A Switching Adaptive Controller for the Reduction of Commutation Torque Ripple in BLDCM Drives

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Abstract

A switching adaptive controller with commutation delay compensation is proposed to control the torque output and to reduce commutation torque ripple in uncertain brushless DC motor (BLDCM) drives. After deriving the error dynamics, the conduction and commutation periods of the drive is taken into account separately, and two different controllers are designed for each operation region of the current loop of BLDCM drives. All the system constants in the mathematical model of the drive are considered uncertain, and adaptation rules are derived for these unknown parameters. The stability of the closed-loop system is shown by a common Lyapunov function, and the convergence of the current error to zero is proved as well. Finally, a commutation delay compensation scheme is introduced and added to the controller structure. Various numerical simulations are performed for different working conditions to test the viability of the proposed controller.

1. Introduction

Permanent-magnet brushless direct current motor (BLDCM) with trapezoidal back-EMF, possessing basic structure, higher power density and torque-to-inertia ratio, power efficiency, robustness and ease of control, has been extensively used in industrial products, robotics, medical, automobiles, military applications [1–3]. In recent years, the performance of BLDC motor has been significantly enhanced due to considerable development of power semiconductors, microelectronics, reliability, and motion control technology [4]. Although these features bring several advantages, the BLDC motor has a number of disadvantages compared with other motor types such as high cost, complicated drive scheme and commutation torque ripple. Commutation torque ripple causes a sudden ripple in the output torque that is a major problem affecting adversely in practical applications requiring high performance. In a BLDCM drive with ideal back-emf signals, the form of the phase currents have to be square-wave. However, since this is not possible, the commutation torque ripple is inevitable.

Reduction of commutation torque ripple in BLDCM drives has attracted the considerable attention of researchers in recent decades and there is a huge amount of studies for the solution of this problem [8–10]. In [3], three different methods are tested to reduce the commutation torque ripple in the sensorless drive of BLDC motors. In another method to eliminate commutation torque ripple [10], a switching period is divided into three segments and the modification of pulse width modulation (PWM) signal is carried out accordingly. In [2], considering high and low speed regions distinguished, a modified PWM method is proposed for the reduction of commutation torque ripple in which PWM duties are calculated for conduction and commutation periods separately. Another approach to cope with the commutation torque ripple is to utilize a convenient circuit for different purposes. In such a study [9], an electronic circuit is designed to calculate commutation time that is used to modify PWM signal to reduce commutation torque ripple. In addition to aforementioned studies, many different controller structures are applied to reduce the commutation torque ripple such as the dead-beat controller [11], a finite state model predictive controller [8], direct torque control [7] and energy based methods [12].

Another problem encountered in BLDCM drives is commutation delay. The switching between conduction and commutation periods in a BLDCM drive may occur at any point in the PWM period. Hence a time lag originates between the beginning point of PWM period and the beginning of the commutation defined as commutation delay which has a critical effect on commutation torque ripple. To reduce this adverse effect various methods are proposed such as controlling DC link voltage of the drive [13] and model based prediction method [5, 6].

On the other hand, the BLDCM is a switched system since its dynamical model consists of continuous time subsystems and a rule determining the switching between these subsystems. A large number of real-world systems such as mechanical systems, aircraft, robotic systems are modeled as switched systems and for this reason, the topic has attracted the remarkable attention among the researchers. Stability and stabilization of switched systems are studied extensively, and various control methods are proposed in this manner such as mode-dependent average dwell time, adaptive, backstepping control [14–16]. Finding a common Lyapunov function is a general method for both stability analysis and stabilization of switched nonlinear systems, and an adaptive control approach for such systems is presented in [17]. Both the stability theory of switched systems and the traditional adaptive control scheme are presented for switched systems [18]. Besides, adaptive control with the model reference is investigated for nonlinear switched systems having parametric uncertainties, and an adaptive controller has ensured the boundedness of entire signals for the closed-loop system [19]. In [20], in order to develop the transient performance of the proposed controller and to remove the high-frequency noise in the current, a current control scheme which has two main structures, an integral sliding-mode control method (ISMC) and model reference adaptive control method (MRAC), is proposed for BLDCM.

The main purposes of this paper are controlling the phase currents of uncertain BLDCM, and reducing commutation torque ripple simultaneously. In this manner, an adaptive switching controller is proposed in order to drive the torque error to zero. Two different controllers designed for two distinct operation regions of a BLDCM, and they are combined conveniently by means of a commutation delay compensation method. The controllers and adaptation rules are designed directly by utilizing a common Lyapunov function ensuring the stability of the switched dynamical system. The proposed control structure is tested via numerical simulations and the results are presented.

