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Comparison of Different PWM Switching Modes of BLDC Motor as Drive Train of Electric Vehicles

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Abstract—Electric vehicle (EV) is one of the effective solutions to control emission of greenhouses gases in the world. It is of interest for future transportation due to its sustainability and efficiency by automotive manufacturers. Various electrical motors have been used for propulsion system of electric vehicles in last decades. In this paper brushed DC motor, Induction motor (IM), switched reluctance motor (SRM) and brushless DC motor (BLDC) are simulated and compared. BLDC motor is recommended for high performance electric vehicles. PWM switching technique is implemented for speed control of BLDC motor. Behavior of different modes of PWM speed controller of BLDC motor are simulated in MATLAB/SIMULINK. BLDC motor characteristics are compared and discussed for various PWM switching modes under normal and inverter fault conditions. Comparisons and discussions are verified through simulation results.

Keywords—BLDC motor, PWM switching technique, in-wheel technology, electric vehicle.

I. Introduction

IN-WHEEL technology is one of the main research concentration points nowadays. Using separate wheels mounted inside each tire for propulsion system increases efficiency and safety of electric vehicle. Due to the absence of internal combustion engine, weight of chassis is decreased, therefore efficiency of vehicle will increase [1]. An Intelligent Fully Electronically Controlled Vehicles (IFECV) is being targeted by applying in-wheel technology and by wire technology such as By-Wire Steering, Brake by-Wire instead of conventional control system as well as intelligent control systems like electronic stability control, Intelligent Parking Assist and pre-Collision Safety System [2].

High torque at low speeds, high torque/power to size ratio, constant power in wide speed range, high efficiency, high dynamic response, accurate electronic controllability of motor characteristics, robustness and reliability of motor and its drive, low electromagnetic interface to design integral motor and reasonable cost of production are some of the in-wheel motor application requirements [3]. In addition to all above characteristics, in-wheel motor must be capable of frequent start, stop and reversal of rotation with maximum output torque. In this paper DC brushed, induction, switched reluctance and brushless DC motors are simulated and compared under various working conditions with respect to in-wheel motor requirements. BLDC motor is shown better characteristics compere to other motor types for in-wheel applications.

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BLDC motor is a type of DC motor which commutation is done electronically, not by brushes. Thus it needs less maintenance and also its noise susceptibility is less. High efficiency, high speed ranges and high dynamic response due to permanent magnet (low inertia) rotor are immediate advantages of BLDC motor over brushed DC and induction motors for electric vehicle application. BLDC motor has more complex control algorithm compare to other motor types due to electronic commutation. Commutation is done by knowing exact position of permanent magnet rotor. Typically there are two algorithms for rotor detection. One uses usually sensors (Hall Effect) and the other does not which is called sensorless. Hall Effect sensors are mounted inside motor in 120 electrical degrees to detect rotor position. Optical encoders are used for high resolution applications. Various sensorless techniques which have been reported till now are: 1- back-EMF sensing, 2- back-EMF integration, 3- freewheeling diode conduction of unexcited phase, 4- flux linkage based, 5- speed independent position function and 6- third-harmonic analysis of back-EMF [4]. Sensorless control of BLDC motor is not scope of this paper. In this paper commutation is done by Hall Effect sensors in simulation. Accurate model of motor is required to design complete and precise control scheme of BLDC. Permanent magnet synchronous motor block of MATLAB/SIMULINK is used in simulation.

