Review on VSI Switch Fault Tolerant Control Systems for Electric Vehicle Drivetrains

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Abstract—**Electric Vehicles (EVs) are an effective solution for reducing greenhouse gas emissions to the atmosphere. Safety is the most crucial issue in the automotive industry and any fault in the EV drivetrain may results in a fatal accident. This paper discusses the dynamic performance of EVs under drivetrain Voltage Source Inverter (VSI) switch faults and presents the suitable Fault Diagnosis Algorithm (FDA) and remedial strategy for EV applications. Physical testing of drivetrain faults in EVs is both expensive and extremely difficult; therefore the Nissan Leaf and the Lightning GT EVs are simulated using a validated model of the Permanent-Magnet Synchronous Motor (PMSM) and their performances investigated under faulty drivetrain conditions. Simulation results show the necessity of implementing Fault Tolerant Control Systems (FTCSs) in EV drivetrain electric motor drives. Various fault diagnosis algorithms of the VSI switch faults in PMSM drives are reviewed and their merits and demerits are discussed. Existing fault tolerant control inverter topologies are also reviewed and compared based on EV application requirements. Finally, suitable FDA and fault tolerant control inverter topology for EV drivetrain application are recommended to maintain safe and optimal vehicle performance in the post-fault condition.**

Index Terms—**Electric Vehicles, VSI switch faults, PMSM motors, Fault diagnosis algorithms, Fault tolerant control inverter topologies.**

I. Introduction

ELECTRIC vehicle adoption is limited, in general, due to both high cost and poor mileage. While Hybrid Electric Vehicles (HEVs) are more popular due to the improved mileage; their cost is still much higher than comparable Internal Combustion Engine (ICE) vehicles. Limitations of natural resources, extensive carbon emissions resulting from burning fossil fuels and new standards and policies regarding efficiency and carbon emissions of motor vehicles defined by various governments in transportation sector have lead automotive industries to develop highly efficient, zero-emission and low-cost, pure-electric vehicles for the future. Automobile manufacturers are also working on Fuel Cell Vehicles (FCVs), which produce the electrical energy from the chemical reaction of hydrogen and oxygen. However cost, durability and temperature limitations coupled with a lack of both refueling infrastructure, and suitable solutions to hydrogen storage and on-board delivery, are the main challenges of FCVs [1].

Various electric motors are used for propulsion of EV's so far. Comparison studies show permanent-magnet synchronous motors (brushless DC motors in particular) are the most suitable choice for low- and medium-duty passenger vehicles [2]. In-wheel motor technology have been used by some manufacturers in recent years, however central drive EVs are also popular. Drivetrain electric motors used in commercial passenger EVs around the world are given in Table I with electric vehicles are sorted by the released year. Induction and permanent-magnet synchronous motors are widely used in commercial passenger EV's by various manufacturers; however PMSMs are the most popular in the recent years. PMSM are mainly divided into two categories based on their back-EMF voltage waveform pattern. PMSMs with sinusoidal back-EMF voltage are known as Permanent-Magnet AC (PMAC) motors and those with trapezoidal back-EMF voltage pattern are called Brushless DC (BLDC) motors. High efficiency, high output power to size ratio, constant torque over a wide speed range, fast dynamic response (due to the permanent-magnet rotor), lower maintenance needs (due to the absence of brushes), noiseless operation and high operating speed ranges are the main advantages of PMSMs over other motor types for passenger EV applications [2].

Improving the safety, efficiency and energy storage technologies of electric vehicles are the most significant research interests nowadays. Research on the EV energy storage technologies are concentrated on increasing energy capacities, and thus EV mileage, as well as reducing battery costs, and hence market price. Employing FTCSs effectively improves the reliability of electric motor drives used in EVs drivetrain and consequently the vehicle safety [3]. A FTCS must detect, identify and isolate faults and apply remedial strategies to maintain normal performance of the system in the post-fault condition.

Various electrical and mechanical faults may occur in PMSMs. Stator windings, inverter switches and inverter DC-link are subjected to open/short-circuit faults. Permanent-magnet rotors are subjected to mechanical faults such as eccentricity, asymmetry, inbalanced, damage to the magnet, rotor misalignment and bearing faults [4]. Additionally, the position sensors may suffer their own issues, including failure due to flaws in the magnet core such as corrosion, cracks, residual magnetic fields and core breakage; changing core-magnet fields due to temperature fluctuations; variations in bias current and orientation of induced magnetic fields due to mechanical shocks and vibration [5]; and misalignment of the sensors during installation that adds low-frequency harmonics in the motor torque ripple [6]. Some faults degrade the PMSM performance and trigger further major faults immediately, while others may only cause motor breakdown if they persist for longer periods [7]. Therefore a number of FTCSs should run simultaneously for various faults, with their performance priorities predefined according to the likely effects on motor

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TABLE I
DRIVETRAIN ELECTRIC MOTORS USED IN COMMERCIAL EVS

EV name	Manufacturer company	Electric motor	Country/ Release year
C-ZEN	Courb	Induction	France/2014
Soul EV	Kia	PMSM	South Korea/2014
Lightning GT	Lightning Car	2 in-wheel synchronous	UK/2014
BMW MiniE	BMW	Induction	Germany/2013
SLS AMG Eletric	Mercedes-Benz	4 in-wheel synchronous	Germany/2013
Spark	General Motors	PMSM	USA/2013
Tesla Model S	Tesla Motors	Induction	USA/2012
Fiat 500e	Fiat	PMSM	Italy/2012
Twizy	Renault	Induction	France/2012
QBEAK	ECOmove	2 in-wheel PMAC	Denmark/2012
Focus Electric	Ford	PMSM	USA/2011
VW e-Golf	Volkswagen	PMAC	Germany/2011
Nissan Leaf	Nissan	BLDC	Japan/2010
Fit EV	Honda	PMAC	Japan/2010
Buddy	Buddy Electric	DC	Norway/2010
BYD E6	BYD Auto	BLDC	China/2010
Electron	Ross Blade	Induction	Australia/2010
Morgan Plus E	Morgan motors	BLDC	UK 2010
VW e-up!	Volkswagen	PMSM	Germany/2009
Zoe	Renault	PMSM	France/2009
Fluence ZE	Renault	PMSM	France/2009
C1 ev'ie	Citroen	Induction	France/2009
Mitsubishi i-MiEV	Mitsubishi	BLDC	Japan/2009
Smart	Smart Automobile	BLDC	Germany/2009
Think City	Think Global	Induction	Norway/2008
ZeCar	Stevens Vehicles	Induction	UK/2008
Venturi Fetish	Venturi	4 in-wheel PMSM	France/2006
MyCar	EuAuto Technology	BLDC	Hong Kong/2003
REVAi	REVA Electric	Induction	India/2001

performance if two or more faults happen over a short time intervals [3].

