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Fault Diagnosis of In-wheel BLDC Motor Drive for Electric Vehicle Application

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Abstract— **Permanent magnet Brushless DC (BLDC) motors have been attracted by electric vehicle (EV) manufacturers in the last decade. The paper presents a simple fault diagnosis technique to detect switch faults of three phases Voltage Source Inverter (VSI) drive of BLDC motor in a closed-loop control scheme. The proposed fault diagnosis system is capable to detect the fault occurrence, identify fault type and the faulty switch of inverter based on Discrete Fourier Transform (DFT) analysis of the measured line voltages of BLDC motor. BLDC motor drive and the proposed fault diagnosis system are simulated. Simulation results were validated first by experimental data for BLDC motor operation under healthy condition. A knowledge based table is developed to identify switch faults of VSI by analyzing the simulation results under various fault conditions. The proposed fault diagnosis algorithm does not need massive computational effort and can be implemented as a subroutine with a closed-loop control algorithm of the BLDC motor on a single chip microcontroller. The obtained results show correct detection and identification of inverter switch faults in BLDC motor.**

I. Introduction

Electric Vehicles are one of the solutions for sustainable transportation to reduce the greenhouse gases emission in the world. In-wheel technology is one of the main research focuses for propulsion system of high performance electric vehicles. Different types of motors have been used as an in-wheel motor for drive train of electric vehicles so far. The main characteristics of the in-wheel motors are; high power density, high efficiency, wide speed range with constant power, high torque at low speeds, high torque to size ratio, low moment of inertia, robustness, precise controllability and reasonable cost of production [1]. BLDC motor has been introduced as the most suitable drive train of high performance electric vehicles [2].

Brushless DC motors have been used widely in industrial applications since 1970's. It is a novel type of brushed DC motor that commutation is done electronically. Since exact position of rotor should be known for the electronic commutation; it has a more complex control algorithm compare to other motor types. Position of the rotor can be detected whether using sensors mounted inside motor or sensorless techniques. In this paper Hall Effect sensors with 120 electrical degree phase difference mounted inside the BLDC motor are used to detect rotor position.

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Safety is the most significant factor in electric vehicles; therefore any malfunction of the EV drive train can result in an accident. As such, optimized performance of the propulsion system under various kinds of internal or external faults is one of the most critical issues in EV application. Therefore development of fault diagnosis strategies acts an important role to increase reliability and safety of electric vehicles. The fault tolerant system mainly should perform the following tasks in general:

1) fault detection;
2) fault identification;
3) fault isolation.

Critical situations for an in-wheel motor can be divided into either mechanical shocks (abrupt change of load on motor) or various faults in motor and its controller. Mechanical shocks are not in the scope of this paper. Faults of BLDC motor may happen in stator, rotor or inverter. Various possible faults of in-wheel BLDC motor are summarized in Table I.

TABLE I
Common Faults of In-wheel BLDC Motor

Fault 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

Signal analysis, model based, and knowledge based methods are three basic classifications for fault detection and diagnosis algorithms of BLDC motor [3]. In the first method the features of output signal is extracted and used to detect the faults. The greatest advantage of this method is that there is no need for a dynamic model of the motor; however fault detection is not as quick as other methods. In the second method parameter estimation techniques are used to detect and diagnose faults. This method can be used for online fault detection; however the exact model of motor is needed. In the third method expert systems are developed to detect and diagnose motor faults using fuzzy logic or neural network according to the experienced knowledge [3].

Valuable research work have been published on fault diagnosis systems of BLDC motor for various applications [3-10], however there are very few studies on in-wheel motors fault diagnosis for electric vehicle. Liu *et al.* [3] and Moseler *et al.* [4] have reported model-based fault detection for BLDC motor. Need for exact dynamic model of BLDC motor is the main drawback of these methods. Fault diagnosis systems based on wavelet transform analysis of DC link current and stator current for BLDC motor have been discussed respectively in [5] and [6]. Note that wavelet analysis is complex and requires massive computational effort. A simple fault diagnosis algorithm based on stator current to detect open circuit switch faults of inverter has been presented [7]. The method is very simple and does not need complex mathematics computation. However, fault diagnosis algorithms based on current analysis are not capable of distinguishing whether the fault has occurred in the motor or inverter [8].

