

Direct Torque Controlled Drive Train for Electric Vehicle

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Abstract— Electric vehicle (EV) due to its running zero emission, sustainability and efficiency is of interest for future transportation. In-wheel technology has been one of the main research concentration points in last decade. BLDC motor is on demand for in-wheel application because of its high efficiency, torque/speed characteristics, high power to size ratio, high operating life and noiseless operation. In this paper direct torque control (DTC) switching technique of BLDC motor for EV propulsion system is proposed and simulated in MATLAB/SIMULINK. The Simulation results show effective control of torque and remarkable reduction of torque ripple amplitude as compared to conventional reported switching techniques. Improvements of in-wheel motor's torque controllability result to have more efficient and safer electric vehicle. The simulation results of proposed switching system are satisfactory and show correct performance of system.

Index terms — BLDC motor; In-wheel motors; Direct torque control (DTC); Electric vehicle.

I. INTRODUCTION

IDEA of using electricity instead of fossil fuels for propulsion system of vehicles is not new. Scientists and manufacturers have attempted to design or improve electric vehicles from long time ago. Rodert Anderson built the first electric carriage in 1839. In 1870 David Salomon developed an electric car with a light electric motor. The batteries were heavy at that time; therefore performance was poor [1]. Nowadays hybrid vehicles are more popular due to better mileage and lack of enough infrastructures for charging battery of electric vehicles. Applying in-wheel technology will increase efficiency and safety of electric vehicles. Using in-wheel technology, by wire technology and intelligent control systems instead of conventional hydraulic or pneumatic control systems result to an Intelligent Fully Electronically Controlled Vehicle (IFECV) [2]. Schematic diagram of four wheel drive train of an IFECV is shown in Fig. 1.

Improving performance of in-wheel motor and its controller can increase efficiency, controllability and safety of electric vehicles. Various electrical motors have been used by manufacturers in last decades. Brushed DC, induction, switched reluctance and BLDC motors have been

compared and BLDC has been recommended for high performance electric vehicle. Back-EMF monitoring, flux linkage-based technique and free-wheeling diode conduction are some of sensorless control methods that can be used to commutate BLDC motor instead of using sensors [3]. Reducing complexity of motor construction, cost and maintenance are obvious advantages of sensorless control techniques but sensing back-EMF at low speeds, transient time and discontinuous response due to high commutation rates are its disadvantages.

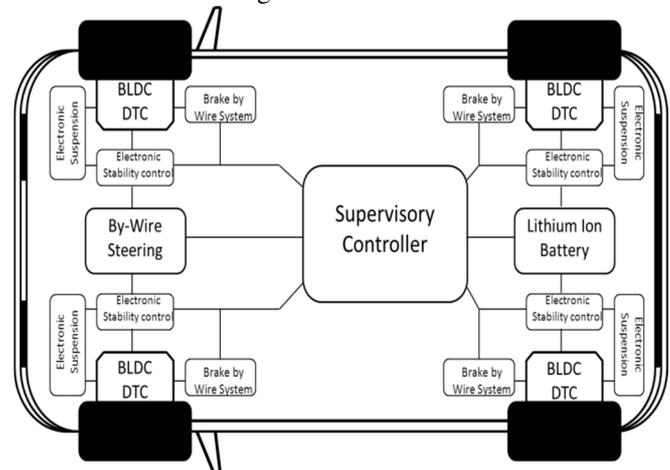


Fig. 1 Four-wheel drive train system of an IFECV

Priceless researches and works have been discussed for developing different control algorithms of BLDC motor [3-7]. Sensorless control technique with a new flux linkage function has been reported for BLDC motors [3]. This method improves problem of sensorless control techniques at low speeds. A speed-independent position function named "G(θ)" has been defined with respect to mechanical angle of rotor. This technique is able to detect position of rotor at around 1.5% of nominal speed. It is suitable for in-wheel application because we need to control the motor from stall position. Four-switch converter with the current controlled PWM control technique has been proposed for BLDC [4]. Difficulties in generating 120° conducting current profiles in three phase winding of BLDC with four-switched converter and current distortion in two phase cause by back-EMF of silent phase are main problems of proposed technique. A new power supply, DSP-controlled PWM chopper and C-dump converter has been presented [5]. A dual speed and current closed-loop control is used to keep ratio of voltage to frequency constant to have constant torque operation of motor. Forced commutation RC circuits and snubber circuits to control commutation and dv/dt rating on switches have been discussed. Simulation results show number of current