Simulation models are used to reduce the expense and length of the design process of advanced systems; as such, the modelling of HEVs has grown since the 1970s [8]. Simulation models are used to study various aspects of vehicle operation such as vibration, handling, noise, dynamic performance, safety, stability, reliability and energy consumption [9]. However there are few simulation models of pure electric vehicles with access to VSI switches, which are vital for studying the vehicle performance under inverter faults in drivetrain electric motors. Therefore the Nissan Leaf from Japan with a central drivetrain and the Lightning GT from UK with a rear by-wheel drivetrain simulation model are modeled in this paper and their performance have been studied under both normal (no-fault) and inverter switch faults conditions. Vehicle dynamics such as vehicle speed, wheel rotation and drivetrain electric-motor characteristics were also compared and analyzed subsequently. Finally, FDAs and fault tolerant inverter topologies of PMSMs are presented and their merits and limitations are discussed based on EV drivetrain application requirements.

II. ELECTRIC VEHICLE MODELING

Steady-state, dynamic and quasi-static are the main vehicle modeling techniques. Steady-state models, as the name implies, are concentrated on the steady-state response of the model, neglecting transient conditions. Transient conditions are considered in dynamic models; therefore these models are more complex to develop and need more computations compared to steady state models. Finally, quasi-static models are a combination of the steady state and transient models, which is more suitable for EV drive train modeling [1].

An EV model consists of a number of sub-systems and components; such as electric motors, motor drivers, motor controllers, gearboxes, tires, coupling mechanical shafts, vehicle body and so on which should interconnected to each other. A complex system including a number of sub-system can be developed as a structural or functional model. A structural model is based on interconnecting sub-systems and components according to their physical structure, whereas a functional model is based on interconnecting mathematical functions of sub-systems [1]. Vehicle simulation packages such as ADvanced Vehicle SimulatOR (ADVISOR), Powertrain System Analysis Toolkit (PSAT), Autonomie, AVL Advanced Simulation Technologies (AVL AST) and Virtual Test Bed (VTB) are examples of the structural model.

ADVISOR is developed by US National Renewable Energy Laboratory (NREL). ICE vehicle, EV, HEV and FCV can be modeled and their performance, fuel consumption and emissions can be analyzed by ADVISOR [9]. PSAT is developed by Argonne National Laboratory, sponsored by the U.S. Department of Energy (DoE) and has been licensed to more than 130 companies, universities, and research laboratories worldwide [10]. It is a quasi-steady model developed in MATLAB/Simulink using C language with hardware in the loop testing capability [9], allowing the modeling of light, medium and heavy duty conventional, hybrid and pure electric vehicles. ADVISOR and PSAT are modeled based on look-up tables and efficiency maps of the drivetrain components and are suitable for dynamic modeling of the overall system under extreme operating conditions [9]. Autonomie is a new simulation software, developed by Argonne National Laboratory in collaboration with General Motors, that has replaced PSAT since 2006. It supports the rapid integration and analysis of powertrain/propulsion systems and technologies under dynamic/transient testing conditions [11]. AVL AST provides a set of comprehensive simulation tools with embedded fully validated physical models that enables vehicle performance analysis and optimization of vehicle and powertrain configurations [12]. Providing validated physical model of components makes AVL AST a reliable vehicle simulation tool that can be used for the product development process, or in research studies for further improvements. VTB provides a combination of topological and mathematical models suitable for the prototyping of large-scale, multi-disciplined dynamic systems with advanced visualizations of simulation results capability [13][14]; It is a powerful tool for EV modeling, however it has limited ability to model communication networks within the vehicle [15].

Studying the vehicle performance under drivetrain fault condition requires an accurate EV model including accessibility to parameters of each components within the three phase VSI, the propulsion electric motors and their control drives. For instance, in the case of studying VSI switch faults effects on EV performance, most of the discussed vehicle simulation packages do not provide user access to the drivetrain electric motors and inverter drive switches. Therefore, in this paper a PMSM motor, its inverter drive and motor controller are simulated and validated through experimental data. The validated PMSM drive is integrated with gearbox, tire, mechanical shafts and vehicle body models from the Simscape library to build an overall EV model in Simulink. The developed model provides accessibility to the inverter switches to implement open/close-circuit switch faults and study the EV performance under such faults.

A. PMSM Drive Modeling and Validation

The principle of PMSMs operation is similar to conventional DC motors that commutation is done electronically rather than by brushes [16]. PMSMs are more efficient, have faster dynamic responses and higher speed ranges compared to conventional DC motors; however, their control drives are more complex due to the electronic commutation [7]. Electronic commutation is based on the permanent-magnet rotor position. PMSM drives are mainly divided into drives using sensors to detect the rotor position and sensorless drives. This paper concentrates on a three phase PMSM using Hall Effect sensors for rotor position detection. The schematic diagram of a PMSM drive is shown in Fig. 1.

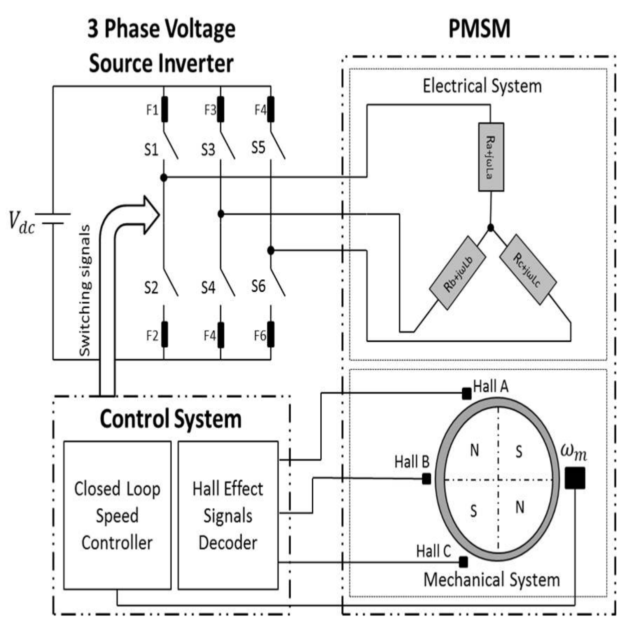

Fig. 1. The schematic diagram of a PMSM drive

An accurate and validated PMSM model is required to study motor performance under inverter drive faults. Therefore in this paper, a PMSM drive is modeled and validated through experimental data. The model consists of a permanent-magnet synchronous motor, a three phase VSI and a closed-loop control algorithm. Hall Effect sensor signals are decoded to detect the permanent-magnet rotor position, and the appropriate voltage space vectors are chosen to commutate the motor based on rotor position. The permanent-magnet rotor position, corresponding Hall Effect signals and inverter switches status of the PMSM are shown in Table II. Switching signals are fed to the three phase VSI to supply voltages to the motor windings. A digital Pulse Width Modulation (PWM) technique is implemented to control the speed. The PWM switching signal is applied to the upper side switches (S_1, S_3, S_5) of inverter.

TABLE II
PMSM DRIVE SWITCHING ALGORITHM

Electrical degree	H_a	H_b	H_c	Inverter switches status					
				S_1	S_2	S_3	S_4	S_5	S_6
30-90	0	1	0	On	Off	Off	On	Off	Off
90-150	1	1	0	On	Off	Off	Off	Off	On
150-210	1	0	0	Off	Off	On	Off	Off	On
210-270	1	0	1	Off	On	On	Off	Off	Off
270-330	0	0	1	Off	On	Off	Off	On	Off
330-30	0	1	1	Off	Off	Off	On	On	Off

Each PMSM drive section is modeled individually and integrated into a Simulink model. A three phase in-wheel PMSM is used as a experimental test motor to validate the simulation model. The experimental test rig of the PMSM drive is shown in Fig. 2. The PMSM model is developed according to real data of the experimental test motor. Specifications of the experimental in-wheel PMSM are given in Table III.