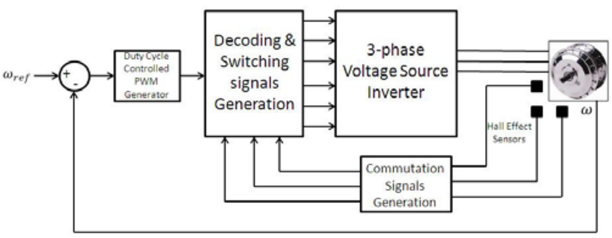

Fig. 1. Overal model of BLDC motor drive

Various algorithms have been used for speed control of BLDC motor. Hysteresis current control and pulse width modulation (PWM) control are the most widely used BLDC motor control techniques [5]. Speed of BLDC motor is directly proportional to its terminal voltages. A three phase voltage source is used to apply voltage to the standard three phase motor. Therefore one of the simplest speed control methods is adjusting the average output voltage of VSI. There two common ways, variable DC link inverter and PWM switching technique. Performance comparison of PWM inverter and variable DC link inverter schemes for high-speed sensorless control of BLDC motor has been discussed by Kyeong-Hwa Myung-Joong [6]. In this paper PWM technique with a proportional integral (PI) duty cycle controller is designed. Different switching modes behaviors of controller in various operation conditions are discussed. Overall schematic diagram of BLDC drive is shown in Fig. 1.

II. Motor Selection

Valuable research has been done in selection of motor for hybrid and electric vehicles [7-9]. Papers [7] and [9]] have suggested that SR motor is a good choice and [8] has recommended BLDC motor. This section endeavors to complete previous research presented in [2]. Transient speed and torque characteristics of all mentioned motors for same load and reference speed under normal and critical working conditions are shown and discussed. Critical condition analysis is important with respect to safety issues. Critical conditions can be considered in two aspects. Electrical faults which may happen inside motor or its controller and mechanical shocks due to change in road condition or sudden brake or change of direction by driver.

A. Normal Condition

Normal condition is assumed as normal operation of vehicle with constant speed on flat, uphill and downhill roads. Brushed DC, induction, switched reluctance and BLDC motors and their drives are simulated. Specification of all motors are presented in appendix A. Simulations have been tested for 1500 rpm reference speed under 10 N.m load torque. Transient speed responses of all motors are presented in Fig. 2.

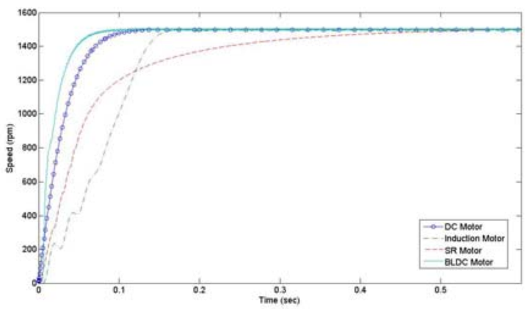

Fig. 2. Transient speed responses

As simulation results show, BLDC motor due to permanent magnet (low inertia) rotor has much faster response than other motor types. Difference in angular velocity of produced flux between stator and rotor results slip in induction motor. Practically rotor speed always lags stator magnetic field speed by slip speed. Slip increases starting vibrations of motor which is not suitable for in-wheel technology. High dynamic response of motor is one of the most important requirements of in-wheel application. Simulation results show tha switched reluctance motor has the poorest dynamic response among all motors.

Transient torque responses of all motors are shown in Fig. 3. It can be seen in Fig. 3 that torque response of BLDC will reach its final value much faster than others. It means BLDC motor has wide speed range with constant torque. Although DC motor has higher initial torque value compare to others but low efficiency and low speed ranges are major weak points of this motor. Induction motor slip is essential to produce torque. Slip is dependent on Supply voltage frequency, rotor resistance and torque load. Change of voltage frequency results in slip variations and torque oscillation in transient condition. One of the most drawbacks of switched reluctance motor is its torque ripple which is remarkable in Fig. 3. Torque ripple causes fluctuation of output power delivered to load which is not suitable for in-wheel application. Therefore, with respect to torque response also it can be seen that BLDC motor is more suitable for in-wheel application.

