seconds after occurrence. Therefore various FTCS's must be run simultaneously, however there should be a priority on implementing the fault isolation and remedial strategies if two or more successive faults happen at the short time intervals.

Signal analysis, model based and knowledge based methods are three main fault diagnosis techniques in the BLDC motor drives [3]. In the signal analysis based fault diagnosis methods, fault is detected through comparison of the extracted features of the motor signals with the ideal condition. There is no need for a dynamic model of the BLDC motor in this technique, however fault detection is not as fast as other methods [4]. Parameter estimation techniques are used for fault diagnosis in the model based methods. This techniques is quite fast and can

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TABLE I
COMMON FAULTS IN BLDC MOTOR DRIVES

Section	Fault type	Description
Stator	Short circuit of windings	Three phase Three phase to ground Two phase Two phase to ground One phase to ground Turn to turn fault
	Open circuit of windings	It may happen by some inverter faults
	Change of resistance	Overheating Overloading
Rotor	Eccentricity Asymmetry Rotor unbalanced Rotor magnet damage Misalignment Bearing fault	
Inverter	Switch faults	Open circuit fault Short circuit fault
	DC link fault	Short circuit to ground Capacitor bank fault
Position sensors	Sensors breakdown	Flaws in the core Change in the bias current Change in core magnetic property Change in induced magnetic field
	Misalignment	

be used for online fault detection systems; however knowing exact model of the BLDC motor is their main drawback [4]. Model based observers are popularly used in fault diagnosis systems; Moseler et al. is reported a model based fault detection technique that can be applied to both end-of-line and online fault detection [5]. However fault detection residuals are influenced not only by system faults but also by disturbances and model uncertainties [6]. Since uncertainties are unknown and cannot be predicted and modelled mathematically; thus there is always a difference between the simulation results and actual system performance that can generate false residuals for the model based fault detection systems [7]. In the knowledge based fault diagnosis methods, expert systems are developed for fault diagnosis using fuzzy logic or neural network based on experienced knowledge of the plant [3]. The knowledge is collected either through consultation with an experienced engineer who has a thorough understanding of the plant, or via comprehensive study of the plant's dynamics through the simulation model [2]. Some systems employ more than one fault diagnosis technique. For instance, Liu et al. is reported fault diagnosis system based on parameter estimation and neural network [3].

There are priceless published research works on fault tolerant control systems of the BLDC motor inverter drive in various application. Fault diagnosis systems based on wavelet transform analysis of DC link current of the BLDC motor are discussed [8]. Complexity and massive computational needs of wavelet analysis is the main drawback of this method. Open circuit switch fault diagnosis algorithm of inverter based on stator current analysis is reported [9]. Although the method is simple and does not need complicated computations, however fault diagnosis methods based on current analysis are not capable of distinguishing either the fault has occurred inside the motor or inverter [10]. Four different inverter switch faults diagnosis techniques based on various voltage sensing points of the BLDC motor have been reported [10]. Voltage errors are signature for fault detection in all four techniques. Fault detection time is significantly improved however these techniques have major limitations. Voltage of neutral point of the BLDC motor is needed for two of presented techniques. Neutral point of the BLDC motor is not stable during high frequency PWM switching therefore these techniques are not consistent for fault diagnosis system in a closed loop control scheme. Applied line voltages of the BLDC motor vary frequently in applications with continuous change of speed and load such as electric vehicles; therefore the ideal reference voltage should also change dynamically for reliable fault detection [2]. A fault detection method based on measured voltage of lower switches in each phase of inverter is proposed for voltage fed PWM inverter [11]. Noise susceptibility of sensors used inside the inverter due to high frequency PWM signal is the main limitation of the presented method. A structured neural network system has been designed by Masrur et al. to detect and isolate the most common inverter faults of induction motor drives for EV and hybrid EV applications [12]. Features to train the neural network and fault detection are extracted from torque, voltage and current signals. The proposed method is fast and accurate; however complexity, number of sensors and need for neutral point voltage of motor are its remarkable drawbacks [2].