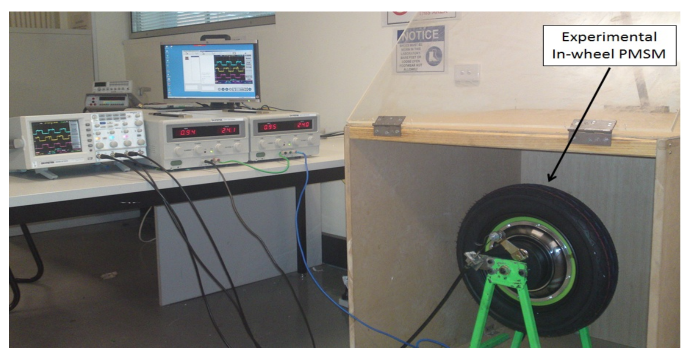

Fig. 2. PMSM experimental test rig

TABLE III
SPECIFICATIONS OF THE EXPERIMENTAL IN-WHEEL PMSM

Description	Value	Unit
DC voltage	48	V
Rated speed	600	RPM
Phase resistance	0.4	Ω
Phase inductance	1.2×10^{-3}	H
Inertia	0.52×10^{-4}	$kg - m^2$
Damping ratio	0.001	$N.m.s$
Poles	8	-

The experimental in-wheel PMSM and the simulation model were tested under the same operating conditions. The inbuilt drum brake of the in-wheel motor hub is used to apply 1.54 $N.m$ torque load (measured based on manufacturer test datasheet) to the test motor at 600 RPM. Speed and torque characteristics of the modeled PMSM are shown in Fig. 3. As can be seen the motor is running at 600 RPM and the produced electric torque is pulsating around the torque load with the torque ripple amplitude of 0.6 $N.m$. The simulation torque response matches closely to the manufacturer test datasheet at 600 RPM.

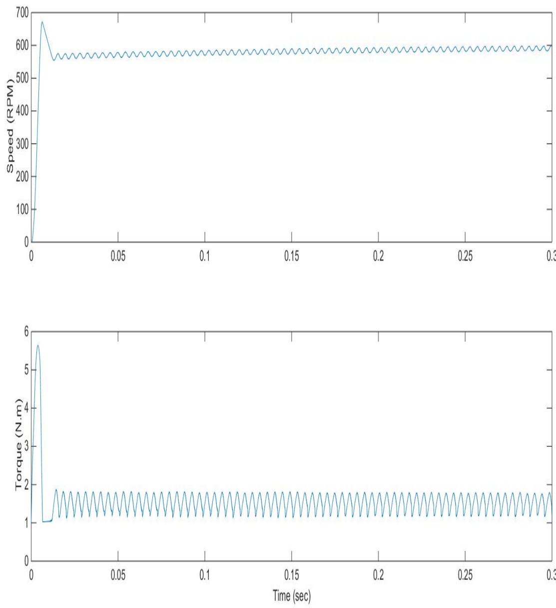

Fig. 3. Speed and torque characteristics of the modeled PMSM

Line voltages and Hall Effect signals of phase A of the test motor and the simulated PMSM model are shown in Fig. 4. The pattern of line voltages and commutation intervals match closely. Good agreements between the simulation and experiment results validate the developed model of the in-wheel PMSM. This validated PMSM model was subsequently used in the Nissan Leaf and the Lightning GT models.

B. Nissan Leaf and Lightning GT Modeling

The Nissan Leaf and Lightning GT electric vehicles are modeled by using real data in the developed model. The schematic diagram of the modeled electric vehicles are shown in Fig. 5. The Nissan Leaf has a central PMSM driven front wheels through a fixed ratio gearbox and a differential, while the Lightning GT has two by-wheel PMSMs propelling each rear wheel through a fixed ratio gearbox.

The Nissan Leaf has a 80 kW PMSM central motor that produces the maximum torque of 280 $N.m$ connected to a gearbox with a final reduction ratio of 7.9377 driving the front wheels. The maximum torque available at wheels is around 2222 $N.m$ by neglecting gearbox and differential losses. This compares with the Lightning GT, which has two

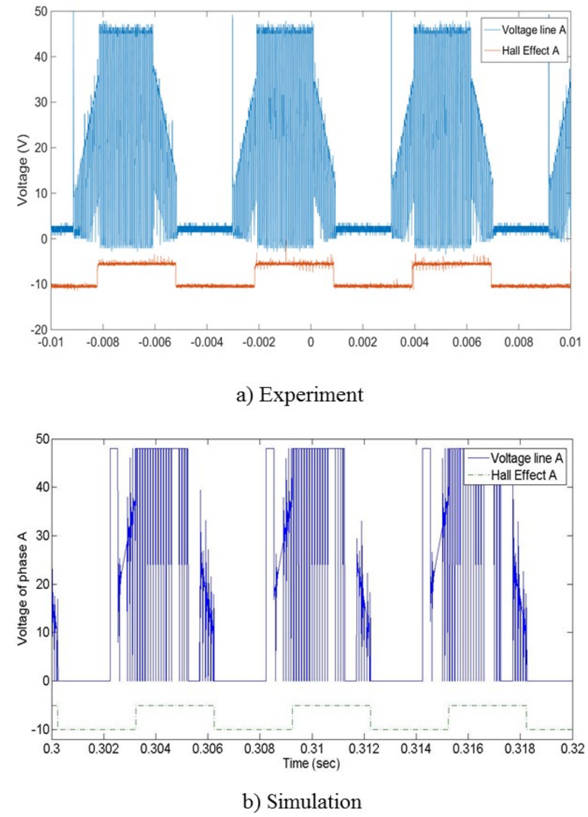

Fig. 4. Line voltage and Hall Effect signal of the PMSM

by-wheel 200 kW PMSMs that each of them produces the maximum torque of 364 $N.m$, connected to a gearbox with final reduction ratio of 5.5 driving the rear wheels with a maximum available torque of around 4000 $N.m$, neglecting gearbox losses. The Nissan Leaf drivetrain configuration is less efficient than the Lightning GT due to the existence of a differential. Drivetrain and vehicle body specification of the modeled EVs are summarized in Table IV.

