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Minimization of torque ripples in BLDC motors due to phase commutation - a review

***Abstract**. The smoothness of variable speed drive operation is critical and a viable measure used in the design and development of motion control applications. The torque produced in a brushless DC (BLDC) motor with trapezoidal back electromotive force (BEMF) is constant under ideal conditions. However, in practice, torque ripple appears on the delivered output torque. Some of these ripples result from the natural structure of the motor, while some are related to the motor design parameters. Nevertheless, these torques could be minimized throughout the machine design process. Another source of ripples is associated with the control and drive side of the motor. This paper focuses on the torque ripples associated with machine control and drives that could be minimized by applying different control techniques. Various applied techniques for minimizing the torque ripples in BLDC are presented based on the motor control side. There are a variety of configurations to be adjusted based on the applied technique; in addition, hardware modifications or additional stages are also required. Other techniques, such as algorithm-based ones, could be applied to standard motor drive configurations.*

***Streszczenie.** Płynność zmian szybkości napędu jest istotną miarą używaną w projektowaniu i rozwoju zastosowań kontroli ruchu. Moment wytwarzany przez bezszczotkowy silnik DC z trapezoidalną zwrotną siłą elektromotoryczną jest stały w warunkach idealnych. Jednak w praktyce pojawiają się zafalowania momentu. Niektóre z tych zafalowań wynikają z naturalnej konstrukcji silnika, ale inną są związane z parametrami projektu i mogą być zmniejszane przez właściwe projektowanie. Inne zafalowania są związane z układem sterowania. Ten artykuł koncentruje się na zafalowaniach wynikających z techniki sterowania. Przedstawiono różne możliwości zmniejszania zafalowań. (**Zmniejszanie zafalowań momentu obrotowego w bezszczotkowych silnikach DC powstających przy komutacji fazy**)*

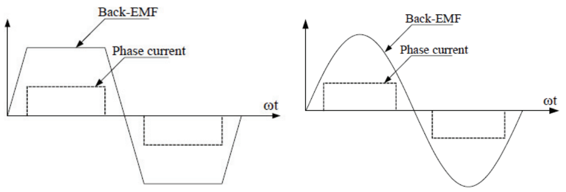
Keywords: brushless DC motor, BLDC, torque ripples, minimization.
Słowa kluczowe: silniki bezszczotkowe, falowanie momentu obrotowego..

Introduction

In conventional DC motors with brushes, the field winding is on the stator and armature winding is on the rotor. The motor is expensive and requires maintenance due to the brushes and accumulation of brush debris, dust, commutator surface wear, and arcing. The brushless DC (BLDC) motor could overcome this issue by replacing the mechanical switching components (commutator and brushes) using electronic semiconductor switches. The BLDC motor has a permanent magnet rotor and a wound field stator, which is connected to a power electronic switching circuit.

BLDC motor drives have high efficiency, low maintenance and long life, low noise, control simplicity, low weight, and compact construction. Due to these features, the BLDC motor has become a very popular and viable product in the market. In fact, the BLDC motor has more advantages compared with other types of AC motors in the market [1].

Based on the shape of the BEMF (Fig. 1), brushless motors can be trapezoidal or sinusoidal. In the BLDC motor, permanent magnets produce an air gap flux density distribution, which is trapezoidal, resulting in trapezoidal BEMF waveforms.



(a) (b)

Fig. 1: (a) Trapezoidal Induced EMF, (b) Sinusoidal Induced EMF

Torque pulsations in BLDC motors brought about by the deviation from ideal conditions are either related to the design factors of the motor or to the power inverter supply, thereby resulting in non-ideal current waveforms [2]. Undesirable torque pulsation in the BLDC motor drive causes speed oscillations and excitation of resonances in mechanical portions of the drive, leading to acoustic noise and visible vibration patterns in high-precision machines [3]. BLDC motor torque pulsations produce noise and vibration in the system. Therefore, minimization or elimination of noise and vibration is a considerable issue in BLDC drive.

Torque pulsations are mainly minimized by two techniques: improved motor designs and improved control schemes. Improved motor design techniques for pulsating torque minimization include skewing, fractional slot winding, short pitch winding, increased number of phases, air-gap windings, adjusting stator slot opening and wedges [2], and rotor magnetic design through magnet pole arc, width, and positions [4].