2. Mathematical Model of BLDCMs

The mathematical model of the current dynamics of the BLDCM drive considered in this study can be given as

$$L\frac{di_\alpha}{dt} = v_\alpha - Ri_\alpha - e_\alpha \tag{1}$$

with

$$i_a + i_b + i_c = 0 \tag{2}$$

where $\alpha \in \{a, b, c\}$, i_a, i_b, i_c are the phase currents, v_a, v_b, v_c are the phase voltages, R and L are the resistance and inductance of the stator windings per phase, respectively, and e_a, e_b, e_c are induced back-emf signals having a trapezoidal form. In the BLDC motor drive, the mechanical dynamics can be given by

$$J\frac{d\omega}{dt} = T_e - T_l - \beta\omega \tag{3}$$

where T_e and T_l are torque produced by electrical power and the load torque, respectively. J is moment of inertia, ω is angular velocity of the rotor. The expression of electromagnetic torque equation generated by a BLDC motor can be given as

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega}. \tag{4}$$

During the operation of a BLDCM drive, two or three phases are conducted simultaneously that are called conduction and commutation periods, respectively. When the drive switches from a conduction to a commutation period, the connection of a phase is separated from the supply (this phase is called *outgoing*) while another phase is connected to the supply (this phase is called *incoming*). The connection status of the third phase is not changed that is called *uncommutated* phase. The commutation period ends when the current of the outgoing phase vanishes. The change of output torque is almost the same as the change of the uncommutated phase current when back-emf signals are assumed to have trapezoidal form. Therefore, controlling the uncommutated phase current can be considered as controlling the output torque.

Considering that x, y, z are uncommutated, incoming and outgoing phase indices respectively, the uncommutated phase dynamics can be obtained as

$$L\frac{di_x}{dt} = v_x - Ri_x - e_x - \frac{1}{3}(v_z - e_z). \tag{5}$$

Here, v_z is a constant value whose sign depends on the direction of the outgoing current since the outgoing current flows to the supply via a diode. In addition, the following continuous time dynamical equation is valid for the conduction periods

$$L\frac{di_x}{dt} = v_x - Ri_x - e_x. \tag{6}$$

The mathematical model of the electrical equivalent of a BLDCM drive can be considered as a switched system and switched nonlinear dynamical systems can be represented by

$$\dot{x} = f_\sigma(t, x), \tag{7}$$

where $x \in \mathbb{R}^n$ denotes the continuous states, $f_i : \mathbb{R}^n \longrightarrow \mathbb{R}^n$ are vector fields. Switching signal $\sigma : [0, \infty) \longrightarrow \mathcal{M}, \mathcal{M} = 1, 2, \ldots, m$ is a piecewise constant function of time. The switching signal may be time dependent ($\sigma = \sigma(t)$) or state dependent ($\sigma = \sigma(x(t))$ which is the case in this study. Since the electrical equivalent of a BLDC motor has two subsystems (commutation and conduction), phase current model of a BLDCM can be considered as a switched system having a state depending switching signal. The switching signal is dependent on the values of the θ angle and i_a, i_b, i_c currents. The dynamics of uncommutated current for the commutation subsystem and for the conducting subsystem can be rewritten as:

$$\theta_1\frac{di_x}{dt} = \begin{cases} v_x - \theta_2 i_x + \frac{1}{3}v_z - \frac{2}{3}\theta_3\omega, & \sigma = 1, \\ v_x - \theta_2 i_x - \theta_3\omega, & \sigma = 2. \end{cases} \tag{8}$$

where $\theta_1 = L$, $\theta_2 = R$, $\theta_3 = k_e$ and k_e is the speed constant. Our aim here is achieving the phase current i_x to track a predefined and possibly time varying trajectory with the condition of $\theta_i, i = 1, 2, 3$ being uncertain constant parameters.

3. Controller Design

Before giving the design of the proposed controller, the error dynamics is derived. In this manner, the current error can be defined as

$$e(t) = i_d(t) - i_x(t) \tag{9}$$

where $i_d(t)$ denotes the reference current value regarding the desired output torque. Therefore, the mathematical model of the system with the error dynamics can be obtained for all subsystems as following

$$\theta_1\frac{de}{dt} = \begin{cases} -v_x - \frac{1}{3}v_z + \theta_1\frac{di_d}{dt} + \theta_2 i_x + \frac{2}{3}\theta_3\omega, & \sigma = 1, \\ -v_x + \theta_1\frac{di_d}{dt} + \theta_2 i_x + \theta_3\omega, & \sigma = 2. \end{cases} \tag{10}$$

In order to provide the convergence of the error to zero under the presence of uncertainties, adaptive controllers are designed for each subsystem. v_x is considered as the control input in the controller design procedure. In adapted signals, the estimation errors can be defined as $\tilde{\theta}_j = \theta_j - \hat{\theta}_j, j \in \{1, 2, 3\}$ where $\hat{\theta}_j, j \in \{1, 2, 3\}$ are the adapted signals.