TABLE IV
SPECIFICATIONS OF THE MODELED ELECTRIC VEHICLES

Description	Nissan Leaf	Lightning GT
Drivetrain Type	A Central Motor	Two By-Wheel Motors
propelled wheels	Front Wheels	Rear wheels
Electric Motor Type	PMSM	PMSM
Max Power (kW)	80	2 × 200
Max Torque ($N.m$)	280	2 × 364
Gearbox Ratio	7.9377	5.5
Kerb Mass (kg)	1567	1850
Vehicle Dimension (m) Length/Width/Height	$4.445/1.77/1.55$	$4.445/1.94/1.2$
Ground Clearance (m)	0.16	0.2
Frontal area (m^2)	2.46	1.94
Wheelbase (m)	2.7	2.59
Tire Size	$205/55R16$	$245/45R20$
Top Speed (km/h)	145	210
Battery (kWh)	24	44
Battery Charger (kW)	6.6	18

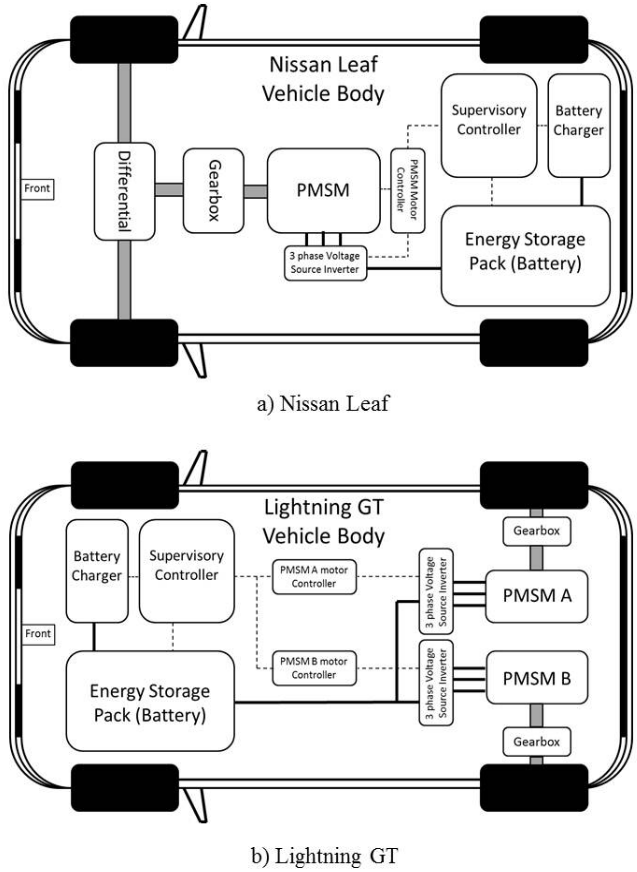

Fig. 5. The schematic diagram of the modeled vehicles

III. EV Dynamics Analysis

A. No-Fault Condition

The developed electric vehicle models are tested to run from zero up to 100 km/h vehicle speed on a flat road (zero percent grade) under no-fault condition. Speed of the EVs and the angular velocity of their wheels are shown in Fig. 6. Simulation results show that it takes 7.2 seconds for a Nissan Leaf to reach 100 km/h, whereas this time is 6 seconds for a Lightning GT. The wheel speeds correspond to approximately 650 RPM for the Nissan Leaf, versus 520 RPM for the Lightning GT. The Nissan Leaf wheel speed is higher due to the smaller diameter of its tire.

The drivetrain electric motor speed and torque of the Nissan Leaf and the Lightning GT are shown in Fig. 7. Presented speed and torque for the Lightning GT is related to one of the rear by-wheel motors. The Nissan Leaf electric motor speed is higher since its gearbox reduction ratio is larger than the Lightning GT gear ratio. Initial produced torque by one of the Lightning GT by-wheel motors are much higher since its maximum power is 2.5 time more than the Nissan Leaf central motor. Nissan Leaf drivetrain motor produces a pulsating torque around 20 $N.m$, while the Lightning GT rear motor produces around 30 $N.m$ pulsating torque.

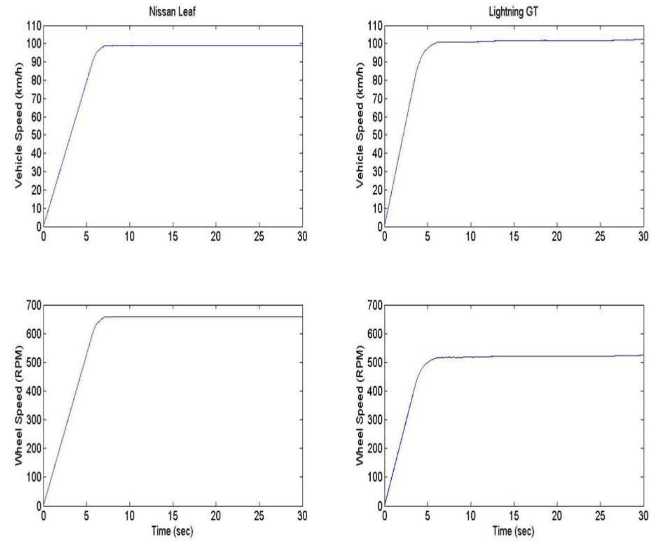

Fig. 6. Modeled Nissan Leaf and Lightning GT vehicle and wheel speed under no-fault condition

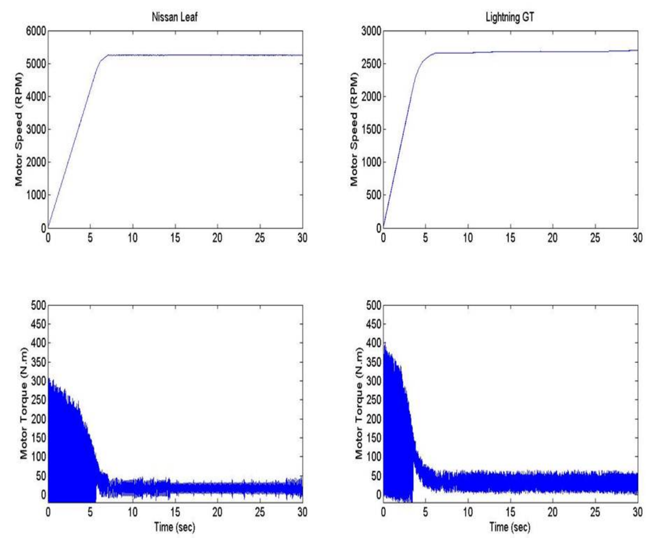

Fig. 7. Modeled Nissan Leaf and Lightning GT drivetrain electric motor speed and torque under no-fault condition

B. Inverter Switch Fault Condition

It is estimated that power switch failure causes 38% of the faults in AC drives [17]; further, switch faults and DC-link faults are also the most common faults in three phase inverter drives of PMSMs. In general switch faults are divided into open and short-circuit faults. Recent studies are focused on open-circuit faults since the short-circuit faults can be removed by connecting six fast active fuses in series with inverter switches; thus, short-circuit faults can be treated as open-circuit faults in FDAs [3][18]. Performance of the PMSM under open-circuit faults condition results in increas both the torque ripple frequency and amplitude of the motor [19].

The developed electric vehicle models were tested to run from zero up to 100 km/h vehicle speed on a flat road. Open-circuit faults of switch S_1 (refer to Fig. 1) of the inverter was applied to the central PMSM of Nissan Leaf and rear by-wheel PMSM A (refer to Fig. 5) of Lightning GT at $t = 20$ s when the vehicles' speed have reached $100\ km/h$. No fault protection systems were implemented for the PMSM motor drives, to observe the maximum fault effects on the electric vehicles' performance. Speed of the modeled EVs under open-circuit fault condition are shown in Fig. 8. As can be seen in the figure, speed of the both vehicles is suddenly increased and vehicles becomes unstable after fault occurrence.

