Modeling and simulation of brushless dc motor control system for EPS applications

Conference Paper · May 2012

DOI: 10.1109/CSAE.2012.6272955

3 authors:

Xuewu Ji
Tsinghua University

Xuefeng Zhang
Wanxiang Qianchao Transmission Shaft Co. L...

Yahui Liu
Tsinghua University

Modeling and Simulation of Brushless DC Motor Control System for EPS Applications

Xuewu Ji
State Key Laboratory of Automotive Safety and Energy
Tsinghua University
Beijing 100084, China
jixw@mail.tsinghua.edu.cn

Xuefeng Zhang
Wanxiang Qianchao Transmission Shaft Co. Ltd
Hangzhou 311215, China
zhangxf-007@163.com

Yahui Liu
State Key Laboratory of Automotive Safety and Energy
Tsinghua University
Beijing 100084, China
liuyh@mail.tsinghua.edu.cn

***Abstracts*—This paper presents an advanced model of a brushless dc motor(BLDCM) control system for the electric power steering(EPS) applications considering the suppression of torque ripples. All modules of the EPS system with a BLDCM are modeled under the Matlab/Simulink environment. Among them, the DSP module and the back-EMF module are achieved by the C MEX S-function. The DSP module can output six PWM signals and commutation logic is just considered as a real DSP chip. Furthermore, all six PWM signal ports can be controlled independently, which is convenient in the suppression of commutation torque ripples. The back-EMF module can realize any waveform of back-EMF and the ADC module performs a sample-and-hold function. The model with all the modules considered highlights the consistency with the actual system, which can be used to study the suppression of the torque ripple of the BLDCM, as well as to provide an effective platform for the development of an EPS system with a BLDCM.**

Keywords-modeling and simulation, brushless dc motor, electric power steering, C MEX S-function, torque ripple

I. INTRUDUCTION

During recent two decades, the BLDCM is widely used as actuators for motion control applications due to its high torque-to-weight ratio, easy control, high efficiency and free of commutation maintenance. The above properties make this type of motors most suitable for use in vehicles. Considering the development efficiency and cost of manufacturing actual prototype, a simulation scheme of an EPS system with a BLDCM is desirable for rapid prediction of the motor drive system in the design process. It makes possible to vary and optimize components and subsystems designs and to predict the performance of the system for given goals and constraints.

Several simulation models have been proposed for the analysis of BLDCM drives under Matlab/Simulink environment [1-10]. In most of them, the motor is simplified as a machine of perfect trapezoidal back-EMF waveform [1-7], which is inconsistent with reality and may cause wrong simulation results. Furthermore, to reduce the cogging torque, the motor is designed mostly with skewed slots, which will further lead to the back-EMF waveform more like sinusoidal type. Therefore, Y. S. Jeon and R. A. Guinee use the FFT algorithm and M. A. Jabbar uses Finite Element method to approximate the real back-EMF waveform[8-10]. Although, these two modeling methods are quite precise, but the simulation speed may be significantly affected when the back-EMF module is embedded into the whole control system. On the other hand, in the field of suppression of torque ripples, plenty of research[11-13] has been conducted and some results are obtained, but the specific modeling approach is not yet given in details. The commutation torque ripple was considered in W. Hong's research of modeling and simulation[3], but only the differences of commutation torque ripple between the trapezoidal and sinusoidal motors was analyzed, the suppression scheme of torque ripples can not be achieved using the model.

Based on a motion control chip TMS320LF2407A, form the point of view of torque ripple suppression and its impact on the EPS system, this paper presents a simulation model focusing on the consistency with the actual system and gives the detail modeling process of an EPS system with a BLDCM including the Digital Signal Processor(DSP), PWM module, ADC trigger and sampling module, inverter, back-EMF and EPS test bench modules. To solve the problem of the impact of non-ideal back-EMF on the simulation speed of whole system, a C MEX S-function is adopted to improve the simulation accuracy and speed. Based on this model, much research work can be carried out such as optimization of torque ripple suppression algorithms, comparison of various PWM modes, the impact of torque ripples on the EPS system, PI parameter tuning, design of assist characteristics of EPS, the system response rate and etc.