Four different fault detection techniques with respect to various voltage sensing points of BLDC motor have been introduced to detect and identify power switches fault of inverter [8]. Fault detection signatures for all techniques are voltage errors. Here fault detection time is significantly improved however these techniques have two major limitations. First, voltage of neutral point of the BLDC motor needs to be measured for two of presented techniques in [8]. Hence neutral point of BLDC motor is not stable during PWM switching; these techniques are not consistent for fault diagnosis system in a closed loop control scheme. Second, applied line voltages of BLDC motor vary frequently for applications with continuous speed and load change such as electric vehicles. Therefore the ideal reference voltage should also change dynamically for reliable fault detection.

A fault detection method using measured voltage of lower switches in each phase of inverter has been proposed for voltage fed PWM inverter [9]. Noise susceptibility of sensors used to measure the voltage of switches inside the inverter due to high frequency PWM signal is the main limitation of presented method. A structured neural network system has been designed by Masrur *et al.* [10] to detect and isolate the most of common types of inverter faults of induction motor drive for EV and hybrid EV applications. Features to train the neural network and fault detection are extracted from torque, voltage and current signals in electric drive system. High accuracy and fast fault diagnosis are the main advantages; however complexity, number of sensors and need for neutral point voltage of motor are drawbacks of the proposed method.

Fault diagnosis of switch faults of VSI drive of BLDC motor in a closed loop control scheme for electric vehicle in-wheel application is presented in this paper. Digital PWM technique is used to control the speed of motor in a closed loop scheme. A Proportional Integral (PI) controller is designed to adjust the duty cycle of high frequency PWM signal with respect to speed error. Controlled PWM signal is applied to upper switches of each leg of VSI. Fault detection technique, Fault identification algorithm and fault isolation of BLDC motor drive are discussed in the following.

II. Fault Detection

In this paper, open and short circuit switch faults of three phase VSI drive of BLDC are investigated. Any malfunction of inverter switches during high frequency PWM switching effects directly on the applied voltages of the BLDC motor. Therefore three line voltages of BLDC motor are measured with respect to negative terminal of DC link of inverter for fault detection and identification. BLDC motor drive, six switching steps of VSI, ideal line voltages and commutation signals are shown in Fig 1.

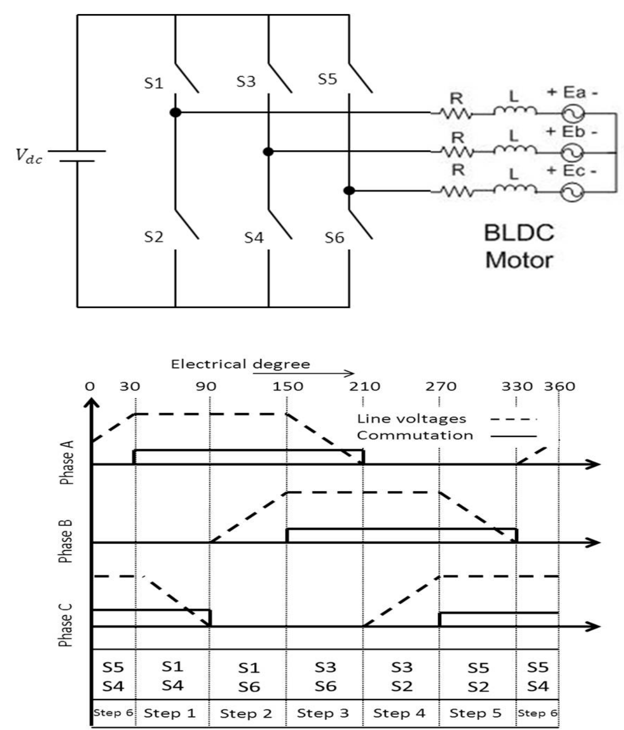


Fig. 1. BLDC motor drive, six switching steps of VSI, ideal line voltages and commutation signals

In applications such as EV with the frequent variation of motor speed, changes of controller reference speed should be considered for fault diagnosis. Pattern change of applied voltages of the BLDC motor for a constant reference speed and torque load is a signature of the fault occurrence. Discrete Fourier transform is used for pattern recognition of line voltages. Frequency spectrum of the measured voltages are extracted by (1) for the specific intervals of time. The minimum time interval for proper fault detection is one electrical rotation of motor. The calculated Spectral Energy

Density (SED) of the DFT from (2) is compared with the SED value of previous time intervals to detect any error. This procedure is repeated in an infinite loop while the BLDC motor is operating.