Designing of the controller, analyzing the stability of the closed loop system and determining the parameter adaptation laws a common candidate Lyapunov function is proposed as

$$V = \frac{1}{2}\left(\theta_1 e^2 + \sum_{i=1}^{3}\frac{1}{\gamma_i}\tilde{\theta}_i^2\right) \tag{11}$$

where $\gamma_i, i = 1, 2, 3$ denotes positive constant adaptation gains. For commutation and conducting periods, the time derivative of the common candidate Lyapunov function can be obtained

$$\dot{V} = \theta_1 e\dot{e} - \sum_{i=1}^{3} \frac{1}{\gamma_i}\tilde{\theta}_i\dot{\hat{\theta}}_i. \tag{12}$$

Utilizing (10) and using the control inputs

$$v_x = \begin{cases} \hat{\theta}_1 \dfrac{di_d}{dt} + \hat{\theta}_2 i_x - \dfrac{1}{3}v_z + \dfrac{2}{3}\hat{\theta}_3\omega + k_1 e, & \sigma = 1, \\ \hat{\theta}_1 \dfrac{di_d}{dt} + \hat{\theta}_2 i_x + \hat{\theta}_3\omega + k_2 e, & \sigma = 2, \end{cases} \tag{13}$$

with $k_1, k_2 \in \mathbb{R}^+$, the time derivative of the common candidate Lyapunov function, can be rearranged as

$$\dot{V} = \begin{cases} \begin{array}{l} -k_1 e^2 - \tilde{\theta}_1 \left(e\dfrac{di_d}{dt} - \dfrac{1}{\gamma_1}\dot{\hat{\theta}}_1 \right) \\ -\tilde{\theta}_2 \left(e i_x - \dfrac{1}{\gamma_2}\dot{\hat{\theta}}_2 \right) - \tilde{\theta}_3 \left(\dfrac{2}{3}e\omega - \dfrac{1}{\gamma_3}\dot{\hat{\theta}}_3 \right), \end{array} & \sigma = 1, \\ \begin{array}{l} -k_2 e^2 - \tilde{\theta}_1 \left(e\dfrac{di_d}{dt} - \dfrac{1}{\gamma_1}\dot{\hat{\theta}}_1 \right) \\ -\tilde{\theta}_2 \left(e i_x - \dfrac{1}{\gamma_2}\dot{\hat{\theta}}_2 \right) - \tilde{\theta}_3 \left(e\omega - \dfrac{1}{\gamma_3}\dot{\hat{\theta}}_3 \right), \end{array} & \sigma = 2, \end{cases} \tag{14}$$

Designing the adaptation laws as

$$\dot{\hat{\theta}}_1 = \gamma_2 e \frac{di_d}{dt}, \tag{15}$$

$$\dot{\hat{\theta}}_2 = \gamma_1 e i_x, \tag{16}$$

$$\dot{\hat{\theta}}_3 = \begin{cases} \dfrac{2}{3}\gamma_3 e\omega, & \sigma = 1, \\ \gamma_3 e\omega, & \sigma = 2, \end{cases} \tag{17}$$

and utilizing them, the derivative of the common candidate Lyapunov function which is eventually a negative semi-definite function can be obtained as

$$\dot{V} = -k_\sigma e^2. \tag{18}$$

It can be concluded with (11) and (18) that the switched dynamical system given in (10) with the control input in (13) and the adaptation rules in (15)-(17) is stable. Moreover, invoking the LaSalle-Yoshizawa theorem [22], it can be shown that

$$\lim_{t\to\infty} e = 0. \tag{19}$$

The control inputs obtained for each subsystem can not be applied directly to the BLDCM drive since the drive circuit can only be run with discrete signals. Hence the control signals in continuous time must be converted to digital counterparts. Discrete time structure of the designed controller is given by

$$v_x(k) = \begin{cases} \begin{array}{l} \hat{\theta}_1(k) i_d(k+1) + \hat{\theta}_2(k) i_x(k) \\ -\dfrac{1}{3}v_z(k) + \dfrac{2}{3}\hat{\theta}_3(k)\omega(k) + k_1 e(k), \end{array} & \sigma = 1, \\ \begin{array}{l} \hat{\theta}_1(k) i_d(k+1) + \hat{\theta}_2(k) i_x(k) \\ +\hat{\theta}_3(k)\omega(k) + k_2 e(k), \end{array} & \sigma = 2, \end{cases} \tag{20}$$

where $k = 0, 1, 2, ...$ is the number of sampling instant. Therefore, the input signal to be applied to the system is