978-1-4673-0089-6/12/$26.00 ©2012 IEEE

II. EPS Test Bench System Model

The EPS test bench system with a BLDCM is shown in Fig.1, which is mainly composed of the steering mechanism, a torque sensor, a BLDCM and an electronic control unit (ECU). The basic operation principle is that the signals of vehicle speed and torque sensor are detected by the ECU, which then controls the BLDCM to output proper assistant torque to help the driver's steering operation. As the part of the modeling of steering mechanism is relatively mature, only the modeling process of BLDCM and its control system are given here.

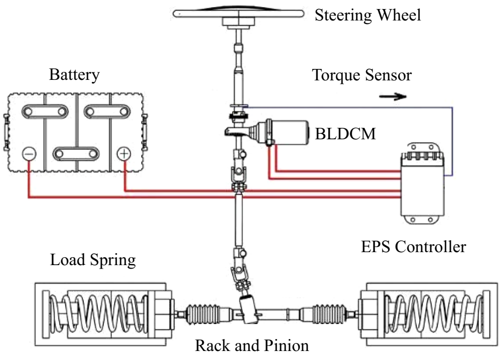

Fig.1 Schematic diagram of the EPS test bench

Fig.2 shows a BLDCM drive system model, the three-phase windings are Y-connected and supposed to be symmetrical. Here, R denotes the phase resistance, L stands for the sum of self- and mutual-inductance, and r for sampling resistance. The equations of terminal voltage and electromagnetic torque are as follows:

$$U_k = R i_k + L\frac{d i_k}{dt} + e_k + V_{no} \quad (k = a,b,c)$$

$$T_e = (i_a e_a + i_b e_b + i_c e_c)/\omega_m$$

Where $U_{k=a,b,c}$, $e_{k=a,b,c}$ and $i_{k=a,b,c}$ represent the three-phase terminal voltages, back-EMF and currents respectively, V_{no} the neutral voltage of the motor, T_e the electromagnetic torque, and ω_m the angular velocity of rotor.

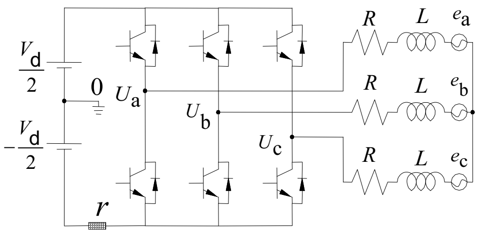

Fig.2 BLDCM and Inverter Equivalent Circuit

The mechanical part of BLDCM can be modeled as:

$$T_e = J_m\dot{\omega}_m + B_m\omega_m + T_L$$

Where J_m and B_m are inertia and damping ratio of the rotor respectively, T_L is the load as well as the assistant effort of the motor during steering operations.

III. Model of BLDCM Control System

An EPS system is actually a torque following system and only needs a current control loop. In most simulation of BLDCM speed control, the current hysteresis controller is commonly used. However, it involves high cost and switching noise in actual implementation. Moreover, it does not match the actual conditions using dedicated control DSP chip and PWM control strategies. In this paper, an increment digital PID controller is adopted to achieve close loop control of the motor current. The whole BLDCM control system simulation model includes a BLDCM, a three-phase inverter, a DSP unit and a PWM&ADC module. The specific modeling process of each module is given in the following sections.

A. BLDCM Module

The BLDCM module consists of three parts shown in Fig.3. One is the electrical part which produces the electromagnetic torque and current of the motor. Another is a mechanical part which represents the revolution of rotor. And the last one is the back-EMF part which generates the back-EMF waveforms according to the speed and angle of the rotor. The electrical part is composed of basic resistance and inductance units in the Simulink/PSB toolbox to imitate the equivalent resistance and inductance of the stator, therefore, the commutation process is conducted automatically by the Simulink according to the commutation logic just as an actual operation of the motor. The back-EMF part is achieved using C MEX S-functions and the input signals include motor speed and angular displacement. It can output any back-EMF waveform in terms of the rotor speed and angular displacement signals without influence on the simulation speed.

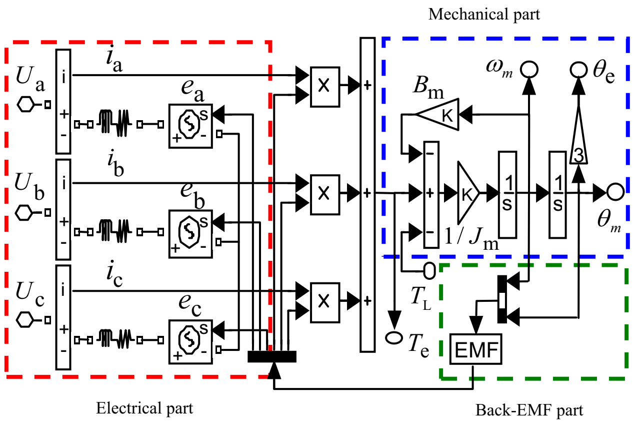

Fig.3 Simulink Diagram of BLDCM

B. Three-phase Inverter Module

The inverter module is composed of IGBT and Diode units in the Simulink/PSB toolbox in accordance with the topological structure of actual inverters including the power source and the dc-linked sampling resistor shown in Fig.4. Parameters of all power components can be set the same as an actual system.