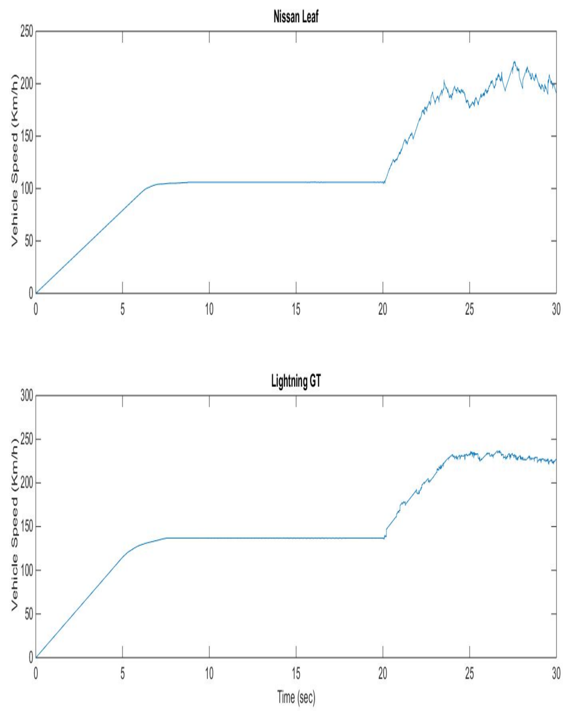

Fig. 8. Modeled Nissan Leaf and Lightning GT vehicles speed under open-circuit fault condition

The drivetrain electric motor speed and torque of the Nissan Leaf and the Lightning GT under open-circuit fault of the inverter switch S_1 are shown in Fig. 9; this reveals that the PMSMs completely destabilized after the fault, with torque and speed response sharply deteriorating. High amplitude notches are seen in the torque responses of the faulty PMSMs since no electrical protection is implemented in the simulation models. In practice, the produced electric torque is directly proportional to the motor current and the maximum current capability of EV battery is normally limited to up to 8 times its nominal current in lithium-ion battery cells; this current is enough to burn all HV cables. Therefore, over current/overload protection relays trips as soon as the motor current goes over the predefined limit and disconnect the HV battery contacts to avoid further damage to the motor winding, inverter, power distribution unit, high voltage cables and energy storage system. Subsequently, the electric motor acts as a fly wheel and sharply decreases vehicle speed; in such a scenario the driver should be informed of fault occurrence, for example through a warning light indicator, to allow them to stop the vehicle in a safe position.

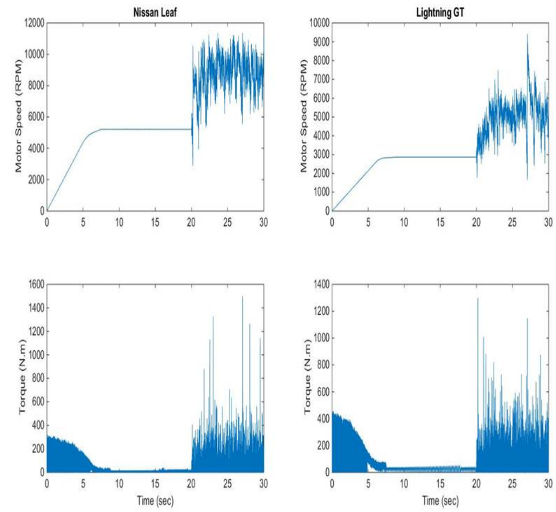

Fig. 9. Modeled Nissan Leaf and Lightning GT drivetrain electric motors speed and torque under open-circuit fault condition

Simulation results show unstable and unsafe performance of both EVs under inverter switch fault; therefore VSI switch fault occurrence puts the electric vehicle and its passengers' lives at risk and makes the vehicle a hazard to others on the road. Comparing the EVs performance under VSI switch open-circuit faults with no-fault condition proves the necessity of FTCSs for the EV drivetrain electric motors to improve safety and reliability of the electric vehicles in the post-fault condition.

IV. Fault Diagnosis Algorithms

Fault diagnosis includes two main actions, fault detection and fault identification. Signal analysis, model-based and knowledge-based methods are the main fault diagnosis techniques in the BLDC motor drives [20]. Signal analysis based methods focus on extracting some features of the motor signals such as voltage or current and comparing the extracted features with the ideal scenario under no-fault conditions [3]. The main advantage of this method is that no dynamic model of the electric motor is needed; however, the fault detection process is not as fast as other techniques. Model-based techniques are fast and can be used for on-line fault detection systems; however, it needs exact model of the motor and, furthermore, fault diagnosis residuals are affected not only by system faults, but also by system model uncertainties and disturbances [7][21]. System uncertainties cannot be modeled mathematically and there are always variations between the simulation model and actual system performance that may generate false residuals for the model-based fault diagnosis systems [22]. The knowledge-based fault diagnosis methods employs fuzzy logic or neural network control systems to diagnose the fault-based on experience or performance knowledge of the plant [3].

Recently, a number of fault diagnosis techniques are usually embedded in advanced FDAs concurrently.

Existing fault diagnosis systems are mainly categorized into current-residual-based FDAs and voltage-residual-based FDAs. Voltage-residual-based FDAs are inherently faster and have higher immunity to disturbance and false fault diagnosis, yet require extra voltage sensors [23][24]. Current-residual-based FDAs are popular due to existence of the current sensors inside inverters; however, they are not fast, resistant to disturbance nor capable of allocating the fault occurrence inside either the motor or inverter [25]. They are also highly sensitive to transients scenarios that frequently occur in electric vehicles [24]. Since reliability of the fault detection is highly significant in EV drivetrain applications, this paper focuses on voltage-residual-based FDAs for the PMSMs.

Four inverter fault diagnosis techniques based on various voltage sensing points of the PMSM are proposed that have improved the fault detection time significantly [25]. Voltage errors are fault detection signatures in all reported techniques. Neutral point voltage of motors are needed in two of proposed techniques. These techniques are not reliable for fault diagnosis in a closed-loop control scheme since neutral point voltage of the PMSM is not stable and floating during the high frequency PWM switching [3]. The pattern of the line voltages of the PMSM is dependent on both operating speed and load torque of the motor; therefore the ideal reference line voltages should change dynamically for reliable fault diagnosis in applications that require continuous change of speed and load, such as electric vehicles [3]. Switch fault detection method is proposed for voltage fed PWM inverters based on the voltages across the lower switches of each inverter leg [26]. The high noise susceptibility of the voltage sensors used inside the inverter, due to high frequency PWM switching, is the main drawback of the reported technique that can decrease the reliability of the fault detection [3]. An inverter switch fault detection using Field Programmable Gate Array (FPGA) is reported by Karimi *et al.* that improves the fault detection time to less than 10 μs [27]. Although, the proposed fault detection algorithm is so complex, however, it is so fast due to the inherent high speed capability of the FPGAs. A neural network based fault diagnosis algorithm is proposed by Masrur *et al.* for the most common inverter faults of induction motor drives in EV applications [28]. Features used to train the neural network to detect various faults are extracted from torque, voltage and current signals of the motor. The proposed method is complex, needs a large number of sensors and the neutral point voltage measurement, but has the advantage of being extremely rapid [3]. A sectoral open-circuit switch fault diagnosis method for the inverter drive of PMSMs are proposed by Choi and Lee [29]. This technique is based on comparison of pole voltages with the generated sector-averaging residual. The main limitations of the proposed technique are its complexity and the offset compensation needs of the generated averaging residual value within sectors due to the integration process. A low-cost open-circuit fault diagnosis technique is proposed for the PWM VSI drive of PMSMs that is based on Model Reference Adaptive System (MRAS) techniques and requires no extra voltage sensors [30]. The proposed method needs an exact model of the PMSM; increasing the complexity of the proposed algorithm; however the fault detection time is improved to less than $0.91\ ms$.