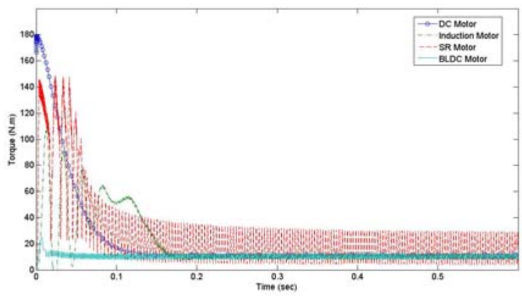

Fig. 3. Transient torque responses

Torque versus speed characteristic of brushed DC, induction, SR and BLDC motors from zero speed to reference speed (1500 rpm) are shown in Fig. 4. It shows that BLDC motor has the minimum torque oscillation in transient time. Torque of BLDC will reach its final value almost when speed of motor reaches 54 precent of its final value. Therefore, Fig. 4 shows better torque/response of BLDC motor compare to brushed DC, induction and SR motors.

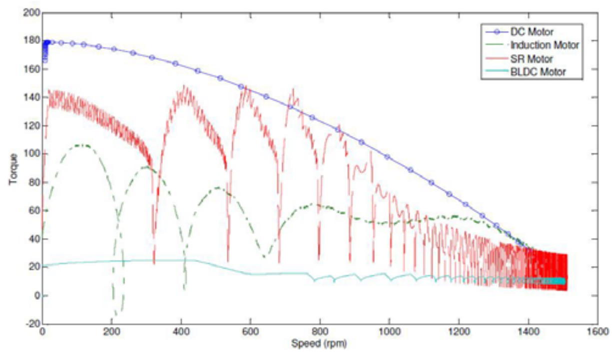

Fig. 4. Transient torque/speed responses

B. Critical Condition

Critical condition is assumed as operation of motor under electrical faults or mechanical shocks. Robustness and reliability of motor and its drive is very important with respect to automotive applications. Therefore in-wheel motor and its controller should be robust during occurrence of electrical faults or mechanical shocks. Various types of electrical faults and mechanical shocks may happen in motors. Three phases to ground fault of line voltages has been chosen for testing simulations in critical condition. For DC motor phase to ground electrical fault is applied. Fault is applied at 0.4 second for duration of 0.1 second. Speed characteristics under same electrical fault condition and duration is shown in Fig. 5.

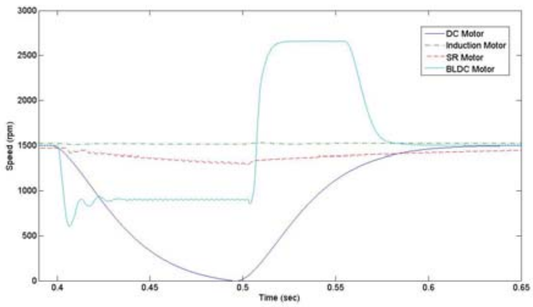

Fig. 5. Speed responses under same electrical fault condition

As it can be seen induction and SR motors have more robust speed response. Speed response of BLDC motor due to its permanent magnet rotor and high dynamic response is not desirable. DC motor speed goes to zero that is not acceptable for electric vehicle. Fig. 6 shows torque response of motors during fault. It depicts from figure that torque fluctuation of BLDC and induction motors are less than others. Torque ripple amplitude of SR motor is increasing during fault condition. DC motor behaves as generator during fault. Though torque response of motor is more important than speed response for in-wheel application, induction and BLDC are better than DC and SR motors.