For improved motor control schemes, digital control-based techniques, such as adaptive, preprogrammed current, harmonics injection techniques, estimators and observers, speed loop disturbance rejection, high speed current regulators, commutation torque minimizations [2],[4], and others, will be introduced in details in this paper. The digital control found in many applications in motor drive systems, is used in applications requiring high-speed and precision control. Advanced microprocessors, microcontrollers, and digital signal processors are used to generate and analyze drive system signals as well as detect and protect the system from abnormal over-voltage conditions.

PM BLDC control drive system

The BLDC control drive system is based on the feedback of rotor position, which is obtained at fixed points typically every 60 electrical degrees for six-step commutation of the phase currents [5]. The BLDC drive system consists of the BLDC motor, power electronics converter, sensor, and controller as shown in Fig. 2.

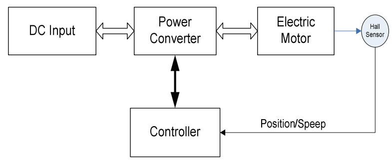


Fig. 2: BLDC drive system components

To switch the motor stator coils in the correct sequence and at the correct time, the position of the rotor field magnets must be known. The exact location of the rotor field magnets can be sensed by Hall Effect sensors or by using encoders. The function of the controller is to switch the appropriate currents in the right stator coils at the right time and sequence by taking the information supplied by the sensor and processing it with preprogrammed commands to achieve the desired motor performance. For a BLDC motor drive with a 120 electrical degree conduction time, the current produces the torque spike every 60 degrees, causing the rotor to pulsate at a frequency six times the fundamental one. As the torque is a product of induced voltage and current, and the voltage does not change spike-wise, these spikes are mainly produced by the rapid transition of the current with a slight delay at the switching instants [6].

Sources of torque ripples in PM BLDC motors

As shown in Fig. 3, the general sources of torque ripples in BLDC motors fall in three main categories: a) Motor Nature, b) Motor Structure, and c) Motor Control.

a. Motor nature: Ripples associated with motor nature refer to the physical properties and parameters of the motor's manufactured materials. Better selection of materials lead to better performance.

b. Motor structure: This is associated with the motor's design parameters, such as shape and dimensions. Careful consideration of these parameters leads to good performance design.

c. Motor Control: Many techniques have been introduced to minimize torque ripples. This paper will highlight the minimization of torque ripples in BLDC motors from the motor control side.

As stated by Jahns [2], a pulsating torque (PT) refers to any source of divergence from ideal conditions in either the motor or associated power converter in a PMAC motor drive, which typically gives rise to undesired torque pulsations. There are various sources of harmonic torque components.

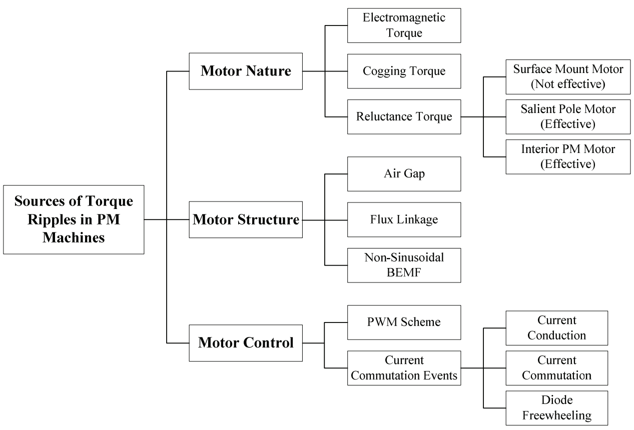


Fig.3: Sources of torque ripples in PM BLDC motors

The PT is the sum of the cogging and ripple torque components. Cogging torque ripple comes from the interaction of the teeth and slots with permanent magnet. It is usually reduced through rational motor structuring, such as skewing stator teeth or rotor magnet poles, notching in teeth, shifting magnet poles pair, and setting the optimum ratio of pole arc to pole pitch. No stator excitation is involved in cogging torque production [2].

Ripple torque components are generated by the interaction of stator current magnetomotive forces, which could be the mutual or alignment and the reluctance torque. Mutual torque results from the interaction of the current's mmfs with rotor magnet flux distribution. The reluctance results from the interaction of the current's mmfs with the angular variation in the rotor magnetic reluctance. In surface-mounted PMAC machines, no reluctance torque is generated.