C. DSP Module

The DSP module consists of DSP algorithms, Drive Signals and PWM&ADC modules as shown in Fig.5. A C MEX S-function is adopted to achieve the control algorithms, which is the central controller of an EPS system to carry out the main functions of the system such as sampling and processing the signals of steering torque, vehicle speed, motor current and position, regulating PI parameters, and controlling the motor to output corresponding assistant effort.

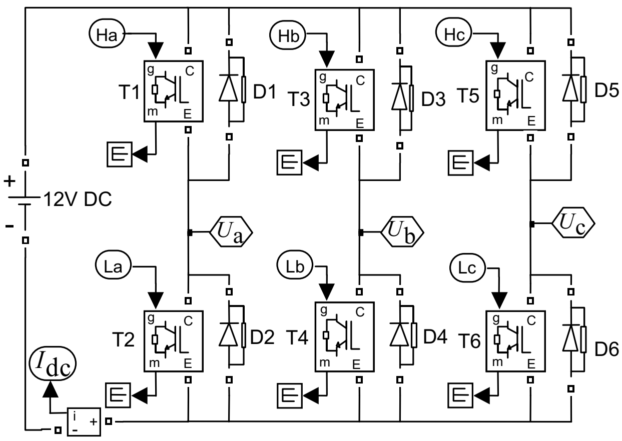

Fig.4 Simulink diagram of inverter

The Drive Signals module acts as a PWM function on a real DSP chip. The commutation logic and the duty signal are combined into PWM drive signals to control the motor. The power switching device is ON as long as its gate signal is greater than zero and OFF while less than or equals to zero. Therefore, if there is only one pin for each channel, then only two drive states exit-PWM and off. This can not satisfy the need of analysis for a variety of PWM modes. In this paper, for one drive signal, the DSP module outputs two signals of pin 1 and pin 2. The signal of pin 1 is multiplied by a PWM signal and added to pin 2 connected to the gate of one power device. Thus, if each drive signal has three states, then several PWM modes can be achieved. For example, the channel of Ha can output three states-ON, PWM and OFF, pin 1 and pin 2 only need to output (0,1), (1,0) and (0,0), respectively.

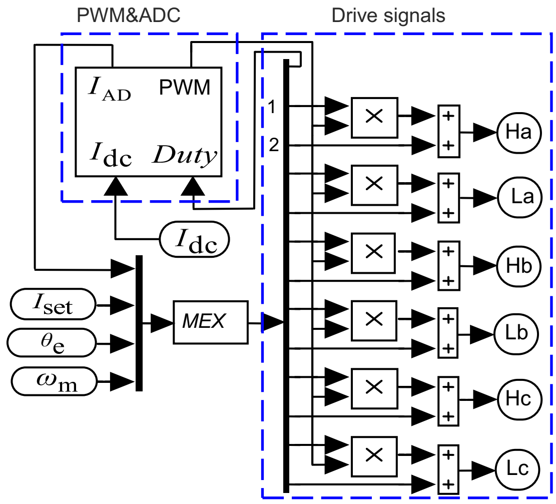

Fig.5 the DSP Module

There are two kinds of counting modes for actual DSP General Timers: continuous increase counting mode and increase/decrease counting mode. To improve the control precision, continuous increase counting mode is usually adopted. Under this mode, a comparative interrupt is needed to trigger the ADC module to sample the current pass through the dc-linked resistor. With this function, the details of PWM&ADC module is shown in Fig.6, which is composed of Repeating Sequence, Switch, Pulse, Delay and Triggered Subsystems.