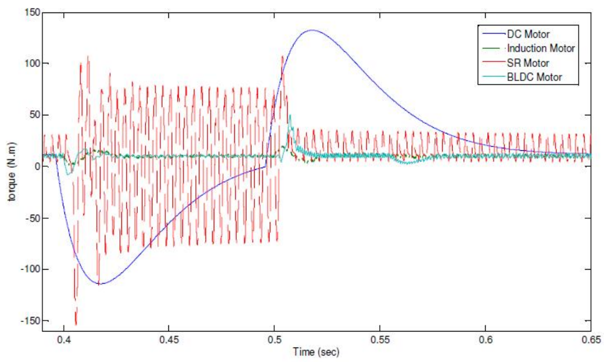

Fig. 6. Speed responses under same electrical fault condition

A mechanical shock is a sudden change of load torque on motor. It may happen due to variation of road condition or sudden brake or change of direction by driver. Sudden change of load torque by 30 percent of its value has been chosen to test motors behavior under same mechanical shocks. Speed and torque responses of all motors under same mechanical shocks are shown in Fig. 7. Results show induction motor has the minimum change in speed response. DC and SR motors almost have same speed response to mechanical shocks. Although BLDC has sharp notches in time of load change, but fast dynamic response of motor causes speed to return to its reference value quickly. These sharp notches are decreased in DTC model of BLDC. As it can be realized, induction and BLDC motor has better torque responses compared to DC and SR motors. Torque ripple of SR motor is increased exactly after the shocks happen.

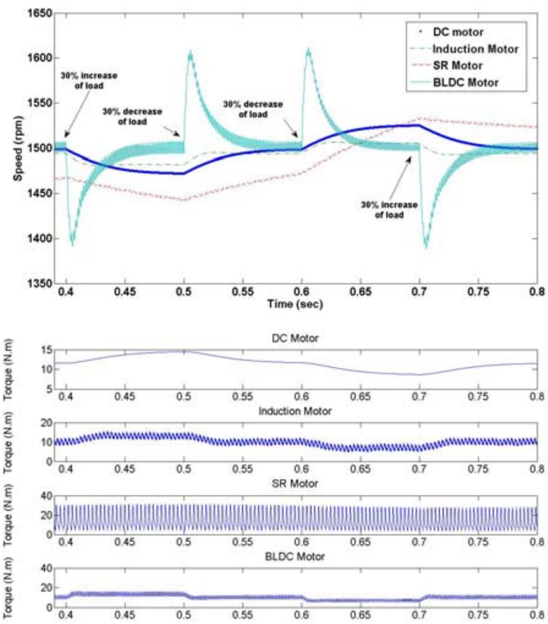

Fig. 7. Speed and torque responses under same mechanical shocks

Simulation outcomes show that induction motor is the most robust among all, but speed range limitations, low efficiency of motor in high speeds and slip of motor in low speeds makes the induction motor not a good choice for high performance electric vehicles. BLDC motor has more desirable torque response in critical condition with respect to SR motor. Robustness of BLDC can be increased by implementing of fault detection, diagnosis and prevention techniques in controller. There are different fault diagnosis techniques for BLDC motor such as signal signature analysis [10] and parameter and state estimations technique [11]. Fault detection, diagnosis and prevention systems are not in the scope of this paper, so it is left for further studies and research in future.

Therefore, with respect to better torque/speed characteristics, higher efficiency, higher dynamic response, high output power to size ratio, higher operating life and noiseless operation, low EMI radiation and high IP rating; BLDC is recommended for in-wheel applications in EVs.

III. PWM Control Technique

A vehicle is supposed to continuous change of speed especially in urban areas. Therefore the controller technique should be as simple as possible as well as quick response. On the other hand drive train controller should be robust due to safety point of view. It should be able to handle some sort of common electrical faults or mechanical shocks till fault tolerant system takes an appropriate decision to handle the fault at least up to the point for repairmen.

PWM technique is one of the most popular speed control techniques for BLDC motor. In this technique a high frequency chopper signal with specific duty cycle is multiplied by switching signals of VSI. Therefore it is possible to adjust output voltage of inverter by controlling duty cycle of switching pulses of inverter. A three phase VSI with MOSFET switches is modeled in MATLAB/SIMULINK to supply BLDC motor.

Duty cycle of chopping signal can be determine by a PI controller [12] or toggle between two predefined duty cycles (high and low duty cycle) [5]. In this paper a PI controller is designed to control duty cycle of chopping signal according to speed error. An embedded MATLAB function is written to generate high frequency (10 KHz) according to the defined duty cycle value. There are three different methods to apply chopping signal to the VSI. These three modes are: apply chopping signal 1- to upper side switches of each leg of inverter, or 2- to lower side switches of inverter, or 3- to all six switches at the same time. In each mode applied voltage to the motor is different, thus output characteristics of BLDC motor is also different. From now on numbers are used to specify any of switching modes. In this paper behavior of BLDC motor for various switching modes in normal and critical condition are compared and discussed.