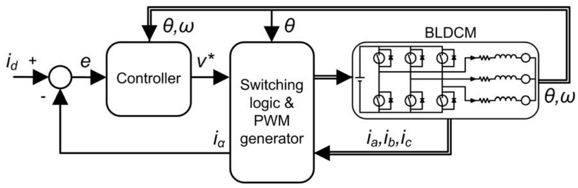


Figure 1. Simulation block diagram.

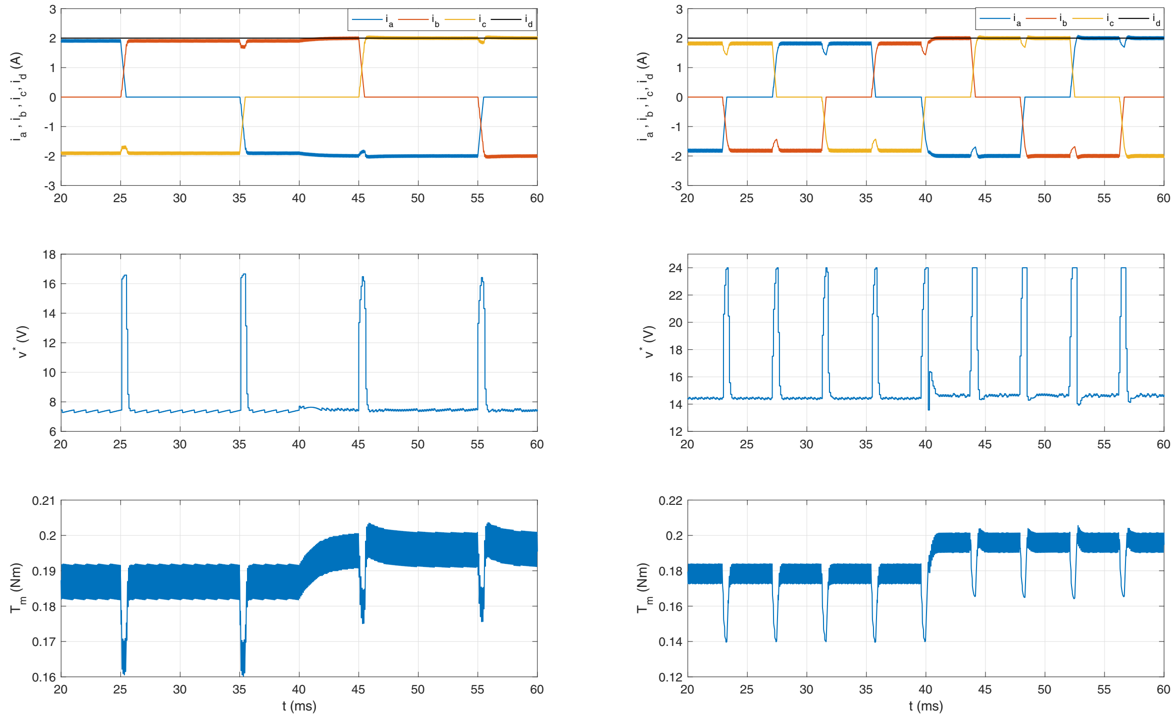
determined for both conduction and commutation periods. The equivalent voltage is generated by the utilization of a PWM signal with a fixed frequency. However, since the beginning or end of commutation periods may occur at any time in a PWM period, the reference voltage for a conduction period may be applied in a commutation period or vice versa. This inappropriate situation causes undesired ripples in the output torque. Hence, the output torque is negatively affected by mixed periods (the mixture of commutation and conduction periods). This situation is called commutation delay, and in order to overcome this negative effect, a weighting average of the control signals obtained for both conduction and commutation models can be used. However, in order to use the weighting average approach, the beginning and the ending points of a commutation period have to be known precisely. Then, the control signal for a mixed period can be determined by the contributions of each model.