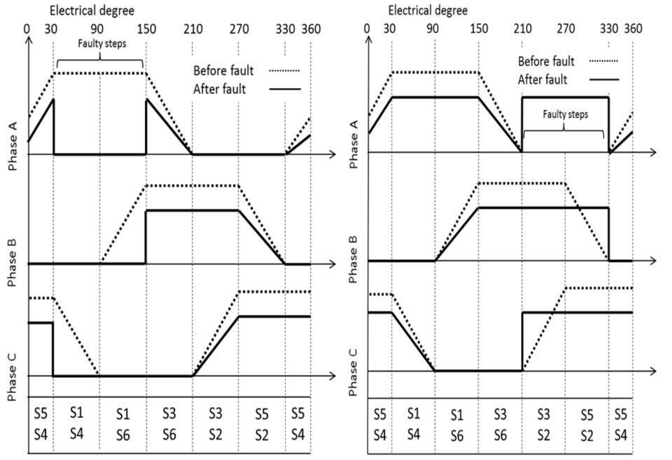
This paper presents a signal analysis based expert system for fault diagnosis of open circuit switch faults of the BLDC motors VSI drives. This paper is an extended research work on a reported paper by authors [2] which the proposed fault diagnosis algorithm is validated by experiment data. In this study; six fast active fuses are connected in series with inverter switches; therefore short circuit fault is removed fast by implemented fuses and is treated as an open circuit fault by the proposed FTCS.

II. FAULT DIAGNOSIS

Switching algorithm of the BLDC motor based on rotor position is shown in Table II. Inverter switch faults affect directly on the applied voltages to the motor. Line voltages of the BLDC motor are calculated at each switching step under faulty conditions and results are compared with the healthy condition. BLDC motor line voltages under open circuit faults of the inverter switches S_1 and S_2 (as shown in Fig. 1) and healthy condition are shown in Fig. 2.

TABLE II
SWITCHING ALGORITHM OF THE BLDC MOTOR

Switching steps	Rotor angle (Electrical degree)	Conducting switches
Step 1	30-90	S_1 , S_4
Step 2	90-150	S_1 , S_6
Step 3	150-210	S_3 , S_6
Step 4	210-270	S_3 , S_2
Step 5	270-330	S_5 , S_2
Step 6	330-30	S_5 , S_4



a) Open Circuit Fault S1 b) Open Circuit Fault S2

Fig. 2. BLDC motor line voltages under inverter switch faults

BLDC motor line voltages are analysed for the inverter switch faults diagnosis. Line voltages are sensed regarding the VSI DC link negative terminal to eliminate unwanted common mode noises and filtering needs. In applications with the frequent changes in speed and load, transition period in variations of the BLDC motor operating condition should be considered in the fault diagnosis. Fault detection and identification algorithms of the VSI open circuit switch faults in the BLDC motor drive are discussed in the following.

A. Fault Detection

Any pattern change of the BLDC motor line voltages under constant speed and load operating condition are signature of the fault occurrence. Discrete Fourier transform is used for pattern recognition of the BLDC motor line voltages. In practice, line voltages are measured for the specific intervals of time continuously while the BLDC motor is operating. The minimum time interval that line voltages are needed to be measured for correct fault detection is one electrical rotation. The time length of one electrical degree rotation is dependent on the motor speed. Measured line voltages are saved in the memory of the micro-controller and DFT and Spectral Energy Density (SED) of them are calculated for each phase of the motor from equations (1) and (2). Calculated SED values of each time interval are compared with the SED values of the previous time interval (as shown in equation (3)) to find the SED errors of each phase.

$$V(f)=\sum_{n=0}^{N-1} V_n e^{-j2\pi k\frac{n}{N}} \qquad k=0,1,...,N \tag{1}$$

$$E_m(f)=|V(f)|^2 \tag{2}$$

$$\varepsilon_m = E_m(f)-E_{m-1}(f) \tag{3}$$

If the calculated SED errors of the BLDC motor line voltages exceed a predefined limit, fault occurrence is detected. Five percent of the SED values under healthy condition are defined as a limit to avoid any short term disturbance detection.

B. Fault Identification

The BLDC motor drive is modelled to study the behaviour of the motor under inverter switch faults. A practical experimental set-up of a low voltage BLDC motor drive is developed to validate the simulation model. The low voltage development control board of microchip using PIC18F4231 micro-controller is programmed as the BLDC motor drive. Experimental test rig of the BLDC motor is shown in Fig. 3. Specifications of the experimental BLDC motor are given in Table III.