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spikes which cause increase on torque ripple of BLDC motor which is not suitable for in-wheel application. An adaptive fuzzy control scheme via parallel distributed compensation has been applied to control velocity of small BLDC motors [6]. Simulation results show stable velocity control of BLDC motor in case of any parameter perturbation. Although stability and smoothness of torque is essential in high performance EV's, but it would be constructive for other applications like scooters and electric bikes. A digital controller of BLDC motor with two mode of operation, namely conduction angle control and current mode control has been introduced [7]. Torque is directly proportional to current in BLDC, thus current control results to torque control of motor. Speed ripple of BLDC is reduced via proposed digital controller up to maximum of 3.4 percent. This method could be more suitable for EV application if torque ripple reduction also has been considered.

DTC technique is a sensorless control technique. It does not use any sensor for detecting rotor position. Torque control is one of important factors in drive train of electric vehicle. Reduction of torque ripples cause to deliver smoother power to the wheel. Delivering as minimum as possible ripple free torque with desired value to the wheels in various conditions, essentially increase safety and efficiency of electric vehicle. Therefore DTC switching technique is recommended for high performance electric vehicles.

In this paper direct torque control (DTC) switching technique of BLDC motor for EV propulsion system is proposed. Principle of DTC switching technique of three phase BLDC motor for electric vehicle applications is explained in section two. Simulation results of proposed direct torque control switching technique of BLDC motor are shown and discussed in section three..

II. DIRECT TORQUE CONTROL OF BLDC USING THREE PHASE CONDUCTION MODE

Direct torque control (DTC) was proposed for the first time by Takahashi and Noguchi in 1986 [8] and Depenbrock in 1988 [9] for induction motors. Recently, many researches worked on DTC of BLDC motor for specific applications which needs precise torque control. Various methods of implementing DTC of BLDC have been reported [10-15]. DTC technique of BLDC has been applied to drive train of hybrid electric vehicle [15]. Overall block diagram of DTC of BLDC motor is shown in Fig. 2.

Torque error, stator flux error and stator flux angle are regularly used to select proper voltage space vector for switching in DTC technique. In this paper flux linkage error is eliminated Because of variations of stator flux magnitude regarding changes in resistance, current and voltage and specifically sharp dips at every commutation [10]. BLDC operates in both constant torque region and constant power region. Back-EMF of motor is below DC voltage source of inverter in constant torque region (below base speed) and is increased more than DC voltage value above nominal speed. Therefore stator inductance avoids abrupt increase of phase current and deteriorates output torque of motor. Therefore in this paper operation of BLDC motor is considered at constant torque region.