A simple fault diagnosis algorithm for inverter open-circuit switch faults in permanent-magnet synchronous motor drives has been reported by this author in an earlier paper [3]. A knowledge-based expert system is introduced to both detect the open-circuit fault occurrence and identify the VSI faulty switch based on the motor line voltages signal analysis. Switching algorithm of the PMSMs based on permanent-magnet rotor are shown in Table II. Inverter switch faults affect directly on the applied voltages to the motor. The ideal PMSM line voltages under no-fault and open-circuit faults of inverter switches S_1 and S_2 (refer to the Fig. 1) conditions are shown in Fig. 10 [3].

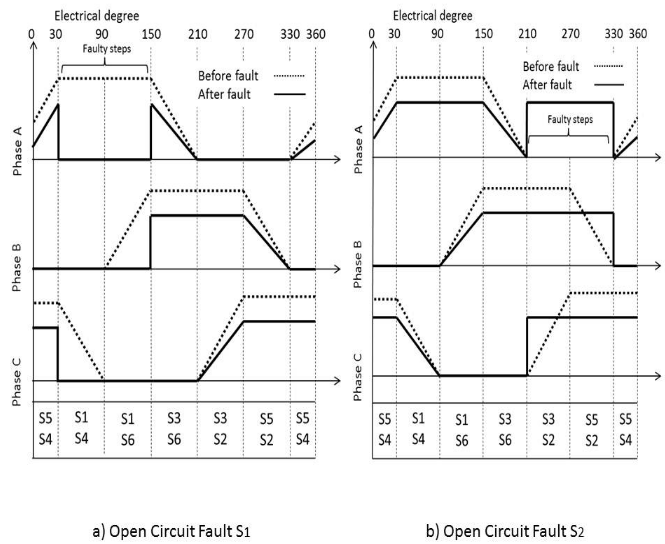

Fig. 10. The PMSM line voltages under no-fault and inverter open-circuit fault conditions

This proposed fault diagnosis is based on Discrete Fourier Transform (DFT) analysis of the PMSM line voltages. Line voltages are measured for the specific intervals of time with respect to the negative terminal of VSI DC-link to eliminate unwanted common mode noises and filtering needs [3]. Spectral Energy Density (SED) of the PMSM line voltages calculated from equation (2) are signature of both the fault detection and identification. Calculated SED values of the successive time intervals are compared as shown in equation (3). A knowledge-based system is developed based on line voltages SED errors by studying the PMSM performance under various VSI switch fault conditions through a validated PMSM model. The proposed FDA is validated through experimental results.

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

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

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

In the proposed technique, prior knowledge of the line voltage patterns or reference voltage values of the motor are not required for various speed or torque loads. This advantage makes the proposed FDA a highly suitable choice for applications that demand frequent changes of speed and torque load, such as electric vehicles. Fault diagnosis on transient condition during sudden changes of the PMSM speed and torque are the main limitations of the proposed technique. In practical applications, the rate of motor acceleration and deceleration are controlled by both the vehicle supervisory and motor controllers. Therefore, the limitation of the proposed FDA is in scenarios where either the driver severely presses the brake pedal, or the vehicle tire hits an obstacle in the road. In these short-period cases, the PMSM line voltages patterns change very fast due to the permanent-magnet rotor (low inertia rotor), resulting in unreliable diagnoses by signal analysis based FDAs. However, erroneous fault detection can be simply avoided by monitoring both the vehicle speed and brake-pedal PWM signal, as these are inputs to the vehicle supervisory controller.

V. Fault Tolerant Control Inverters

Inverter switch faults must be rectified as fast as possible to maintain the best possible motor performance in the post-fault condition. EV application directly interacts with human safety; therefore the correct performance of the fault tolerant control systems is critical. A faulty switch in the inverter must be rapidly isolated from the PMSM drive system by the integrated electronic switches to avoid further major motor faults. Various fault tolerant control inverter topologies are reported to isolate the fault and retain the PMSM operation in the post-fault condition. Some of these inverter topologies are presented and their merits and demerits are discussed for EV application.

The four-switch inverter topology was one of the first fault tolerant control inverter designs proposed for AC induction motor drives [31]. There are two configurations of the four-switches inverter topology that can be used to rectify inverter faults. One method is to connect the faulty phase to the center point of the DC-link that is known as Stator Phase Connection (SPC) hardware reconfiguration and is shown in Fig. 11 [32]. Lee *et al.* studied the feasibility of the SPC-type four-switch inverter topology for permanent-magnet BLDC motor drives [33]; in this method, the average voltage across the motor terminals available in the post-fault condition is $\sqrt{3}$ times less than in the healthy condition [31]. It is possible either to increase the DC-link voltage by factor of $\sqrt{3}$, or change the motor winding from the star to the delta connection to address this issue [32]. None of the above techniques are feasible in EV applications. The DC bus voltage cannot be increased since there is both a fixed EV nominal battery voltage and other HV systems, connected to the same DC bus, that cannot function at higher voltages. Changing the motor winding configuration to delta also requires additional space and hardware that is difficult to fit in the already confined space of modern EVs. Although the vehicle performance is going to be degraded using SPC four-switch inverter configuration, this topology improves the reliability of the PMSM drive for a short time after the occurrence of the fault, allowing the vehicle to survive until servicing [3].

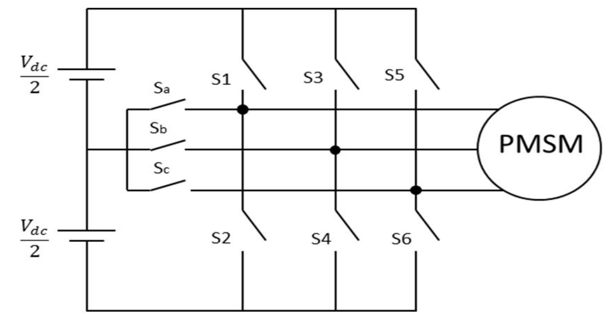

Fig. 11. SPC Four-Switch Inverter Topology

The other method is to connect the neutral point of the motor to the center point of the DC-link that is known as Stator Neutral Point Connection (SNPC) hardware reconfiguration and shown in Fig. 12 [32]. In this method, in the post-fault condition the imposed currents of the working phases are $\sqrt{3}$ times more than the healthy condition [32]. Therefore, for long-term operation higher current rates are required for the inverter semiconductors and HV cables, leading to extra expenses when designing and manufacturing the inverter. Additionally the neutral point of PMSM motors are not normally designed to be accessible by most of manufacturers, which limits applications of SNPC [31]. Therefore the SNPC four switches inverter topology is not suitable for EV drivetrain application.