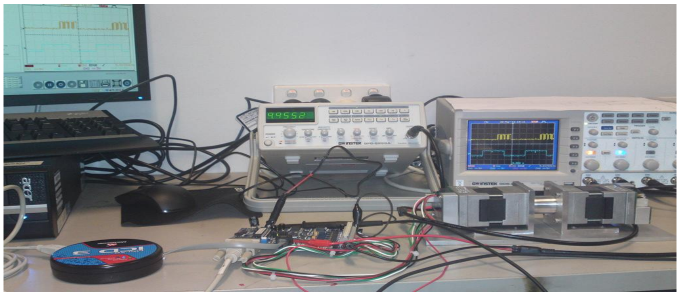


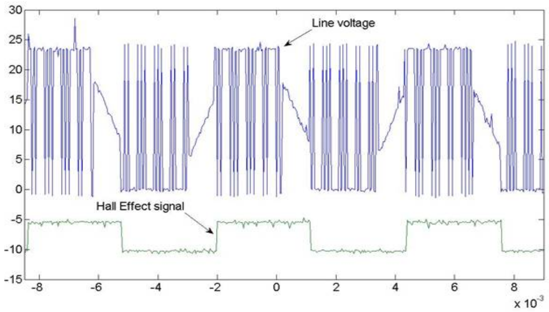
Fig. 3. BLDC motor test rig

Experimental motor specifications are implemented in the simulation model. A Proportional Integral (PI) controller is used to adjust the duty cycle of a high frequency PWM signal based on speed error. PWM speed controller is coded and embedded in Simulink model of the BLDC motor drive. High frequency PWM signals are applied to all switches of VSI.

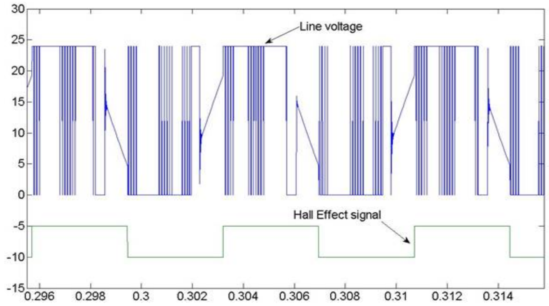
TABLE III
EXPERIMENTAL BLDC MOTOR SPECIFICATIONS

Description	Value	Unit
DC voltage	24	V
Rated speed	3000	RPM
Rated Torque	0.28	$N.m$
Phase resistance	2.015	Ohm
Phase inductance	4.60×10^{-3}	H
Inertia	4.43×10^{-6}	$kg.m^2$
Torque constant	0.069	$N.m/A$
Poles	8	-

Experimental BLDC motor and its simulation model are tested at 2000 rpm reference speed under 0.1 N.m load torque. The line voltage and corresponding Hall Effect signals of experimental BLDC motor drive and its simulation model are shown in Fig. 4. Good agreement between simulation and experiment results validates the BLDC motor model. Open circuit faults of the VSI switches are applied to the validated BLDC motor model. Spectral energy density errors of line voltages are calculated and analysed before and after the fault occurrence. A knowledge based system is designed for fault identification based on SED errors analysis of all phases in various fault conditions.



a) Experimental



b) Simulation

Fig. 4. Phase A line voltage and Hall Effect signal of the BLDC motor

1) Open circuit of switch S_1: Open circuit fault of switch S_1 is applied at $t = 0.5$ s to the BLDC motor model. Three phase line voltages of the motor during the open circuit fault of switch S_1 are shown in Fig. 5. Line voltages are measured with respect to the negative terminal of the inverter DC link.