In order to predict the beginning time of the next commutation period, assuming the rotor speed is constant between two sampling time instants, the rotor angle can be predicted from the mathematical model. After the determination of an upcoming mixed period, the control signal is computed from the control signals obtained each working regions (see [5] for details). Although the beginning of a commutation period can be predicted by measuring the speed, the end point of a commutation period is predicted by utilizing the current dynamics in the aforementioned studies. In order to apply such an approach, all the model parameters have to be known. Since the adaptive structure designed in this study does not guarantee the convergence of the adapted signals, this approach cannot be utilized. Instead, the ending of a commutation period is predicted by computing the slope of the outgoing current from measurements obtained after the occurrence of the commutation. As a result of this process, the proposed adaptive controller has three different switched signals for conduction, commutation, and mixed periods.

4. Simulation Results

To validate the feasibility of the proposed adaptive switched controller, numerical simulations are carried out in MATLAB. The shapes of back-emf signals are assumed to be trapezoidal with $k_e = 0.049$V·s/rad. Phase inductance and phase resistance values are taken as $L = 2.5$mH and $R = 0.58\Omega$. Rated values for the phase to phase voltage and phase current are assigned as 24V and 3A, respectively.

A general block diagram of the numerical simulation is given in Figure 1. After the current error is obtained, the proposed nonlinear adaptive controller computes the control signal which is the voltage that should be applied to the uncommutated phase. Note that, there are two active phases at a time and the active phases depend on the electrical angle of the motor. In order to select the phases to be connected with the



(a) $\omega = 500$ rpm.

(b) $\omega = 1200$ rpm.

Figure 2. Simulation results: Change of phase currents, control input and output torque.

Table 1. Absolute value of max. error on torque, average and RMS values of the output torque for 500 rpm and 1200 rpm rotor speeds.

	ω	$\|e_{max}\|$	T_{mavg}	T_{mrms}
Controller 1	500 rpm	0.0359	0.1859	0.1860
Proposed	500 rpm	0.0209	0.1957	0.1958
Controller 1	1200 rpm	0.0565	0.1749	0.1751
Proposed	1200 rpm	0.0318	0.1933	0.1935

DC supply, a switching logic is run (see [23] for details). This switching logic also determines the switch to which the PWM signal is applied since one of the active switches is always hold ON which is the higher or lower switch of the uncommutated phase.

Supply voltage of the 3 phase voltage fed inverter is set to 24V in simulations and so the maximum voltage of the motor is saturated with 24V. The switches of the inverter are considered ideal, and frequency of PWM signals is taken as 10kHz. Hence, the sampling period of the controller and adaptation laws is 100μs. A conditional anti-windup scheme is used when adapted signals are updated. Namely, adaptation is paused when the inverter is saturated. The mathematical model is solved numerically using Euler method with $0.5\mu s$ fixed steps. The controller and adaptation gains are taken as $k_1 = k_2 = 1$, $\gamma_1 = 100$, $\gamma_2 = 5$, $\gamma_3 = 5$, respectively. The rotor speed is considered fixed during the simulations. 50% of the parameter values of uncertain parameters are used in the simulations.

Numerical simulations have been performed for 500 rpm and 1200 rpm fixed rotor speeds. Phase currents and current reference, the control input, and mechanical torque output are presented for each simulation. Each result is given for 40ms duration. The parameter adaptation and the commutation delay compensation are run after the first half of the presented simulation results.

The results for 500 rpm rotor speed and 1200 rpm rotor speed are depicted in Figure 2. It is observed from simulation results that a steady-state error occurs before the beginning of the adaptation since the parameter values used in the controller supposed to have 50% uncertainty. After the adaptation runs, this steady-state error vanishes rapidly and the reference signal is tracked successfully for different operation speed values. The change of the adapted parameters shows that they are bounded and they converge to a constant value. Table 1 present the numerical results of absolute value of maximum torque error, average torque and RMS value of torque obtained in simulations. The advantage of the proposed controller against the Controller 1-which is applied without adaptation and commutation delay compensation- can also be observed from these numerical results. Besides, improvement on the commutation torque ripple can be observed when a switching adaptive controller with commutation delay compensation is applied. In addition to this, introducing the mixed periods to the controller has provided a better result on the commutation torque ripple. Eventually, simulation results present the success of the proposed switched adaptive current controller in BLDCM drives for different operation speed values.

5. Conclusion

A switched adaptive controller with a commutation delay compensation is presented for BLDCM drives. The adaptive part of the controller especially deals with uncertainties while the commutation delay compensation part aims to reduce the commutation torque ripple. The design procedure is based on a Lyapunov function which provides the stability analysis as well. The proposed control structure consisting of a combination of switching adaptive controller and a commutation delay compensation works successfully that is validated via numerical simulations.

6. Acknowledgment

This work is supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK) under grant no 115E790.

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