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

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

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

If SED errors (ε_m) of any of the line voltages calculated by (3) exceeds a certain limit for a constant reference speed condition, fault occurrence is detected. Ten percent of SED values of each phase under healthy operation condition are considered as a limit to avoid short term disturbance detection.

III. Fault Identification

In practice voltage sensors measure the line voltages of BLDC motor for a minimum time period of one electrical degree rotation. Note that the length of one electrical degree rotation depends on reference speed of controller. The sensors output (measured voltages) are converted to a digital signal if needed and are saved in the memory of microcontroller. Discrete Fourier transform and spectral energy density of the saved voltage values are calculated. Two fault flags are defined based on SED errors of the line voltages of BLDC motor. Afterward, fault type and faulty switch is identified through a developed multidimensional knowledge base table.

A three phase in-wheel BLDC motor hub designed for electric motor cycle application is used as a practical test motor. Experimental setup of BLDC motor that is used to validate simulation model is shown in Fig. 2. The simulation model is developed based on specification of the experimental test motor. Three phase in-wheel BLDC motor specification is given in Table II.

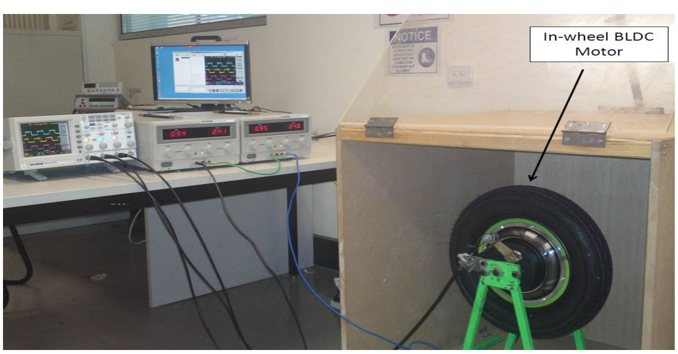


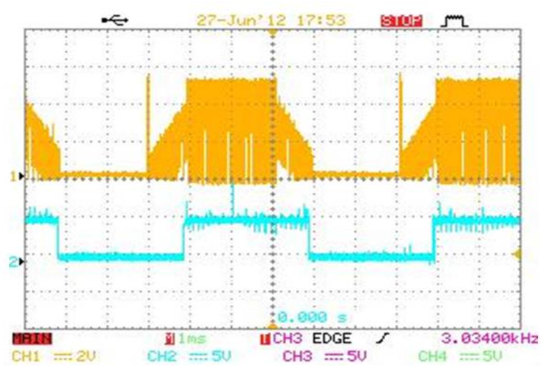
Fig. 2. Experimental test setup of BLDC motor

The simulation results of BLDC motor for normal operation are validated by experimental data. Subsequently, different inverter switch faults are applied to the validated simulation model. Line voltages of motor are studied during the fault conditions and the results are analyzed ultimately to develop a knowledge based table for fault identification.

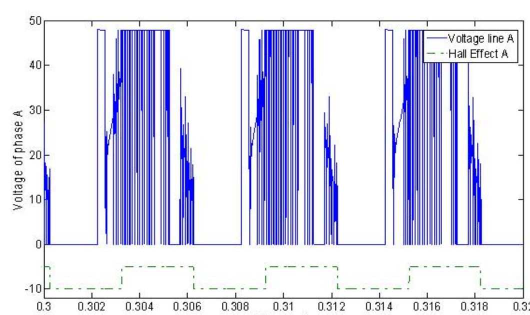
TABLE II
In-wheel BLDC Motor Specifications

Description	Value	Unit
DC voltage	48	V
Rated Speed	600	RPM
Phase resistance	0.4	ohm
Phase inductance	1.2e-3	H
Inertia	0.52e-5	$Kg - m^2$
Damping ratio	0.001	$N.m.s$
Poles	8	-

The in-wheel BLDC motor hub and simulation model are tested under the same operating conditions for 600 RPM reference speed. Inbuilt drum brake of the in-wheel motor hub is employed to apply torque load to the test motor. Applied load torque to the motor according to manufacturer test datasheet is 1.54 N.m. Good agreements between the simulation results and the test data validates simulation model of in-wheel BLDC motor. Experimental and simulation results of the line voltage and corresponding Hall Effect signal of phase A are shown in Fig. 3 respectively.



a) Experimental



b) Simulation

Fig. 3. Line voltage and Hall Effect signal of phase A of BLDC motor

Behavior of BLDC motor for open and short circuit faults of upper switch (S_1) and lower switch (S_2) of phase A of inverter are presented in this paper. Spectral energy density errors of all phase voltages are determined for each fault condition. Switch faults are applied at $t = 1$ to the BLDC model and all line voltages are measured with respect to the negative terminal of DC link of inverter.