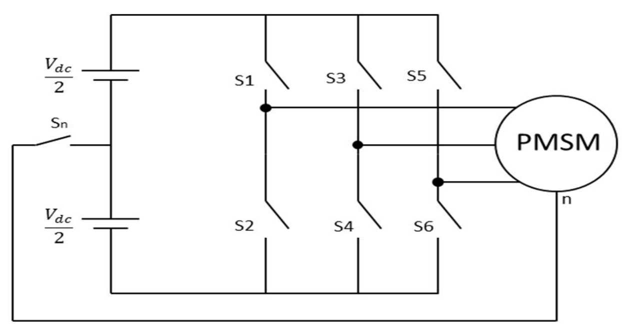

Fig. 12. SNPC Four-Switch Inverter Topology

Bolognani *et al.* reported a fault tolerant drive for PMSMs that employs a redundant extra inverter leg connected to the neutral point of the motor in the post-fault condition, as shown in Fig. 13 [34]. The proposed inverter is also called double-switch redundant inverter topology since it needs two extra fuses and electronic switches for the extra inverter leg. The proposed model does not have the DC-link center point balancing issues; however, it needs the neutral point of the PMSM [31]. In the post-fault condition, over-current is required to maintain the rated output torque, as the average motor line voltages is $\sqrt{3}$ times less than the healthy condition [35]. Therefore double switch-redundant inverter topology is unsuitable for EV drivetrain application.

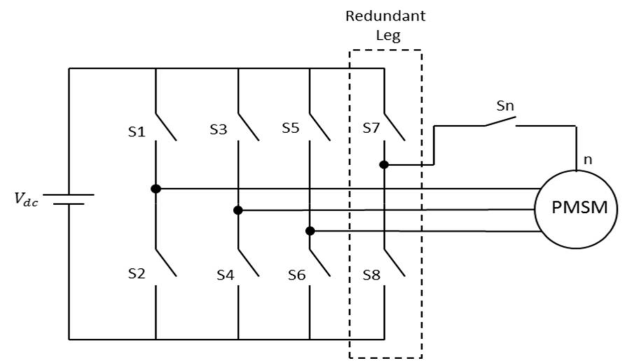

Fig. 13. Double-Switch Redundant Inverter Topology

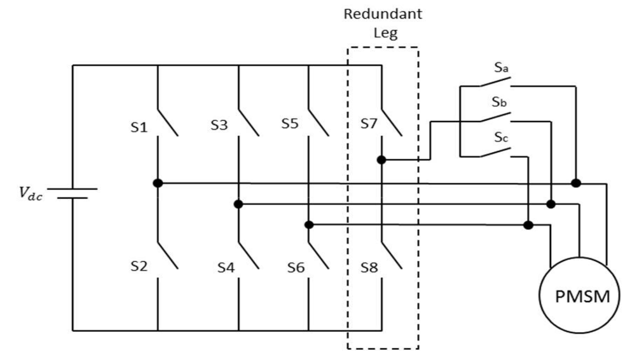

Fig. 14. Phase-Redundant Inverter Topology

The idea of having two inverter in parallel, known as cascaded-inverter topology, proposed for induction motors in the 1980's [36]. The cascaded-inverter topology concept can also be used for PMSMs. The proposed idea maintains the same performance of the motor in the post-fault condition. However, using two inverters in EV drivetrain increases the production cost and is again difficult due to the confined space in the vehicle. A fault tolerant inverter topology is introduced for EV traction applications that employs two permanent-magnet synchronous electric motors [35]. In the proposed model, on occurrence of a fault, the faulty phase of the inverter is isolated and the second inverter is used to drive both motors. The proposed inverter topology maintains vehicle performance in the post-fault condition; however, since one phase leg of inverter is supplying two motors, the current rating is halved, degrading the motor performance. Therefore, it can be used as a temporary solution in the post-fault condition for EV application with two propelling PMSMs up to the point that vehicle get service.

A simple, modular and easy controlled fault tolerant inverter topology is proposed for the permanent-synchronous motors [37]. The proposed method employs a phase-redundant leg to be replaced by the faulty leg of inverter in the post-fault condition as shown in Fig. 14. Transition to the phase-redundant inverter topology is fast enough to neglect the disturbances on the permanent-magnet synchronous motor operation. It does not degrades the motor performance in the post-fault condition, although the VSI manufacturing cost and size is slightly increased. Therefore this paper recommends the phase-redundant inverter topology is the most suitable fault tolerant control inverter for EV drivetrain applications.

VI. Conclusion

Permanent-magnet synchronous motors are popular in passenger electric vehicles produced by various manufacturers. Reliable performance of the PMSMs increases reliability of the EV drivtrain and consequently improves safety of the vehicle. Therefore in this paper, the PMSM drive is modeled, validated through experimental data and used as the drivetrain electric motor to simulate the Nissan Leaf and the Lightning GT electric vehicles. The simulated EVs are tested under VSI switch faults of the PMSM and their dynamic performance are discussed and compared with no-fault condition. Simulation results demonstrate the need of fault tolerant control systems in EV drivetrain electric motors to improve safety and reliability of the electric vehicles in the post-fault condition. Various voltage-based faults diagnosis algorithms for VSI switch faults in PMSM drives are reviewed and their merits and demerits are discussed with a view towards EV drivetrain application. Fault tolerant control inverter topologies for PMSMs are also discussed and compared based on EV drivetrain requirements, and their advantages and disadvantages are highlighted. The paper recommends the suitable VSI switches FDA and fault tolerant control inverter topology for PMSMs used as EV drivetrain electric motors.

References

[1] C. C. Chan, A. Bouscayrol, and K. Chen, "Electric, hybrid, and fuel-cell vehicles: Architectures and modeling," *IEEE Transaction on Vehicular Technology*, vol. 59, pp. 589–597, February 2010.

[2] A. Tashakori, M. Ektesabi, and N. Hosseinzadeh, "Characteristics of suitable drive train for electric vehicle," in *Proceeding of the International Conference on Instrumentation, Measurement, Circuits and Systems (ICIMCS 2011)*, (Hong Kong,China.), pp. 535–541, Dec 2011.

[3] A. Tashakori and M. Ektesabi, "Inverter switch fault diagnosis system for bldc motor drives," *Engineering Letters*, vol. 22, no. 3, pp. 118–124, 2014.

[4] A. Tashakori and M. Ektesabi, "Fault diagnosis of in-wheel bldc motor drive for electric vehicle application," in *In proceeding of the 2013 IEEE Intelligent Vehicles Symposium*, (Gold Coast, Australia), pp. 925–930, June 23-26 2013.

[5] E. Balaban, A. Saxena, P. Bansal, K. Goebel, and S. Curran, "Modeling, detection, and disambiguation of sensor faults for aerospace applications," *IEEE Sensors Journal*, vol. 9, no. 12, pp. 1907–1917, 2009.

[6] N. B. Samoylenko, Q. C. Han, and J. Jatskevich, "Dynamic performance of brushless dc motors with unbalanced hall sensors," *IEEE Transactions on Energy Conversion*, vol. 23, no. 3, pp. 752–763, 2008.

