Torque ripple reduction of brushless DC motor based on adaptive input-output feedback linearization

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ABSTRACT

Torque ripple reduction of Brushless DC Motors (BLDCs) is an interesting subject in variable speed AC drives. In this paper at first, a mathematical expression for torque ripple harmonics is obtained. Then for a non-ideal BLDC motor with known harmonic contents of back-EMF, calculation of desired reference current amplitudes, which are required to eliminate some selected harmonics of torque ripple, are reviewed. In order to inject the reference harmonic currents to the motor windings, an Adaptive Input-Output Feedback Linearization (AIOFBL) control is proposed, which generates the reference voltages for three phases voltage source inverter in stationary reference frame. Experimental results are presented to show the capability and validity of the proposed control method and are compared with the vector control in Multi-Reference Frame (MRF) and Pseudo-Vector Control (P-VC) method results.

1. Introduction

Brushless DC Motors are widely used in many applications such as transport systems and servo drives. Typically, the advantages of these motors, including simple construction, good torque-speed characteristic, high power density, fast dynamic response, high efficiency, long life time and easy to control [1,2].

The major weakness of BLDC motors is the higher torque ripple generation. Some of this ripple is due to the harmonics content of back-emf and can be minimized by feeding the safe stator harmonic current. Therefore, there are two main techniques for torque ripple reduction of BLDCMs: motor structure modification and stator current-shape improvement.

Torque ripple reduction methods based on stator current shaping are such as model reference adaptive control [3], phase current perfectly match to back-EMF [4], lead angle injection in respect to back-emf zero crossing [5–7], current controlled modulation technique [8,9], Pulse Width Modulation (PWM) control [10], direct torque and indirect flux control [11] and also harmonic current injection [12–19]. In [3], an inner control loop is used for shaping of the stator phase currents based on model reference adaptive control. The stator phase current reference is quasi rectangular and the back-EMF shape is trapezoidal. Torque ripple reduction is done by adaptive correction of the stator current slope. If the back-EMF is non-ideal trapezoidal form, the mentioned method cannot be used and should be replaced with adaptive methods to change the amplitude and phase of the harmonic currents which are injected to the stator currents.

Most of the methods for torque ripple reduction using stator current shaping are based on harmonic injection to the stator current. In order to calculate the reference harmonic current amplitudes which are needed to inject to the stator windings, some offline and online techniques have been reported.

In online methods, the stator reference current harmonics are calculated based on some torque ripple minimization algorithms such as repetitive control [12], adaptive self-tuning method based on Fourier coefficients of the generated torque [13], modified vector control [14], cycle average torque control [15] and adaptive decision fusion algorithms [16].

In offline methods, generation of reference currents are performed by constructing a lookup table indexed by position, speed, and required average torque [17–20]. In these methods, the amplitudes of reference current harmonics are precisely calculated to completely eliminate the selected harmonics of torque ripples [18], or by using an optimization method the reference current harmonics are calculated to minimize the torque ripple and even motor losses and maximize the torque per current ratio [19].

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In order to inject the calculated harmonic currents to the stator windings, the conventional FOC method cannot be used. Since the harmonic contents of the stator currents in the rotational reference frame will oscillate with 6th multiples of the fundamental frequency, so the Multi-Reference Frame (MRF) method [20–22] can be used, which is complicated and time consuming method.

Vector control in a MRF is proposed in [20] in order to harmonic injection into the stator windings. In that method, the amplitude of the desired q-axis current, in the each reference frame is assumed as a constant coefficient of the square wave harmonics and the d-axis reference current is set to zero and then the stator current components in the stationary reference frame at each frequency is obtained by Park transformation. Afterwards, the stator reference current components in the stationary reference frame are calculated by the summation of each harmonic current. Then the reference of the stator voltage is calculated by using two PI current controllers. In [21], a MRF synchronous estimator is proposed. The estimation of the stator current harmonic amplitudes using transformation matrices gives a heavy computational burden.

In [22], an adaptive notch filter is used to estimate the stator current harmonics to be implemented in a multi reference frame, and then, by using PI regulators the stator reference voltage components in each reference frame can be derived. After that, by transformation of these reference voltages to the stationary frame and adding them, the stator reference voltages are calculated.

So, with the purpose of harmonic current injection in the stator winding, while the machine back-EMF is non-ideal, the control methods which are employed in the stationary reference frame are preferred.