A. Short Circuit of S_1

Three line voltages of BLDC motor during the short circuit fault of switch S_1 are shown in Fig. 4.

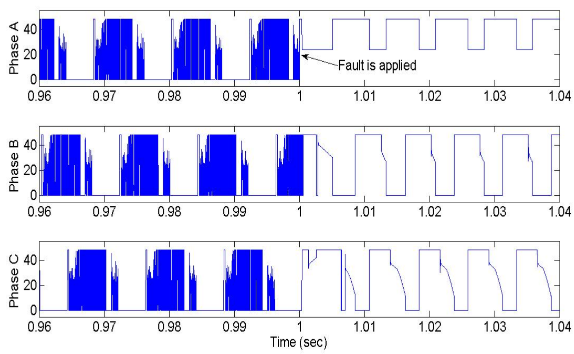


Fig. 4. Line voltages during short circuit of S_1

It can be seen in the figure that line voltages of all phases are changed but the most variation is related to phase A (the faulty phase). Therefore the SED error of phase A should be greater than the other phases. Spectral energy density errors of line voltages of BLDC motor for short circuit fault of switch S_1 are given in Table III.

TABLE III
SED VALUES FOR SHORT CIRCUIT OF S_1

Description	Phase A	Phase B	Phase C
SED befor fault $[E_{m-1}(f)]$	1664	1631	1612
SED after fault $[E_m(f)]$	7730	4950	4946
SED error $[\varepsilon_m]$	6066	3319	3334

B. Short Circuit of S_2

Three line voltages of BLDC motor during the short circuit fault of switch S_2 are shown in Fig. 5.

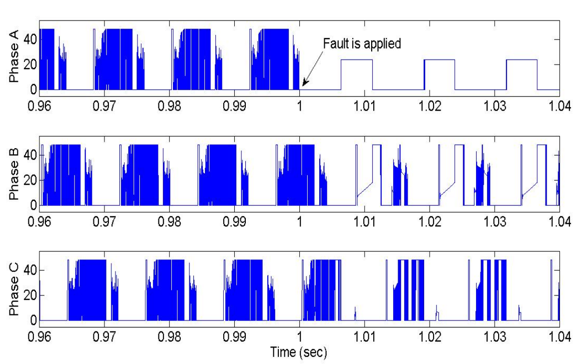


Fig. 5. Line voltages during short circuit of S_2

Phase A (the faulty phase) has the most line voltage variation and the least variation is related to phase C. Therefore the SED error of phase C should be the minimum and SED error of phase A should be the maximum. Spectral energy density errors of line voltages of BLDC motor for short circuit fault of switch S_2 are given in Table IV.

TABLE IV
SED VALUES FOR SHORT CIRCUIT OF S_2

Description	Phase A	Phase B	Phase C
SED befor fault $[E_{m-1}(f)]$	1664	1631	1612
SED after fault $[E_m(f)]$	746	1414	1525
SED error $[\varepsilon_m]$	-918	-217	-87

C. Open Circuit of S_1

Three line voltages of BLDC motor during the open circuit fault of switch S_1 are shown in Fig. 6.

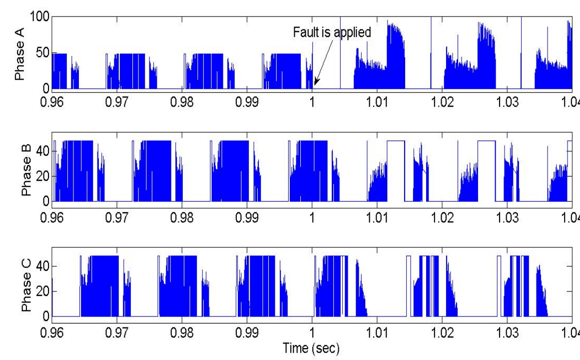


Fig. 6. Line voltages during short circuit of S_1

It is seen in the figure that line voltage of phase A (the faulty phase) displays large positive amplitude spikes and has totally deteriorated. Voltage of phase B has also changed, though phase C has little variation. Therefore the SED of phase A has the maximum error. Spectral energy density errors of line voltages for open circuit fault of switch S_1 are given in Table V.