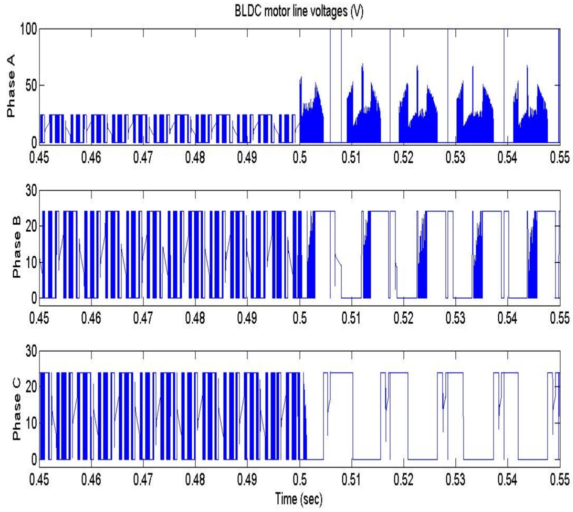


Fig. 5. BLDC motor line voltages during open circuit fault of switch S_1

Large positive amplitude spikes are added to the line voltage of phase A (the faulty phase) under fault condition. Voltage of phase A has been deteriorated after the fault occurrence. Line voltages of phases B and C have been also changed, though phase A has the most variations. Spectral energy density errors of the BLDC motor line voltages under open circuit fault of switch S1 are given in Table IV. SED error of phase A line voltage is maximum as it has the most pattern change.

TABLE IV
SIMULATION SED VALUES FOR OPEN CIRCUIT FAULT OF S_1

Description	Phase A	Phase B	Phase C
SED before fault $[E_{m-1}(f)]$	963.95	958.56	954.67
SED after fault $[E_m(f)]$	1.0862e+05	1019.76	902.06
SED error $[\varepsilon_m]$	107656.05	61.2	-52.61

2) Open circuit of switch S_2: Open circuit fault of switch S_2 is applied at $t = 0.5$ s to the BLDC motor model. Three line voltages of the motor during open circuit fault of switch S_2 are shown in Fig. 6.

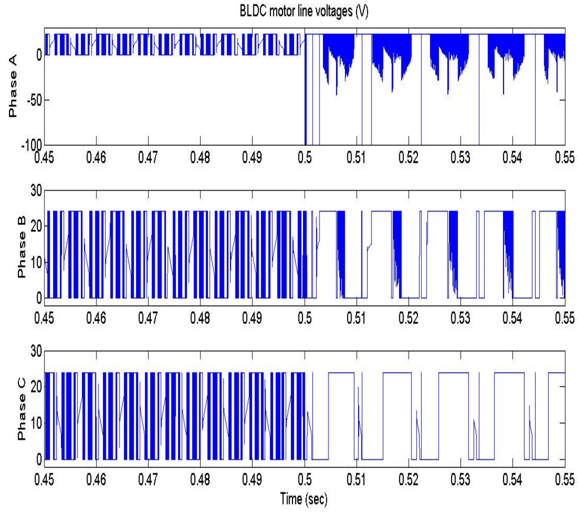


Fig. 6. BLDC motor line voltages during open circuit of switch S_2

Large negative amplitude spikes are added to the line voltage of phase A (the faulty phase) under fault condition. Line voltages of phases B and C have been significantly varied, however changes of line voltage of phase A is more than other two phases. Spectral energy density errors of the BLDC motor line voltages for open circuit fault of switch S_2 are given in Table V. SED error of phase A line voltage is maximum as it has the most distortion.

TABLE V
SIMULATION SED VALUES FOR OPEN CIRCUIT FAULT OF S_2

Description	Phase A	Phase B	Phase C
SED before fault $[E_{m-1}(f)]$	963.95	958.56	954.67
SED after fault $[E_m(f)]$	1.0912e+05	1076	1115.5
SED error $[\varepsilon_m]$	108156.05	117.44	160.83

C. Fault Diagnosis Algorithm

BLDC motor line voltages are also studied under open circuit switch fault of other inverter phases through the simulation model. Results show that the presented and discussed

SED errors of phase A can also be generalized for the other two phases due to symmetry of the BLDC motor [2]. Two identification flags are defined, one to identify faulty switch named as *Switch Fault Flag* (SFF) and the other to identify the faulty phase named as *Faulty Phase Flag* (FPF). Quasi-fuzzy if-then rules are developed to assigned numeric values to the flags according to linguistic variables. Since the faulty phase always has the most pattern change; thus maximum SED error value indicates the faulty phase of the inverter. Numeric values of SFF of each phase and FPF are determined as below,

- SFF is '-1' if SED error is negative and below the limits;
- SFF is '0' if SED error is in the limits;
- SFF is '1' if SED error is positive and over the limits;
- FPF is '0' if no fault is detected;
- FPF is '1' if maximum SED error is related to phase A;
- FPF is '2' if maximum SED error is related to phase B;
- FPF is '3' if maximum SED error is related to phase C.