A. Normal Condition

It is considered that BLDC motor is operating on 1500 RPM reference speed under constant 10 N.m load torque. BLDC speed characteristics of all three modes of PWM switching are shown in Fig 8. It can be seen that switching mode 1 has highest peak overshoot and mode 3 has the lowest in transient condition. High peak overshoot is not suitable for in-wheel motors. All three modes have almost the same speed fluctuation in steady state. Therefore mode 3 has better speed response in normal condition.

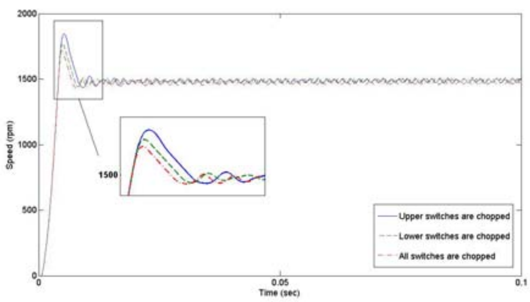

Fig. 8. BLDC speed responses of different PWM switching modes

Torque characteristics of BLDC motor for all PWM switching modes are shown in Fig. 9. Torque characteristics are magnified in transient situation. It can be seen that torque response of mode 1 has negative value where other two modes have zero value at same time. Torque ripple amplitude of mode 3 is the highest where other two modes have almost same ripple amplitude. Lowest torque ripple is more desirable for in-wheel application regarding delivering smooth torque to the wheels.

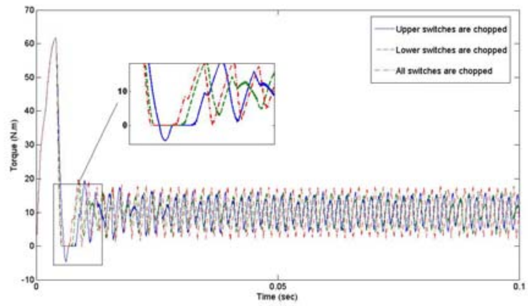

Fig. 9. BLDC torque responses of different PWM switching modes

PI duty cycle controller output is shown in Fig. 10. PWM duty cycle is chosen by controller for each mode is different. Mode 3 has smaller duty cycle changes limit compare to other modes in steady state condition.

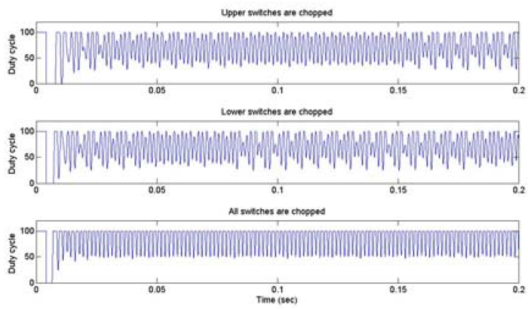

Fig. 10. Duty cycle values of different PWM switching modes

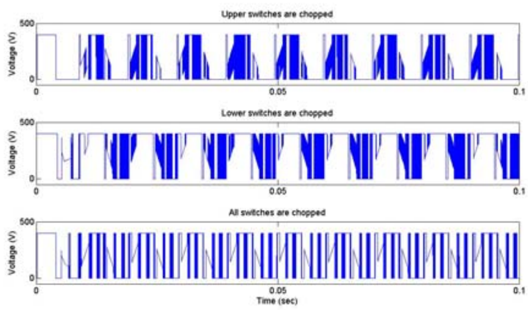

Fig. 11. Phase A terminal voltages of different PWM switching modes

Output voltages of phase A of inverter for different switching modes are shown in Fig. 11. As it can be seen in figure DC bus voltage is chopped during upper side switch conduction of phase A leg and is zero for lower side switch conduction. In mode 2 DC bus voltage is chopped during conduction of lower switch but it did not change during upper side switch conduction. In mode 3 DC bus voltage is chopped during conduction of both switches.