TABLE V
SED VALUES FOR OPEN CIRCUIT OF S_1

Description	Phase A	Phase B	Phase C
SED befor fault $[E_{m-1}(f)]$	1670	1631	1613
SED after fault $[E_m(f)]$	62784	1918	1662
SED error $[\varepsilon_m]$	61114	287	49

D. Open Circuit of S_2

Three line voltages of BLDC motor during the open circuit fault switch S_2 are shown in Fig. 7. It is seen that the line voltage of phase A (the faulty phase) displays large negative amplitude spikes. Voltage of phase B and C are also significantly changed. Therefore the SED error of phase A should be a maximum compared to other two phases. Spectral energy density errors of line voltages for open circuit fault of switch S_2 are given in Table VI.

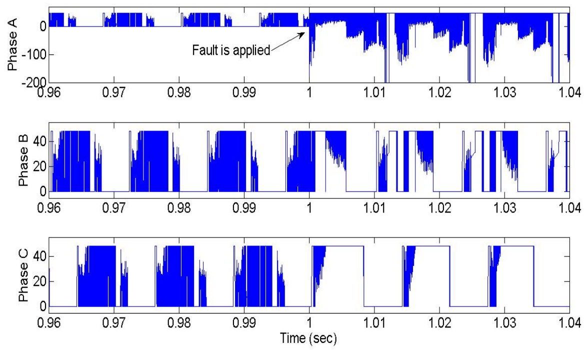


Fig. 7. Line voltages during short circuit of S_2

TABLE VI
SED VALUES FOR OPEN CIRCUIT OF S_2

Description	Phase A	Phase B	Phase C
SED befor fault $[E_{m-1}(f)]$	1670	1631	1613
SED after fault $[E_m(f)]$	181760	3350	4095
SED error $[\varepsilon_m]$	180090	1719	2482

The expert systems are developed either through consultation with an experienced engineer with a thorough understanding of the plant/process, or via comprehensive study of the plant dynamics through modeling and simulation. In this paper, all the aspects of BLDC motor dynamics under various switch faults of all the legs of inverter are studied through the simulation model. The 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 BLDC motor.

Analyzing the simulation SED error results of different fault conditions of each phase results to develop a multi-dimensional knowledge based table to identify the switch faults of VSI. Ten percent of SED value of a healthy system is considered as a limit to avoid any unwanted disturbance detection. Two identification flags are defined, one to identify type of fault named Fault Type Flag (FTF) and the other to identify the faulty phase named Fault Phase Flag (FPF). Quasi-fuzzy if-then rules are developed to assigned proper numeric values to identification flags according to linguistic variables. The maximum SED error value among SED errors of all the three phases indicates the faulty phase. Numeric values of FTF of each phase and FPF are determined as below,

- FTF is '-1' if SED error is over the limits and negative;
- FTF is '0' if SED error is in the limits;
- FTF is '1' if SED error is over the limits and positive;
- FTF is '2' if SED error is over the limit, positive and larger than ten times SED value of healthy system;
- FPF is '0' if no fault is detected;
- FPF is '1' if maximum SED error related to phase A;
- FPF is '2' if maximum SED error related to phase B;
- FPF is '3' if maximum SED error related to phase C.

The simulation model is also tested under fault condition for various reference speeds and torque loads. Since the switch faults are detected through SED errors of the line voltages, thus there is no need to know exact line voltages patterns for the various speed or torque loads of the BLDC motor in the proposed technique. The developed multidimensional knowledge based table with respect to the simulation results analysis is shown in Table VII.

TABLE VII
RULE BASED FAULT IDENTIFICATION TABLE

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

Sudden change of reference speed cause variations in the line voltages. In the proposed method reference speed is assumed to be constant for the proper fault detection and identification. In case of reference speed variation, fault detection system will wait until the actual speed follows the reference speed. If fault happens during speed transition, any difference (more than the defined limit) between SED values of different phases means of the fault occurrence.

IV. FAULT ISOLATION

Faults in drive train of an electric vehicle must be isolated and rectified in a mean time to maintain the maximum possible safety for the passengers. Therefore after identifying the faulty switch of the VSI, the corresponding faulty leg of inverter must be disconnected from the system. This can be done by implemented controlled switches in each leg of VSI. There are various inverter reconfiguration topologies to maintain motor performance in post-fault condition. Reconfiguration of the three phase voltage source inverter of BLDC motor to the four switches topology inverter in post-fault condition is reported [11]. The proposed four switches topology inverter is shown in Fig. 8.