In [23], a Pseudo–Vector Control method is used to generate the reference harmonic currents of BLDC, in which the quadrature component of the stator current is derived using reference torque and the direct component is set to zero. It is obvious that the effects of the higher order of stator currents on the generated torque cannot be considered in that method.

In this paper, a new method based on input-output feedback linearization technique is proposed for injection of harmonic currents to the stator windings in order to reduce electromagnetic torque ripple from a BLDC motor. Since most of the input-output linearization methods are sensitive to model parameters, an adaptive method is proposed to estimate the stator resistance uncertainties. This method can inject the arbitrary reference current to the stator windings using VSI. The stator reference currents are proposed to be calculated based on the elimination of some harmonic contents in the generated torque. Then, by using non-sinusoidal reference currents, the proposed method is tested. Finally, in order to evaluate the effectiveness of the proposed method, the results of this method are compared with the multi-reference frame [21,22] and pseudo-vector control [23] methods by experimental tests.

2. Mathematical model of the brushless DC motor

In many reported researches the back-EMF waveform of BLDC is assumed to be sinusoidal [24,25]. However, the actual back-EMF waveform might be quite non-sinusoidal. Including the back-EMF harmonics into the voltage and torque equations increases the accuracy of the model. In [26], eighteen states during an electric angle cycle has been obtained for modeling of non-ideal back-EMF of BLDCM. For small-signal analysis of electromechanical systems linearization methods are sensitive to model parameters, an linearization technique is proposed for injection of harmonic currents to the stator windings in order to reduce electromagnetic effects of the higher order of stator currents on the generated torque. Then, by using non-sinusoidal reference currents, the proposed method is tested. Finally, in order to evaluate the effectiveness of the proposed method, the results of this method are compared with the multi-reference frame [21,22] and pseudo-vector control [23] methods by experimental tests.

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In the developed electromagnetic torque in presence of back-EMF harmonics is then defined as the following [28].

The equivalent circuit of BLDC motor for each phase is shown in Fig. 1. The electrical dynamics of the BLDC motor is written by the following voltage equations.

\[ V_{abc} = r_i i_{abc} + \frac{d\lambda_{abc}}{dt} \]  \hspace{0.5cm} (1)

Where the variables are given in vectors such as \( f_{abc} = [f_{dc, fb, fa}]^T \). \( f \) may refer to the stator voltage respect to the neutral point of the motor winding, current and flux linkage. The stator resistance matrix is as (2).

\[ r_i = diag[r_r, r_r, r_r] \]  \hspace{0.5cm} (2)

The flux linkages are then given by

\[ \lambda_{abc} = L_i i_{abc} + \lambda_m \]  \hspace{0.5cm} (3)

Where the inductance matrix is defined by

\[ L_i = \begin{bmatrix} L_i + L_m & -0.5L_m & -0.5L_m \\ -0.5L_m & L_i + L_m & -0.5L_m \\ -0.5L_m & -0.5L_m & L_i + L_m \end{bmatrix} \]  \hspace{0.5cm} (4)

Where \( L_i \) and \( L_m \) are the stator leakage and magnetizing inductances, respectively, and \( \lambda_m \) is the vector of flux linkages.

Assuming that stator windings are wye connected, the sum of the three phase currents equal to zero. Thus, (3) may be simplified as the following.

\[ \lambda_{abc} = L_i i_{abc} + \lambda_m \]  \hspace{0.5cm} (5)

Where \( L_i = L_i + \frac{1}{3}L_m \).

The comprehensive model considered in this paper has to include the desirable amount of back-EMF harmonics. To contain that, the flux linkage vector can be expressed as the following.

\[ \lambda_m = \lambda_m \sum_{n=1}^{\infty} K_n \sin \left( \frac{2n-1}{3} \theta_i \right) \sin \left( \frac{2n-1}{3} \theta_i + \frac{2\pi}{3} \right) \]  \hspace{0.5cm} (6)

Where \( \theta_i \) is the rotor electrical position, and \( \lambda_m \) is the magnitude of the fundamental component of the permanent magnet flux linkage. The coefficient \( K_n \) denotes the normalized magnitude of \( n^{th} \) flux harmonic relative to the fundamental, i.e., \( K_1 = 1 \). Also, the index \( 2n - 1 \) shows that only odd harmonics may be present since the rotor is assumed to be symmetrical.

Fig. 1. The electrical dynamics of the BLDC motor is written by the following voltage equations.
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