B. Critical Condition

Critical condition is considered as mechanical shocks or electric faults. Mechanical shocks also are simulated as abrupt 30 percent change of torque load on BLDC motor. BLDC motor faults in general can be divided to stator faults, rotor faults and inverter faults. Speed control algorithms for all three PWM switching modes are same except that various switches of inverter is chosen for applying chopped signal. BLDC motor behavior will change regarding any specific fault in switches of inverter according to different PWM switching modes. In this section behavior of BLDC motor for inverter faults in various switching modes are compared and discussed. Various types of inverter faults are exist. In this paper open circuit and short circuit of upper side switch of phase A (first leg) of inverter is considered as fault.

1) Mechanica Shocks: The same mechanical shocks same as section two is applied to study BLDC motor's behavior for various PWM switching modes. Reference speed and load torque are 1500 RPM and 10 N.m respectively. Speed responses of all PWM switching modes are stable around reference speed during mechanical shocks. Torque characteristics of BLDC motor are shown in Fig. 12. As it can be seen BLDC motor is following load torque changes. However torque ripple amplitude of mode 3 is more than other two modes.

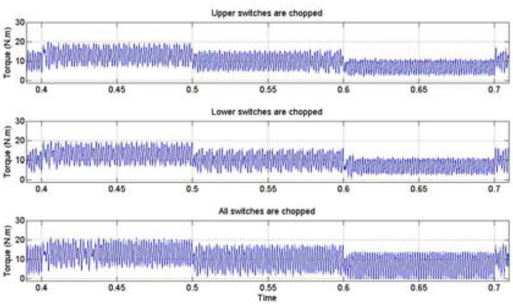

Fig. 12. Torque responses of BLDC during mechanical shocks

PWM duty cycles chosen by controller during mechanical shocks are shown in Fig. 13. It can be seen that higher duty cycle values have been evaluated by controller for higher load torque and vice versa for lower load torques. In modes 1 and 2 duty cycle limit changes are smaller for lower torque loads opposite to mode 3.

2) Open Circuit Fault: An open circuit fault of upper side switch of phase A leg of inverter is applied at 0.2 second to a normal condition operation of BLDC motor for 1500 RPM reference speed under 10 N.m load torque. Speed responses of BLDC shown in Fig. 14 are almost same for all PWM switching modes. BLDC is lost the operating point and speed

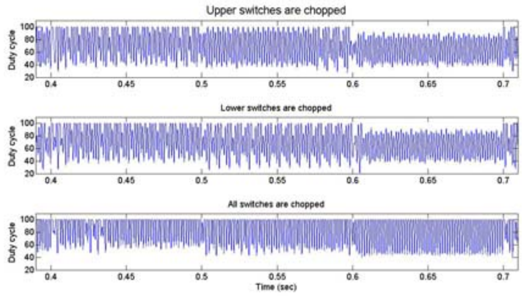

Fig. 13. Duty cycle values during mechanical shocks

is starting to oscillate with approximately 500 RPM amplitude. Therefore BLDC motor is unstable in all modes.

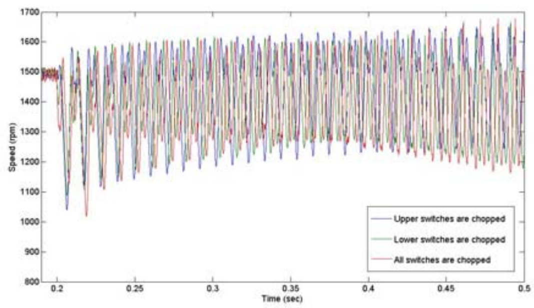

Fig. 14. Speed responses of BLDC during open circuit fault

Current of phase A of BLDC motor during open circuit fault is shown in Fig. 15. In mode 1 current of phase A pass through negative cycle but for other two modes current has both positive and negative cycle. Sharp notches in current waveforms are seen for all modes.