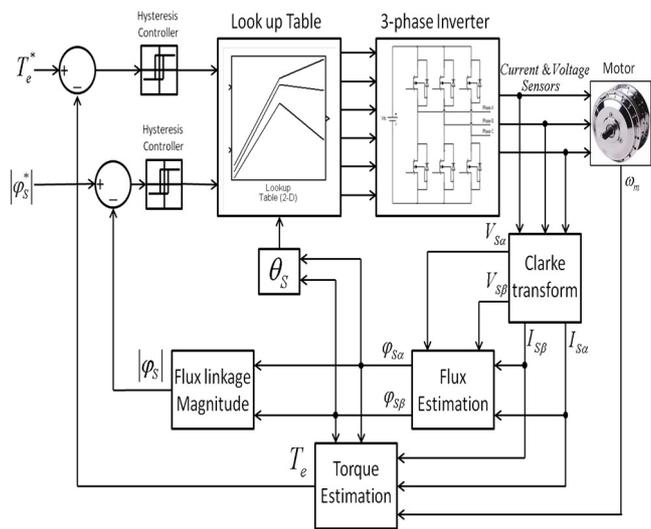


Fig. 2 Overall block diagram of DTC for BLDC motor

Accurate estimation of flux linkage magnitude and torque is required for DTC of in-wheel motors. In some techniques, Current sensors have been used to determine flux linkage and estimate voltage from DC bus of inverter [12], [14] and [15]. This method is too sensitive to voltage errors caused by dead-time effects of inverter switches, voltage drop of power electronic devices and fluctuation of DC link voltage [16]. Therefore in this paper both current and voltage sensors are used for estimation of flux linkage magnitude and torque [13].

Precise estimation are mainly depends on accurate sensing of currents and voltages. Variations of stator resistance due to changes of temperature cause error in stator flux estimation. Pure analogue integrator also produces DC offset in signal. Different techniques have been discussed to solve analogue integrator DC drift error [17]. As it is considered that BLDC motor is working in constant torque region and there is no need of flux magnitude change during operation; second algorithm proposed in [17] with limiting level of $2K_L\pi/(3\sqrt{3})$ is used where K_L is flux linkage of motor.

Clarke transformation is used to convert balanced three phase system (voltages and currents) to $\alpha\beta$ -axis references. Therefore stator flux linkage magnitude, stator flux angle and electrical torque of BLDC motor can be estimated by,

$$\varphi_{s\alpha} = \int (V_{s\alpha} - Ri_{s\alpha}).dt \quad (1)$$

$$\varphi_{s\beta} = \int (V_{s\beta} - Ri_{s\beta}).dt \quad (2)$$

$$\varphi_{r\alpha} = \varphi_{s\alpha} - Li_{s\alpha} \quad (3)$$

$$\varphi_{r\beta} = \varphi_{s\beta} - Li_{s\beta} \quad (4)$$

$$|\varphi_s| = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \quad (5)$$

$$\theta_s = \tan^{-1}\left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right) \quad (6)$$

$$e_\alpha = \frac{d\varphi_{r\alpha}}{dt} \quad (7)$$

$$e_{\beta} = \frac{d\phi_{\beta}}{dt} \quad (8)$$

$$T_e = \frac{3P}{2} \left[\frac{e_{\alpha}}{\omega} i_{s\alpha} + \frac{e_{\beta}}{\omega} i_{s\beta} \right] \quad (9)$$

Where,

R : Stator resistance

L : Stator inductance

V_{α} : α -axis voltage vector

V_{β} : β -axis voltage vector

i_{α} : α -axis current vector

i_{β} : β -axis current vector

$\phi_{s\alpha}$: α -axis stator flux vector

$\phi_{s\beta}$: β -axis stator flux vector

$|\phi_s|$: Stator flux magnitude

θ_s : Stator flux angle

e_{α} : α -axis back-EMF

e_{β} : β -axis back-EMF

T_e : Electric torque

After finding values of stator flux linkage in the stationary $\alpha\beta$ -axis with (1) and (2), flux linkage magnitude and angle can be calculated from (5) and (6). By deriving rotor flux linkage from (3) and (4) torque of BLDC can be evaluated by (9). Torque estimation is an essential issue in direct torque control of BLDC. Therefore, accurate approximation of torque will increase ability of controlling actual electric torque of motor.

Hysteresis controller will generate square wave pulse with respect to torque error. Hysteresis controller output is '1' if the actual value of torque produced by motor is more than reference torque value of controller and is '0' if actual torque value is less than reference value. In this paper hysteresis band limits has been set 1, 0.1 and 0.01 to show torque ripple reduction capability of controller. The maximum switching frequency for minimum value of hysteresis band limits is almost 10 KHz.