[7] A. Tashakori and M. Ektesabi, "Position sensors fault tolerant control system in bldc motors," *Engineering Letters*, vol. 22, no. 1, pp. 39–46, 2014.

[8] K. Butler, M. Ehsani, and P. Kamath, "A matlab-based modeling and simulation package for electric and hybrid electric vehicle design," *IEEE Transactions on Vehicular Technology*, vol. 48, no. 6, pp. 1770–1778, 1999.

[9] D. W. Gao, C. Mi, and A. Emadi, "Modeling and simulation of electric and hybrid vehicles," *Proceedings of the IEEE*, vol. 95, Issue 4, pp. 729–745, 2007.

[10] Argonne National Laboratory, *PSAT Documentation [online]*. Available: http://www.transportation.anl.gov/modelingsimulation/PSAT/.

[11] Argonne National Laboratory, *Autonomie Documentation [online]*. Available: http://www.autonomie.net/.

[12] AVL, *AVL Advanced Simulation Technologies (AST) Documentation [online]*. Available: https://www.avl.com/web/ast/home.

[13] South Carolina's Flagship University, *VTB Documentation [online]*. Available: http://vtb.engr.sc.edu/vtbwebsite/Overview.

[14] L. Gao, R. Dougal, S. Liu, and D. J. Patterson, "Application of virtual test bed in design and testing of hybrid electric vehicles," in *5th International All Electric Combat Vehicle Conference*, (Angers, France), June 2003.

[15] W. Li and A. Monti, "Integrated simulation with vtb and opnet for networked control and protection in power systems," in *Proceedings of the 2010 Conference on Grand Challenges in Modeling & Simulation (GCMS '10)*, pp. 386–391, 2010.

[16] A. Tashakori, M. Ektesabi, and N. Hosseinzadeh, "Modeling of bldc motor with ideal back-emf for automotive applications," in *Proceeding of the World Congress on Engineering 2011 (WCE 2011)*, vol. Vol. 2, (London), pp. 1504–1508, July 2011. Lecturer notes in engineering and computer science.

[17] B. Tabbache, M. Benbouzid, A. Kheloui, J.-M. Bourgeot, and A. Mamoune, "Pwm inverter-fed induction motor-based electrical vehicles fault-tolerant control," pp. 8204–8209, 2013.

[18] B.-G. Park, K.-J. Lee, R.-Y. Kim, T.-S. Kim, J.-S. Ryu, and D.-S. Hyun, "Simple fault diagnosis based on operating characteristic of brushless direct-current motor drives," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 5, pp. 1586–1593, 2011.

[19] Z. Wang, J. Chen, M. Cheng, and Y. Zheng, "Fault-tolerant control of paralleled-voltage-source-inverter-fed pmsm drive," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 4749–4760, 2015.

[20] X.-Q. Liu, H.-Y. Zhang, J. Liu, and J. Yang, "Fault detection and diagnosis of permanent-magnet dc motor based on parameter estimation and neural network," *IEEE Transactions on Industrial Electronics*, vol. 47, no. 5, pp. 1021–1030, 2000.

[21] Z. Wang, R. Schittenhelm, M. Borsdorf, and S. Rinderknecht, "Application of augmented observer for fault diagnosis in rotor systems," *Engineering Letters*, vol. 21, no. 1, pp. 10–17, 2013.

[22] S. Mondal, G. Chakraborty, and K. Bhattacharyya, "Unknown input high gain observer for fault detection and isolation of uncertain systems," *Engineering Letters*, vol. 17, no. 2, pp. 121–127, 2009.

[23] Q.-T. An, L. Sun, and L.-Z. Sun, "Current residual vector-based open-switch fault diagnosis of inverters in pmsm drive systems," *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2814–2827, 2015.

[24] M. Salehifar, R. Arashloo, M. Moreno-Eguilaz, V. Sala, and L. Romeral, "Observer-based open transistor fault diagnosis and fault-tolerant control of five-phase permanent magnet motor drive for application in electric vehicles," *IET Power Electronics*, vol. 8, no. 1, pp. 76–87, 2015.

[25] R. De Araujo Ribeiro, C. Jacobina, E. Da Silva, and A. Lima, "Fault detection of open-switch damage in voltage-fed pwm motor drive systems," *IEEE Transactions on Power Electronics*, vol. 18, no. 2, pp. 587–593, 2003.

[26] O.-S. Yu, N.-J. Park, and D.-S. Hyun, "A novel fault detection scheme for voltage fed pwm inverter," in *Conference of IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics*, (Paris), pp. 2654–2659, 6-10 November 2006.

[27] S. Karimi, P. Poure, and S. Saadate, "Fast power switch failure detection for fault tolerant voltage source inverters using fpga," *IET Power Electronics*, vol. 2, no. 4, pp. 346–354, 2009.

[28] M. Abul Masrur, Z. Chen, and Y. Murphey, "Intelligent diagnosis of open and short circuit faults in electric drive inverters for real-time applications," *IET Power Electronics*, vol. 3, no. 2, pp. 279–291, 2010.

[29] C. Choi and W. Lee, "Design and evaluation of voltage measurement-based sectoral diagnosis method for inverter open switch faults of permanent magnet synchronous motor drives," *IET Electric Power Applications*, vol. 6, no. 8, pp. 526–532, 2012.

[30] S.-M. Jung, J.-S. Park, H.-W. Kim, K.-Y. Cho, and M.-J. Youn, "An mras-based diagnosis of open-circuit fault in pwm voltage-source inverters for pm synchronous motor drive systems," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2514–2526, 2013.

[31] B. Welchko, T. Lipo, T. Jahns, and S. Schulz, "Fault tolerant three-phase ac motor drive topologies: A comparison of features, cost, and limitations," *IEEE Transactions on Power Electronics*, vol. 19, no. 4, pp. 1108–1116, 2004.

[32] A. Mendes and A. Marques Cardoso, "Fault-tolerant operating strategies applied to three-phase induction-motor drives," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 6, pp. 1807–1817, 2006.

[33] B.-K. Lee, T.-H. Kim, and M. Ehsani, "On the feasibility of four-switch three-phase bldc motor drives for low cost commercial applications: Topology and control," *IEEE Transactions on Power Electronics*, vol. 18, no. 1, pp. 164–172, 2003.

[34] S. Bolognani, M. Zordan, and M. Zigliotto, "Experimental fault-tolerant control of a pmsm drive," *IEEE Transactions on Industrial Electronics*, vol. 47, no. 5, pp. 1134–1141, 2000.

[35] W. Wang, M. Cheng, B. Zhang, Y. Zhu, and S. Ding, "A fault-tolerant permanent-magnet traction module for subway applications," *IEEE Transactions on Power Electronics*, vol. 29, no. 4, pp. 1646–1658, 2014.

[36] T. M. Jahns, "Improved reliability in solid-state ac drives by means of multiple independent phase-drive units," *IEEE Transactions on Industry Applications*, vol. 1 A-16, no. 3, pp. 321–331, 1980.

[37] R. Errabelli and P. Mutschler, "Fault-tolerant voltage source inverter for permanent magnet drives," *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 500–508, 2012.