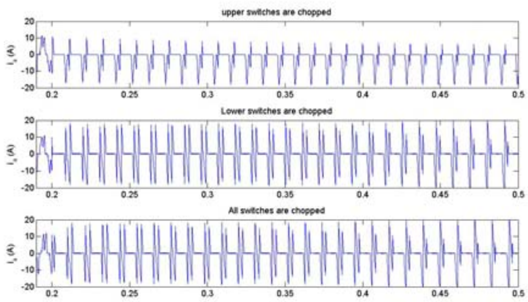

Fig. 15. Current of phase A during open circuit fault

Duty cycle output of PI controller during open circuit fault for all PWM switching modes are shown in Fig. 16. In mode 2 and 3 duty cycle values remain almost constant 100 percent while in mode 1 toggle between 0 and 100 percent.

3) Short Circuit: Short circuit fault of upper side switch of phase A leg of inverter is implemented at 0.2 while motor is working in normal condition. Speed responses during short

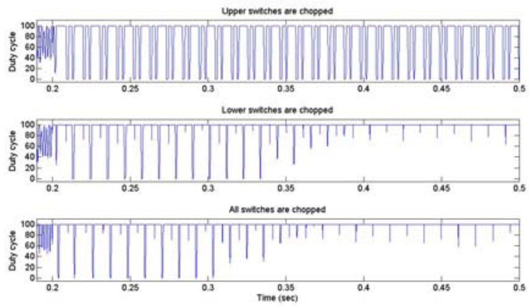

Fig. 16. Duty cycle values during open circuit fault

circuit faults are shown in Fig. 17. Speed of mode 1 is oscillating from 1500 RPM to 2200 RPM. In other two modes speed oscillations are much less than mode 1 and speed value is reducing instead of increasing.

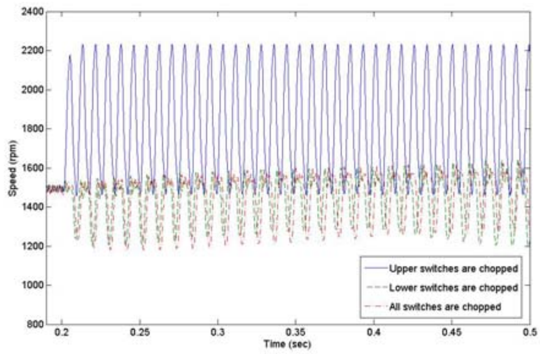

Fig. 17. Speed responses of BLDC during short circuit fault

Torque responses of BLDC motor during short circuit fault are shown in Fig 18. As it can be seen from figure torque ripple amplitude of BLDC motor in mode 1 is much more than other two modes. BLDC motor is completely unstable in mode 1 and became a generator during short circuit fault.

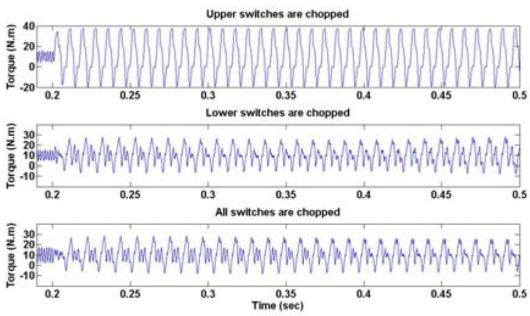

Fig. 18. Torque responses of BLDC during short circuit fault

Duty cycles chosen by PI controller during short circuit fault are shown in Fig. 19. In mode 1 controller is not working after fault and duty cycle is zero and BLDC motor is unstable. But in modes 2 and 3 controller is trying to control the speed by changing duty cycle values.