Since SED errors of the BLDC motor line voltages are fault identification signature in the proposed technique; therefore there is no need to know the exact pattern of the line voltages for the various speeds or torque loads in advance. Simulation results analysis ultimate to develop a multidimensional knowledge based table (as shown in Table VI) to identify switch faults of the VSI.

TABLE VI
RULE BASED FAULT IDENTIFICATION TABLE

Fault type	SFF phase A	SFF phase B	SFF phase C	FPF
No fault	0	0	0	0
Open circuit S_1	1	1	-1	1
Open circuit S_2	1	1	1	1
Open circuit S_3	-1	1	1	2
Open circuit S_4	1	1	1	2
Open circuit S_5	1	-1	1	3
Open circuit S_6	1	1	1	3

III. EXPERIMENTAL RESULT

Electric circuitry of the low voltage (LV) development control board of microchip is modified (as shown in Fig. 7) to test the open circuit fault of inverter switches in the experimental set-up. Hall Effect sensors are used to detect permanent magnet rotor position and control board has an in-built over current protection circuit that avoids phase currents to exceed a predefined limit.

The inverter section consists of three half-bridge gate drivers and a three phase inverter bridge using MOSFETs. Open circuit faults of phase A of inverter is applied to the BLDC motor drive while it is running at 2000 rpm under 0.1 N.m load torque. Line voltages of the experimental BLDC motor under open circuit fault of switch S_1 are shown in Fig. 8.

As shown in Fig. 8, voltage of phase A (faulty phase) is totally deteriorated. Voltages of other phases are also changed, though voltage of phase A has the most variations same as the simulation results. Experimental results prove theoretical calculation of the BLDC motor line voltages under open circuit fault of switch S_1 shown in Fig. 2-a. Experimental SED errors of line voltages for open circuit fault of switch S_1 are given in Table VII. Spectral energy density error of phase A is the maximum, however it is not as large value as simulation results that is due to the over current protection circuit of the control board.

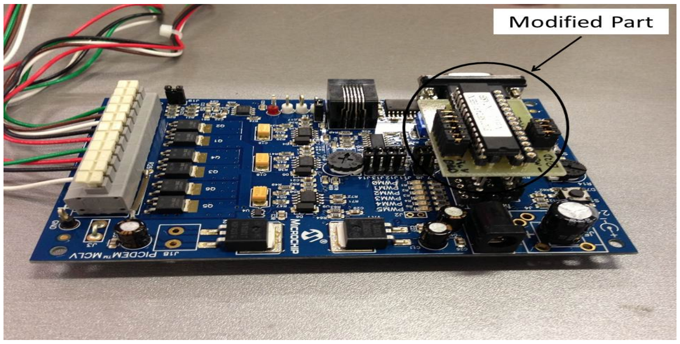


Fig. 7. Modified LV development control board of microchip

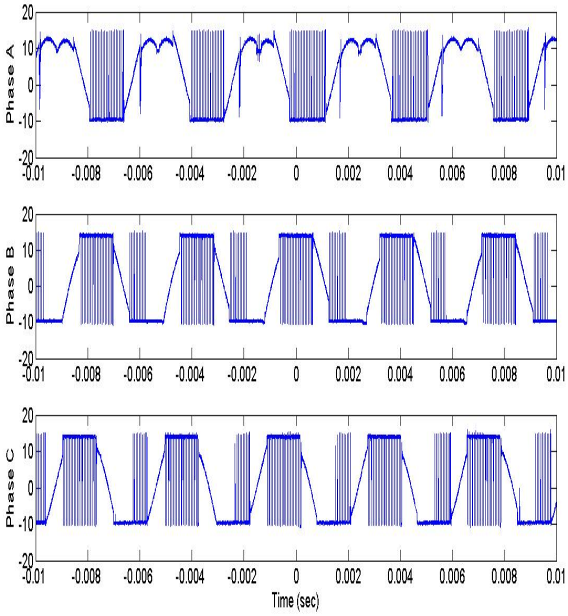


Fig. 8. Experimental line voltages during open circuit fault of switch S_1

TABLE VII
EXPERIMENTAL SED VALUES FOR OPEN CIRCUIT OF S_1

Description	Phase A	Phase B	Phase C
SED before fault $[E_{m-1}(f)]$	314.98	322.17	322.35
SED after fault $[E_m(f)]$	348.34	339.26	302.36
SED error $[\varepsilon_m]$	33.36	17.09	-19.99