Three phase conduction mode is used for switching of VSI of BLDC motor. Six non zero voltage vectors that have been used to switch VSI are $V_1(100)$, $V_2(110)$, $V_3(010)$, $V_4(011)$, $V_5(001)$, $V_6(101)$. Voltage space vectors are chosen with respect to output of torque hysteresis controller and stator flux angle of motor. Estimated stator flux angle of BLDC motor has been divided to six sectors. Each sector is sixty degrees. Sector one is starting from -30 degrees to 30 degrees and so on for other sectors to complete one full rotation of flux linkage. Switching table of inverter to choose space vectors in each sector is shown in Table I.

TABLE I

THREE PHASE CONDUCTION SWITCHING FOR DTC OF BLDC

TORQUE ERROR	FLUX ANGLE SECTORS					
	1	2	3	4	5	6
1	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$
0	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$

III. SIMULATION RESULTS AND DISCUSSION

The proposed direct torque control switching technique for BLDC as in-wheel motor is simulated in MATLAB/SIMULINK. Specification and parameters of BLDC used in this model are listed in Table II. A digital PWM controller is also employed to control the speed of motor. Simulation results are compared with conventional Hall Effect switching method. It is shown that controller is able to estimate torque, flux linkage magnitude and angle of BLDC precisely. Various hysteresis band limits applied to model are able to control electrical torque variation in desired limit. Simulation results show effective improvement of torque control of motor. DTC shows also much faster torque response compared to conventional method for sudden change of torque loads.

TABLE II

BLDC MOTOR SPECIFICATION

DESCRIPTION	VALUE	UNIT
DC VOLTAGE	400	V
PHASE RESISTANCE (R)	2.875	Ω
PHASE INDUCTANCE (L)	0.8	m-H
INERTIA (J)	0.8e-3	KG-m ²
DAMPING RATIO (β)	0.001	N-s/ m ²
FLUX LINKAGE	0.175	Wb
POLE PAIRS	4	-

Speed response and torque response of DTC of BLDC for 1500 rpm speed reference under 10 N.m torque load is shown in Fig. 3. Sampling time is 5 μ s and Hysteresis band limit is set to 0.01. Model is tested for 10 N.m torque load with different hysteresis bands and results are shown in Fig. 4. Width of Hysteresis limit band will determine peak to peak of torque ripple of BLDC motor. Simulation results show that variation of hysteresis band can change torque ripple amplitude which improves torque control capability of BLDC compare to previous works. As it can be depicted from the Fig. 4, hysteresis band limits can control torque ripple amplitude. Peak to peak value of torque ripple can be reduced up to four percent of reference torque (0.4 N.m) in proposed DTC which is 10 times lesser than conventional Hall Effect sensors control technique and 3.75 times lesser than proposed model in [14].

Although reducing hysteresis band limits result in smoother torque but increase switching frequency of VSI. Switching frequency directly affects switching loss of inverter and practically it may not possible to have high switching frequencies. Therefore hysteresis band limits cannot be less than a particular threshold practically.