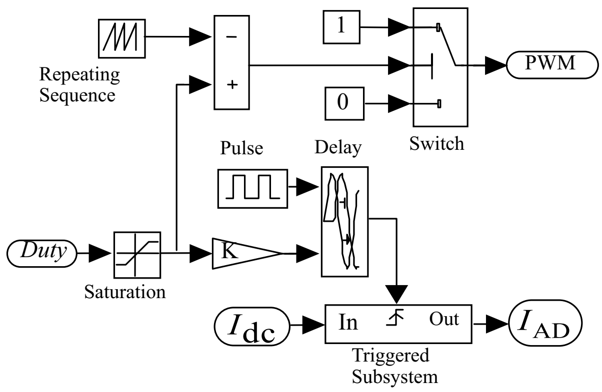

Fig.6 Simulink modules of PWM and ADC

The Duty signal from the DSP algorithms module on the one hand is compared with a saw-tooth waveform signal and the result is linked to a Switch module to output a desired PWM signal. On the other hand, it is also connected to a Delay module to lag the Pulse signal with half duty value as a triggering signal to sample the dc-link current. The source of the Triggered Subsystem is the dc-current which is sampled and held, and its output is connected to the DSP algorithms module. It is the ADC function that realizes the interrupting and sampling process of the dc-current at the midpoint of PWM-ON intervals. Such a feature also can be achieved through setting the C MEX S-function to a variable time sampling mode. However, the control duty calculated at present interruption only will be activated in the next PWM circle in an actual DSP chip. To reflect simultaneously this characteristics and the comparative interrupt sampling function mentioned above, two sampling mode should be set in the C MEX S-function. However, the time point of comparative interrupt sampling is variable, and its implementation is difficult. The PWM&ADC module proposed in this paper avoids the process through the C MEX S-function to complete the comparative interrupt sampling function, and needs only set a periodic interrupt to read all the information needed, which is consistent with an actual DSP in functions, while reducing the number of calls to S-functions during the simulation.

IV. Simulation Model of EPS System with a BLDCM

Fig.7 shows the full simulation model of an EPS test bench system equipped with a BLDCM. The input is the driver's torque acting on the steering wheel, and the two transfer function modules are dynamic models of steering wheel and rack subsystem, respectively. The alignment force is substituted by a spring load system. The assistant motor control system is composed of three parts: DSP, which is the controller just like an actual DSP chip; Inverter, the power device; and the assistant Motor, which involves the mechanical and the electrical parts. Since the extra torque ripples results from lower position accuracy of the Hall position sensors, a high resolution position sensor is usually used in an EPS system. In this paper, the positional signal is directly connected to the DSP module. Table 1 gives the specific parameters of the mechanical steering system.

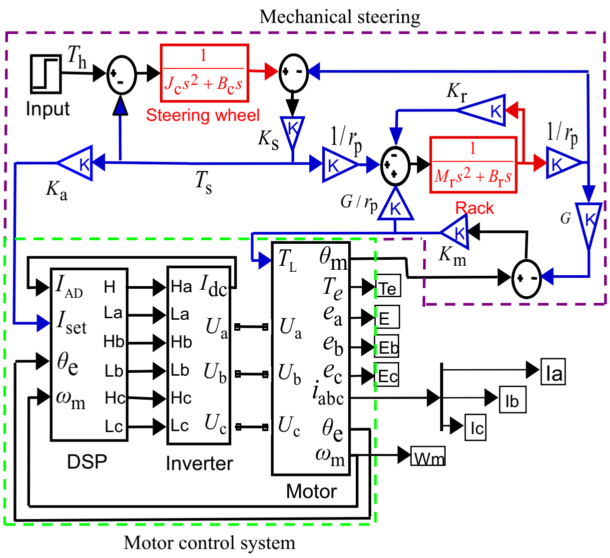

Fig.7 Simulink model of a full BLDCM EPS system

Table 1. Parameters of machinery steering system

Items	Description	Value	Unit
T_h	Steering torque	3	N·m
J_c	Steering wheel inertia	0.025	kg·m2
B_c	Steering wheel damping	0.361	N·m/(rad/s)
K_s	Torsion bar stiffness	115	N·m/rad
K_a	Assistant gain	5.5	
r_p	Pinion radius	0.007	m
K_r	Load spring rate	91060	N/m
M_r	Mass of rack, spring and the guide rod	20	kg
B_r	Rack damping	653.2	N/(m/s)
G	Reduction gear ratio	16.5	
K_m	Motor and gearbox rotational stiffness	125	Nm/rad

V. Simulation Results and Analysis

Based on the above model, a torque step-input is exerted as the steering effort of the driver, the assistant process is carried out to study the influence of torque ripples on the system and suppression schemes due to the commutation and non-ideal back-EMF. The output of the torque sensor and the dc-link current are measured. Parameters of the BLDCM employed are given in Table 2, and the sampling frequency of the DSP module is set to be 50μs just the same as actual system. The simulation results are shown in Fig. 9 to Fig.13.