Line voltages of the experimental BLDC motor under open circuit fault of switch S_2 are shown in Fig. 9. Experimental results prove theoretical calculation of the BLDC motor line voltages under open circuit fault of switch S_2 shown in Fig. 2-b. Experimental SED errors of line voltages for open circuit fault of switch S_2 are given in Table VIII.

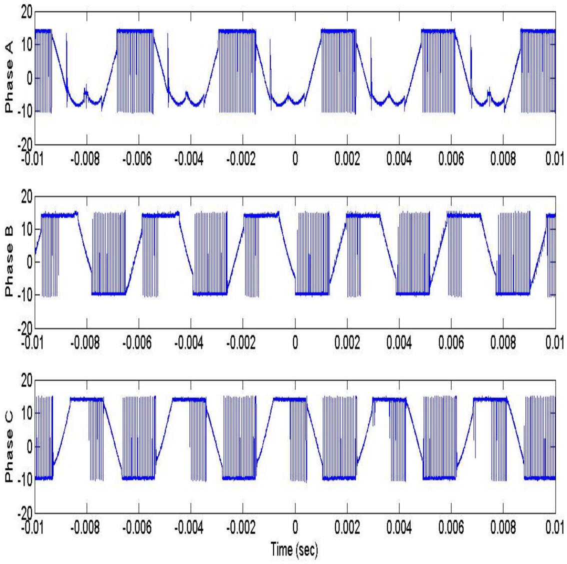


Fig. 9. Experimental line voltages during open circuit fault of switch S_2

TABLE VIII
EXPERIMENTAL SED VALUES FOR OPEN CIRCUIT OF S_2

Description	Phase A	Phase B	Phase C
SED before fault $[E_{m-1}(f)]$	314.98	322.17	322.35
SED after fault $[E_m(f)]$	352.97	344.32	340.12
SED error $[\varepsilon_m]$	37.99	22.15	17.77

Single-sided amplitude spectrum of phase A line voltages of the experimental BLDC motor under no fault, open circuit fault of switches S_1 and S_2 are plotted in Fig. 10. As can be seen, high amplitude harmonics are added to the line voltage of the BLDC motor under inverter open circuit switch fault conditions. Therefore spectral energy density errors of the line voltages are signature for inverter switch fault diagnosis in the BLDC motor drives.

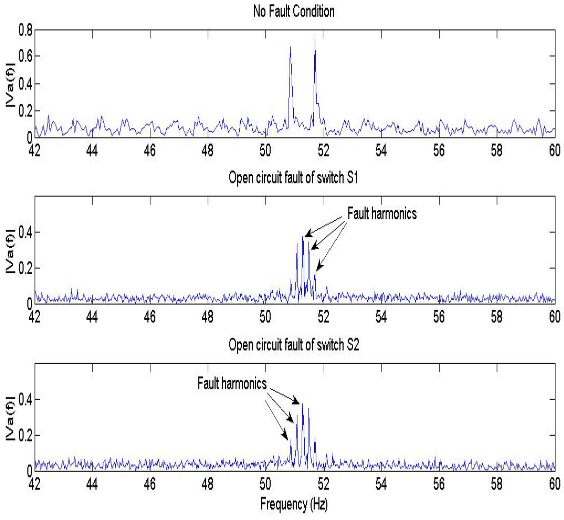


Fig. 10. Amplitude spectrum of phase A line voltage of the BLDC motor

BLDC motor is also tested under various open circuit switch faults of other inverter legs through the experimental set-up. Experimental results are similar to the open circuit switch fault of phase A due to the symmetry. The most spectral density errors are always belong to the line voltage of the faulty phase. Therefore experimental results validate the fault diagnosis algorithm and the multidimensional knowledge based fault identification table developed through simulation results analysis.