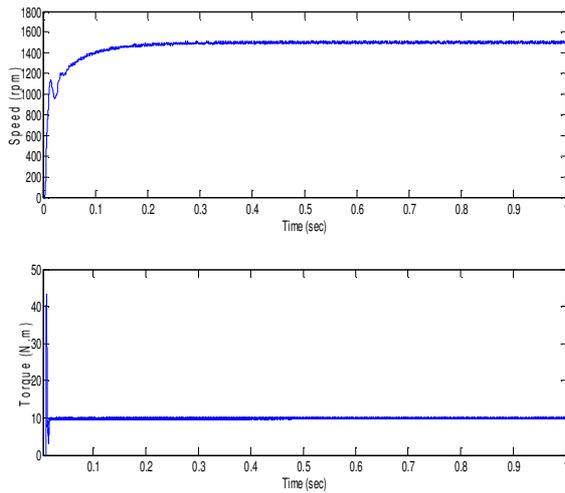


Fig. 3 Speed and torque response of BLDC motor

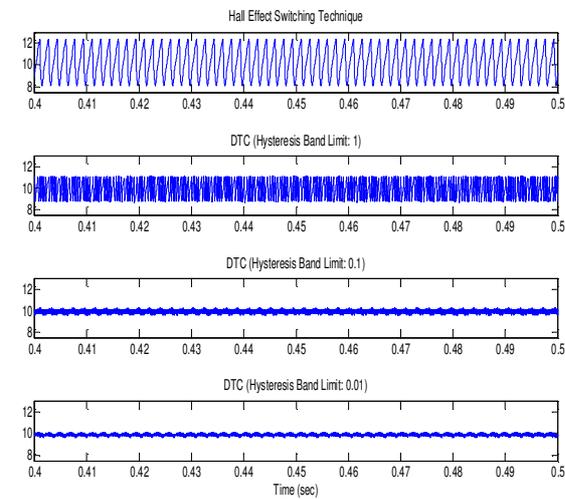


Fig. 4 Pulsating torque of BLDC for different hysteresis band limits

Stator flux magnitude and angle for DTC of BLDC are shown in Fig. 5. It can be observed that stator flux magnitude in constant torque region below base speed is oscillating around 0.22 Wb. Flux magnitude value is close to limiting level ($2K_L\pi/(3\sqrt{3})$) of integration algorithm.

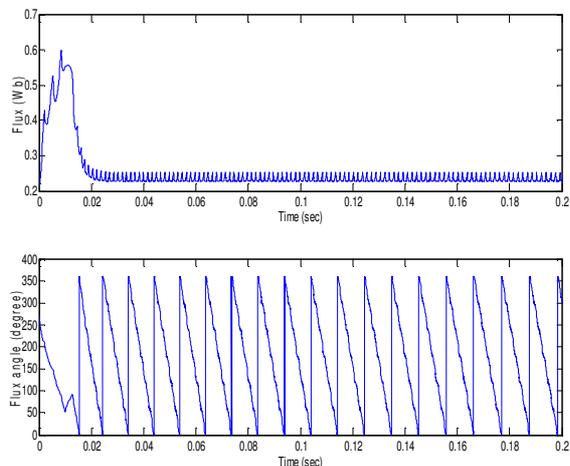


Fig. 5 Estimated stator flux linkage magnitude and angle of BLDC

Stator flux linkage locus of BLDC for different load torques (5 N.m and 10 N.m loads) is shown in Fig. 6. Six flux linkage angle sectors are completely visible in figure. As it can be seen increasing of torque load cause increase of flux magnitude and more sharp changes are observed [10].

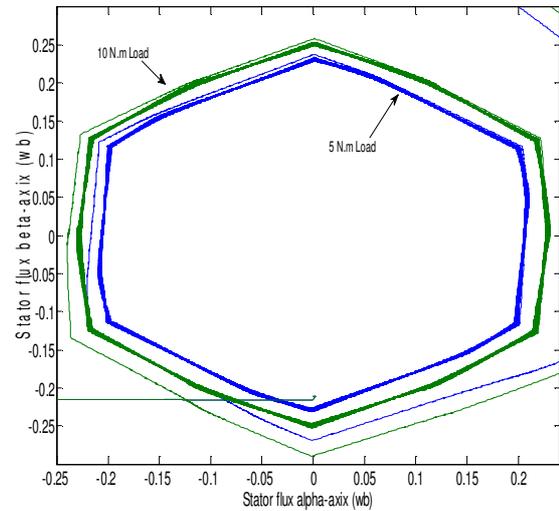


Fig. 6 Stator flux linkage trajectory for 5 N.m and 10 N.m loads

According to in-wheel motor requirements, robustness of motor and controller is critical in safety point of view. To study and compare behavior of DTC technique and conventional switching technique to sudden change of torque load, 50 percent change of torque load (from 10 N.m to 15 N.m) is applied to BLDC model for 1500 rpm reference speed. Speed response and torque response of BLDC motor to 50 percent of load change are shown in Fig. 7 and Fig. 8, respectively.