Table 2. Parameters of the BLDCM

Description	Value	Unit
Pairs of the poles	3	
Rated voltage	12	V
Rated speed	1200	rpm
Phase resistance	0.035	Ohm
Self inductance	0.53	mH
Mutual inductance	0.0014	mH
Back-EMF coefficient	0.0352	V/rad/s
Inertia	3.208×10^{4}	kg·m^2

Fig.9 shows the sampling process of the dc-link current. The thin solid line 1 denotes the waveform of the current on the dc-linked resistor. During the PWM-OFF intervals of the gate signal, the current will not flow through the resistor, only in the PWM-ON intervals is the current visible. The dotted line 2 is the current sample-and-hold value of the ADC module, the sampling point is just at the midpoint of PWM-ON intervals and the sampling value of the current is held until the next sampling point. The thick solid line 3 shows the current value of the DSP module sampled during its periodic interrupt intervals, which achieves real-time sampling functions well just like the actual system.

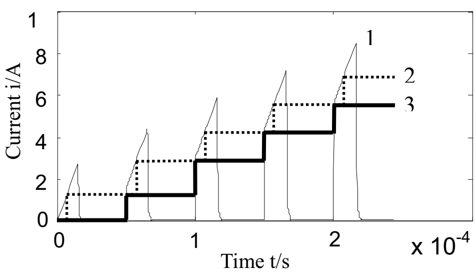

Fig.9 Current sampling

Fig.10 gives the phase current and phase back-EMF waveforms during the whole power steering simulation course. Fig.10(a) shows the motor's sinusoidal phase back-EMF, and Fig.10(b) the relevant phase current amended according to its back-EMF waveforms.

Fig.11 is the simulation results without torque ripple suppression schemes. Fig.11(a) is the output electromagnetic torque of the motor, Fig.11(b) is the torque signal measured though the torque sensor and Fig.11(c) the motor speed.

Fig.12 shows the simulation results with torque ripple suppression schemes, the torque pulsation on the sensor is reduced effectively. Specific torque suppression algorithms and experiment results can be found in literature [14] and [15].

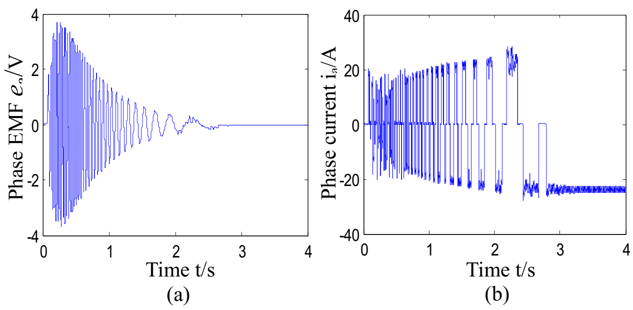

Fig.10 Phase back-EMF and current

(a) phase back-EMF and (b) phase current

Fig.13 gives the simulation results after using the torque signal phase compensation and torque ripple suppression schemes simultaneously, the system oscillation (0-1s) in the Fig.11(b) and Fig.12(b) is reduced. Comparison of Fig.11(b) and Fig.12(b) shows that the EPS system is sensitive to the torque ripple under lower operation speed of the steering wheel. At middle or high motor speed, the impact of torque ripple on the system is negligible due to the system's filter effect.

Fig.14 shows compensation results of commutation currents. Fig.14(a) is the three-phase currents without any control and Fig.14(b) with a direct PWM control algorithm[14]. During the commutation intervals, the electromagnetic torque of the motor is proportional to the un-commutated phase current, which directly reflects the torque ripple of the motor. The dip of un-commutated phase current is compensated effectively.

The above simulation results demonstrate that torque ripple suppression schemes can be easily performed on the proposed model. Furthermore, the control strategies such as torque signal phase compensation, friction compensation and inertia compensation, fuzzy control and alignment control at a system level can also be implemented on the DSP mode, and the EMF module can achieve sinusoidal, trapezoidal or any other back-EMF waveforms using the FFT method.