IV. REMEDIAL STRATEGIES

Any inverter drive malfunction must be rectified in a mean time to maintain the maximum possible motor performance. In applications such as EV drive train and medical instruments that involves direct human interaction, safe operation of the motor drives after fault occurrence is the main concern. Faulty phase of inverter must be disconnected from the power supply through implemented electronic switches to avoid further major faults in the BLDC motor drive [2]. There are various VSI reconfiguration topologies to isolate and rectify switch faults and retain the BLDC motor operation in post-fault condition. Post-fault strategies are not in the scope of this paper, however two simple reported inverter topologies are discussed below.

VSI reconfiguration to the four switches inverter topology (as shown in Fig. 11) is proposed for BLDC motors in post-fault condition [13]. In the proposed inverter topology, the faulty leg of VSI is connected to the midpoint of the inverter DC link. Employing the four switches inverter topology degrades performance of the BLDC motor however it increases the reliability of the motor drive for a short time after fault detection [2]. Therefore four switches inverter topology is recommended for applications that do not involves direct human interaction.

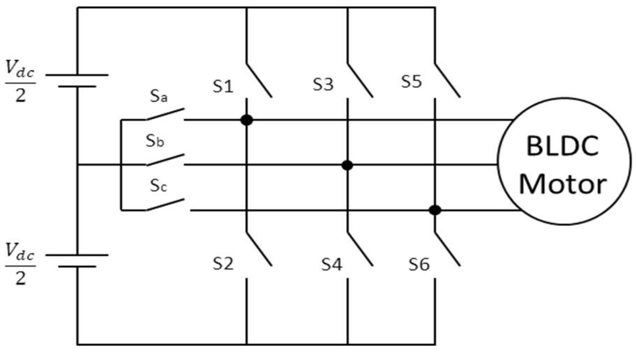


Fig. 11. Four switches inverter topology

Errabelli and Mutschler are proposed a simple, modular and easy controlled fault tolerant control VSI with a redundant leg for BLDC motors [14]. In the proposed method, a redundant leg is replaced with the faulty leg in post-fault condition. BLDC motor performance is not degraded in this technique, however VSI manufacturing cost is much higher due to the extra two switches. Transition to the proposed VSI configuration is quite fast that disturbance on BLDC motor operation is negligible. The proposed VSI model with a redundant leg is shown in Fig. 12. VSI model with a redundant leg is more suitable for applications that safety is the main issue such as propulsion system of the electric vehicles [2].

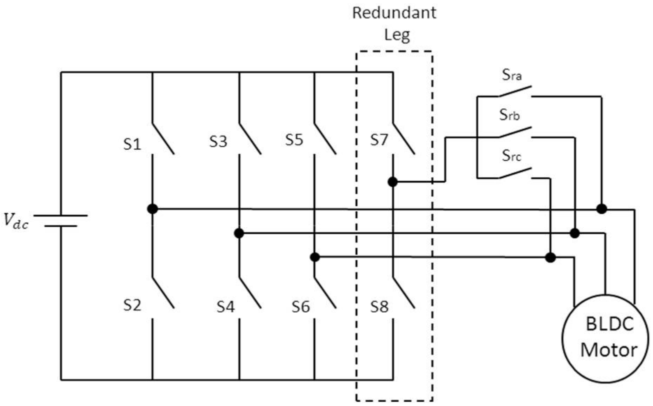


Fig. 12. Fault tolerant control VSI with a redundant leg

V. CONCLUSION

In this paper, a new fault diagnosis system is proposed to detect and identify the inverter open circuit switch faults in the BLDC motor drives. BLDC motor behaviour is analysed under the VSI open circuit switch fault conditions through a validated simulation model. A multidimensional knowledge based table is developed to identify the inverter open circuit switch faults based on DFT analysis of the line voltages. Spectral energy density errors of the line voltages are signature of the fault detection and identification, therefore having pre knowledge of the line voltage patterns of the BLDC motor for various reference speed or torque loads is immaterial. Therefore the proposed fault diagnosis algorithm is suitable for applications with the frequent change of speed and load. Effectiveness of the fault diagnosis algorithm is investigated through experimental test rig. Experiment results proves correctness of the proposed fault diagnosis algorithm. The inverter model with a redundant leg is recommended for applications that safety is the main concern. The proposed fault tolerant control system improves safety and reliability of BLDC motor drives.

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