The corresponding BLDC motor phase of faulty leg of VSI will be connected to midpoint of DC link of inverter (through the control switches S_a, S_b, S_c in Fig. 8) to achieve four switch mode operation of inverter and avoid further major faults inside the in-wheel BLDC motor. Performance of BLDC motor is degraded on four switches inverter configuration; however reliability of BLDC drive is increased for a short time after fault occurrence until the vehicle gets the proper service.

A simple, modular and easy controlled fault tolerant VSI is proposed by R. R. Errabelli and P. Mutschler for the

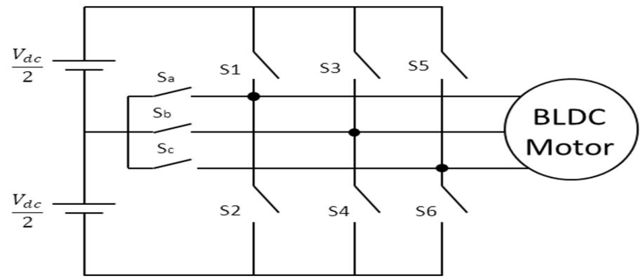


Fig. 8. The four switches topology inverter

BLDC motor drives [12]. In the proposed fault tolerant VSI, a redundant leg is added that will be replaced by the faulty leg in post-fault condition. The proposed fault tolerant VSI with a redundant leg is shown in Fig. 9. Fault isolation and redundant leg insertion to the circuit are done by using independent controlled switches (the control switches S_{ra}, S_{rb}, S_{rc} in Fig. 9).

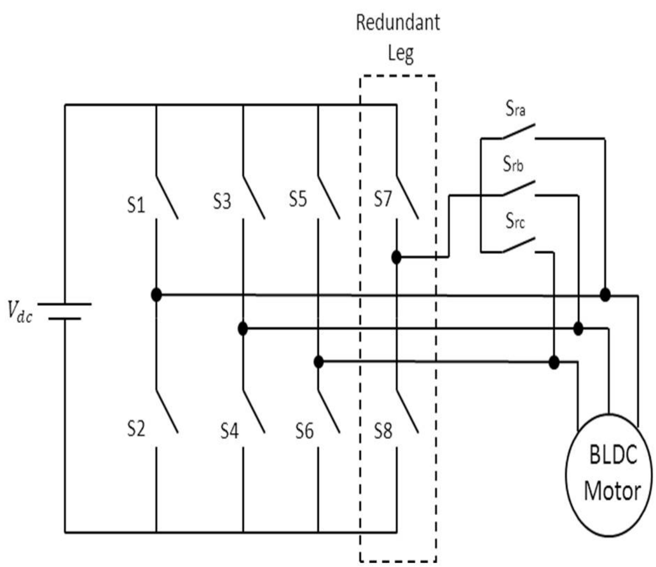


Fig. 9. The fault tolerant VSI with a redundant leg

The post-fault performance of the BLDC motor drive is the same as the normal pre-fault operation. VSI configuration transition of the proposed model is fast enough and disturbance on BLDC drive operation is negligible. Although the performance of BLDC motor is not degraded by the proposed fault tolerant VSI compare to the four switches inverter configuration, however its manufacturing cost is much higher. The proposed VSI model in [12] is recommended for BLDC motors.

V. CONCLUSIONS

In this paper a simple fault diagnosis system is presented to detect switch faults of three phases VSI drive of in-wheel BLDC motor with a closed-loop PWM speed control scheme. Discrete Fourier transform is used to extract the features of the line voltages of BLDC motor. Spectral energy density errors of the line voltages of BLDC motor are signatures for fault detection. Different switch faults are applied to the validated simulation model of BLDC motor. A multidimensional knowledge based table is developed to identify the switch faults of VSI by analyzing the simulation results. In the proposed technique switch faults are detected through SED errors of the line voltages and there is no need to know the exact values of the line voltages of BLDC motor for various speed or torque loads. Therefore the developed fault diagnosis algorithm is suitable for applications with frequent change of speed and load such as electric vehicle. Simulation results of the proposed fault diagnosis system for in-wheel BLDC motor are satisfactory and show correct detection of faulty switch of VSI. The fault tolerant VSI with an extra redundant leg is recommended to isolate and rectify the fault and increase the reliability of EV drive train in post-fault condition. Consequently safety of the electric vehicles is improved.

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