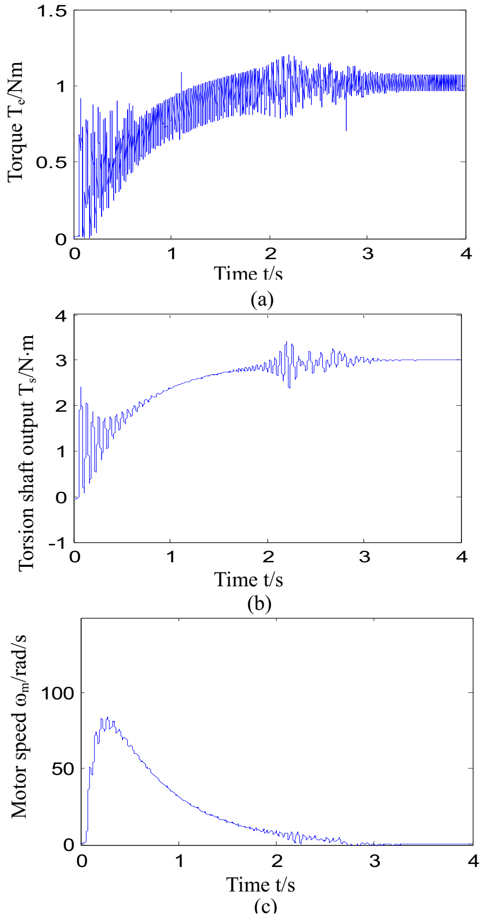

Fig.11 Simulation results without torque ripple suppression schemes (a) electromagnetic torque, (b) torque sensor output without any scheme to suppress the torque ripple and (c) motor speed

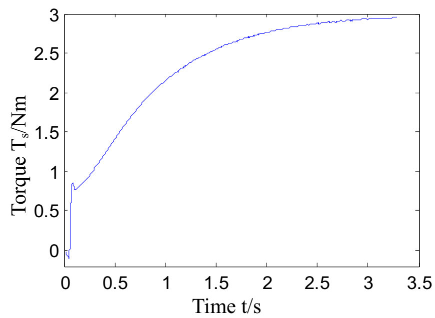

Fig.13 Torque sensor output with torque signal phase compensation and torque ripple suppression schemes

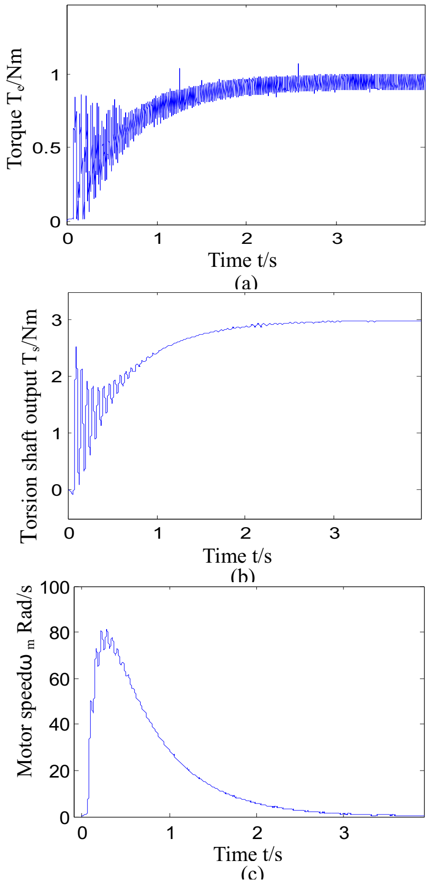

Fig.12 Simulation results with torque ripple suppression schemes (a) electromagnetic torque, (b) torque sensor output with suppressing the torque ripple and (c) Motor speed

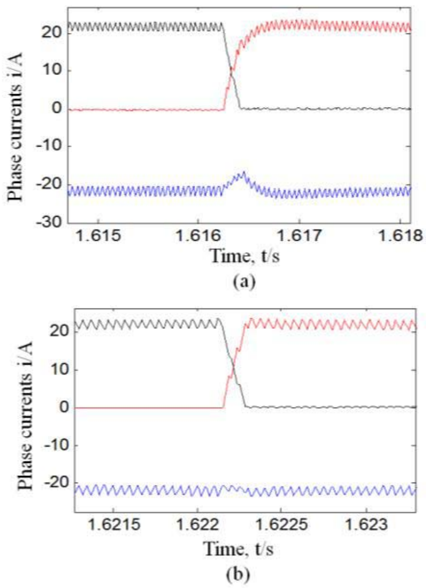

Fig.14 Compensation of commutation currents (a) phase currents without any control and (b) phase currents with a direct PWM control algorithm

VI. Conclusions

Based on foundational Simulink modules and C MEX S-functions, a simulation model of a BLDCM based EPS test bench system is proposed. All simulation results show that the model reflects real characteristics of the motor precisely and features a high simulation speed. It is convenient to carry out the study on torque ripple suppression schemes and various system control algorithms for BLDCM employed in an EPS system.