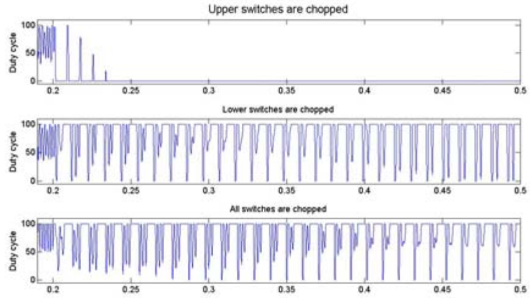

Fig. 19. Duty cycle values during short circuit fault

Simulation results of modes 1 and 2 will be swapped with the assumption of lower side switch faults of phase A leg of inverter instead of upper side switch. But behavior of mode 3 will be the same. With respect to all comparisons although modes 1 and 2 have better characteristics in normal condition of BLDC motor but mode 3 is shown more robust and stable during open and short circuits fault in inverter. Safety is one of important parameters for an electric vehicle. Thus robustness of electric vehicle drive train during any abnormal situations is important. Therefore PWM switching mode 3 is recommended for BLDC motor as drive train of electric vehicles.

IV. Conclusion

There is a growing attention to the electric vehicle in automotive industry to have sustainable transportation in future. In-wheel technology is a modern propulsion system in electric vehicles. Selection proper motor for high performance EV to achieve maximum efficiency and safety is essential. In this paper, DC brushed, induction, brushless DC (BLDC) and switched reluctance motors and their respective controllers are simulated and compared with respect to in-wheel requirements in two various normal and critical (electric faults and abrupt mechanical shocks). BLDC is recommended for drive train of electric vehicles due to better torque/speed characteristics, higher efficiency, higher dynamic response, high output power to size ratio, higher operating life and noiseless operation.

PWM technique is simulated to control speed of BLDC motor. A PI controller is employed to define duty cycle of PWM signal according to speed error. Various PWM switching modes of BLDC motor are compared under normal and inverter fault (open and short circuit of upper side switch of phase A leg of inverter) conditions. PWM switching mode 3 (all inverter switches are chopped) is more robust during fault compare to other two modes. But BLDC motor has better characteristics with other two PWM switching modes under normal condition. Fault tolerant systems are effective solutions to detect, prevent or handle different type of faults in motor drives. But regarding safety issue which is vital factor in electric vehicles, as result of comparisons PWM switching mode 3 is recommended for BLDC motor in automotive applications.

APPENDIX A
MOTOR SPECIFICATIONS

TABLE I
BRUSHED DC MOTOR SPECIFICATION FOR SIMULATION

DESCRIPTION	VALUE	UNIT
DC VOLTAGE	400	V
RESISTANCE	1.78	ohm
INDUCTANCE	0.21	H
INERTIA	0.08	Kg-m^2
DAMPING RATIO	0.004	$N.m.s$

TABLE II
INDUCTION MOTOR SPECIFICATION FOR SIMULATION

DESCRIPTION	VALUE	UNIT
DC VOLTAGE	400	V
PAHSE RESISTANCE	0.73	ohm
PHASE INDUCTANCE	0.003	H
INERTIA	0.034	Kg-m^2
DAMPING RATIO	0.001	$N.m.s$
POLES	4	-

TABLE III
SWITCHED RELUCTANCE MOTOR SPECIFICATION FOR SIMULATION

DESCRIPTION	VALUE	UNIT
DC VOLTAGE	400	V
PAHSE RESISTANCE	2	ohm
UNALIGNED INDUCTANCE	0.67e-3	H
ALIGNED INDUCTANCE	23.6e-3	H
INERTIA	0.008	Kg-m^2
DAMPING RATIO	0.01	$N.m.s$
POLES	6/4	-

TABLE IV
BLDC MOTOR SPECIFICATION FOR SIMULATION

DESCRIPTION	VALUE	UNIT
DC VOLTAGE	400	V
PAHSE RESISTANCE	2	ohm
PHASE INDUCTANCE	8e-3	H
INERTIA	0.8e-3	Kg-m^2
DAMPING RATIO	0.001	$N.m.s$
POLES	8	-

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