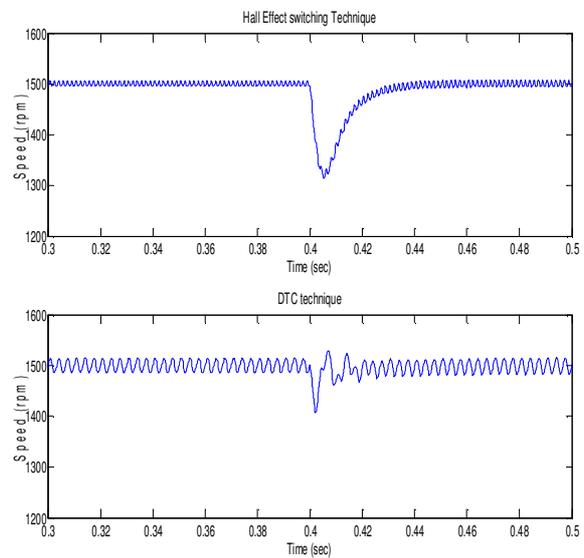


Fig. 7 Speed characteristics under same mechanical shock

Abrupt change of torque load is applied at time 0.4 second. As it can be seen in Fig. 8 speed response of DTC technique is almost fifteen times faster than conventional switching technique under mechanical shock. Although speed fluctuation of DTC is more than conventional switching technique but its torque response is smoother. Fig. 9 shows that dynamic torque response of DTC is much faster than Hall Effects witching technique.

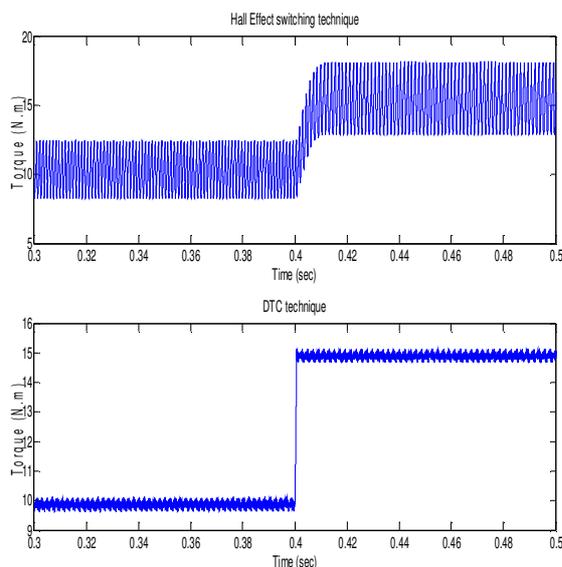


Fig. 8 Torque characteristics under same mechanical shock

IV. CONCLUSION

There is a growing attention to the Electric Vehicle (EV) to control emission of greenhouses gases in atmosphere in automotive industry. In-wheel technology is a modern propulsion system in EV's. BLDC motors are in interest of many manufacturers for EV. In this paper, it is shown that direct torque control (DTC) switching technique of BLDC motor is a suitable choice for drive train of electric vehicles. Simplified proposed DTC model of BLDC motor without flux observation for constant torque region is implemented in MATLAB/SIMULINK. Estimated torque calculated with state observer is similar to actual output torque of motor with a good precision. With adjusting of Hysteresis band limit it is possible to control torque ripple amplitude. In this model, torque ripple amplitude is reduced up to five percent of reference torque. It is a significant improvement compared to former DTC models. Therefore developed DTC switching technique is able to control the pulsating torque of BLDC motor to deliver smoother power to the wheels. Consequently safety and efficiency of electric vehicle is improved.

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