References

[1] P. Pillay and R. Krishnan. "Modeling, simulation, and analysis of permanent-magnet motor drives, part Ⅱ: the brushless DC motor drive", IEEE Trans. Ind. Appl., vol.25, no.2, pp. 274-279, 1989.

[2] N. A. Demerdash and T. W. Nehl. "Dynamic modeling of brushless dc motors for aerospace actuation", IEEE Trans. Aerosp, Electron. Syst., Vol. AES-16, No.6, pp. 811-821, Nov. 1980.

[3] W. Hong, W. Lee and B. K. Lee. "Dynamic simulation of brushless dc motor drives considering phase commutation for automotive applications", IEEE International Electric Machines & Drives Conference, 2007. IEMDC 2007. pp.1377-1383, 3-5 May 2007.

[4] A. Halvaei Niasar, H. Moghbelli and A. Vahedi. "Modeling, simulation and implement of four-switch, brushless dc motor drive based on switching functions", EUROCON '09, IEEE, pp. 682-687,2009.

[5] Hui Zhang, Jinhong Liu, Jing Ren, Yuzhi Zhang and Yongjun Gao. "Research on Electric power steering with bldc drive system". IPEMC'09, pp. 1065-1069, 2009.

[6] Liu Ping, Liu Gang and Zhang Qingrong. "Simulation method and experiment analysis of BLDC motor system for magnetically suspended flywheel", Aerospace Control, Vol. 25, No. 1, pp. 56-61, Feb. 2007. (In Chinese)

[7] Zhang Qingrong, Liu Ping and Yang Chunfan. "Application of DSP in simulation of BLDC control system", Journal of System Simulation, Vol.18, Suppl.2, pp. 817-820, Aug. 2006. (In Chinese)

[8] Y. S. Jeon, H. S. Mok, G. H. Choe, D. K. Kim, and J. S. Ryu. "A new simulation model of bldc motor with real back emf waveform", COMPEL.2000, pp. 217- 220, 2000.

[9] R. A. Guinee and C. Lyden. "A novel modulated single fourier series time function for mathematical modeling and simulation of natural sampled pulse width modulation in high performance brushless motor drives", Proceedings of the 42nd IEEE Conference on Decision and Control. Hawaii, pp. 6230-6235, June 2003.

[10] M. A. Jabbar, H. N. Phyu, Zhejie Liu and Chao Bi. "Modeling and numerical simulation of a brushless permanent-magnet dc motor in dynamic conditions by time-stepping technique", IEEE Trans. on Industry Applications, Vol. 40, No. 3, pp. 763-770, May/June 2004.

[11] Haifeng Lu, Lei Zhang and Wenlong Qu. "A new torque control method for torque ripple minimization of BLDC motors with un-ideal back EMF", IEEE Trans. Power Electron., vol.23, no.2, pp. 950-958, Mar. 2008.

[12] Joong-Ho Song and Ick Choy. "Commutation torque ripple reduction in brushless DC motor drives using a single DC current sensor", IEEE Trans. Power Electron., vol.19, no.2, pp.312-319, Mar. 2004.

[13] C.K. Lee, N.M. Kwok. "Torque ripple reduction in BLDC motor velocity control systems using an optimal controller", Sixth International Conference on Electrical Machines and Drives, Sep. pp.600-605, 1993.

[14] Gao Feng, Zhang XueFeng and Ji Xuewu. "Suppression of torque ripple due to phase commutation in brushless DC motor drives considering the stator resistance", ELECTRIC MACHINES AND CONTROL, vol.14, no.10, pp.26 -31, Oct. 2010. (In Chinese)

[15] Xuefeng Zhang, Xuewu Ji and Feng Gao. "Torque Ripple Suppression of Brushless DC Motors with Non-Ideal Back EMF for EPS Applications". Advanced Materials Research, 2011, 201-203: 1198-1205