The minimization of these torques entails using techniques to adjust the design of PMAC machines to produce characteristics that are as close as possible to the ideal one. The second approach is the utilization of various controls and drive approaches. This paper focuses on the minimization of torque in a BLDC motor using the control side approach.

Control techniques to minimize the torque ripples in BLDC machines

BLDC motors are used in many industrial applications. The associated torque ripples limit the usage where such torque is concerned. In this section, the techniques used to minimize the torque ripples in BLDC motors are discussed from control side. Many techniques have been introduced to minimize the torque ripples.

1. Modified PWM control techniques

As BLDC motors commutate every 60 degrees, the magnetic field unequally circulates and jumps every 60 degrees, thereby producing uneven torque. A pulse width modulation (PWM) control algorithm for eliminating torque ripple caused by stator magnetic field jump has been proposed by Cunshan [7]. His method shows that the stator magnetic field jump causes torque ripple for BLDC motors.

The novel PWM proposed by Wei [8-9] is a scheme to eliminate the ripple current caused by diode freewheeling in the inactive phase of the BLDC motor. The new PWM mode (hereby referred to as PWM_ON_PWM) operates on the principle that the switch is in the PWM mode in the beginning 30° and the last 30° zones, and in continuous ON state in the middle 60° zone.

Previous studies [10-11] have discussed the different influences of four PWM modes on the commutation torque ripples in sensorless BLDC motors control systems. The influences of the PWM mode on the current generated by BEMF during switch-off phase in the control system of a BLDC motor has been discussed in [12]. That study identified two types of currents of the off-going phase, namely, the current generated by phase inductance and that generated by BEMF of the off-phase. The comparison has revealed that the ON_PWM type is the best among the five modes.

Murai [6] proposed a PWM chopping method to improve the torque ripple for BLDC miniature motors. The comparison of the two proposed switching strategies to reduce the torque ripple shows that the PWM chopping method has higher output torque and lower ripples compared with the overlapping method. Husain [13], meanwhile, proposed a torque ripple minimization in switched reluctance motor drives by PWM current control. The proposed strategy of the PWM current control includes a current control strategy during commutation, in which torque ripple minimization is of highest importance for low-speed SRM drives.

A low-cost digital control technique has been proposed [14] with a constant frequency digital PWM controller. In that work, speed regulation is achieved using high duty (D_H) and low duty (D_L). According to Sathyan [14], this concept helps reduce the cost and complexity of motor control hardware and boosts the acceptance level of BLDC motors for commercial mass production applications.

A new digital control concept for BLDC machines has been introduced by Sathyan [15] to develop a low-cost controller for applications where inefficient single-phase induction motors are used. Guangwei [16] proposed a method for commutation torque ripple reduction in a BLDC motor using PWM_ON_PWM mode.

The minimization of torque ripple in PWM AC drives has been presented by Basu [17]. He proposed a PWM technique for minimizing the RMS torque ripple in inverter-fed induction motor drives. A commutation time control for torque ripple reduction of BLDC motors has been presented by Oh [18]. The proposed method is based on a strategy, in which the commutation intervals of the incoming and outgoing phases can be equalized by a proper PWM control.

2. DC Bus Voltage Control

Ki-Yong [19] has proposed a system, in which the torque ripple of a BLDC motor is reduced by varying input voltage. The proposed method varies the input voltage to reduce the current ripples causing the torque ripples in the conduction region. Other methods eliminate the conduction torque ripple in the BLDC motor using cascade BUCK converter.

Jin-soek [20] proposed a new method considering cogging torque for minimization of torque ripples in a BLDC motor using improved DC link voltage control method.

A proposed method for reducing the torque ripples in brushless PM motors by optimizing the supply has been presented by N'Diaye [21]. In this method, an analytical computation of the currents removes electromagnetic torque harmonics.

Gui-Jia [22] proposed a multilevel DC link inverter for brushless permanent magnet motors with very low inductance. The multilevel dc link inverter can dramatically reduce the current ripple for brushless PM motor drives.

3. Current control based techniques

A low-cost drive strategy based on phase current regulation for BLDC motors with low torque ripples has been presented by Xu [23]. The proposed method regulates the motor phase currents with PWM by referring to the error between the reference command current and the detected phase current, which is measured from the DC link. A previous study [24] has proposed a novel commutation torque ripple suppression scheme in BLDC motor based on DC current sensing. The two methods are commutation current prediction and negative DC current elimination scheme. By combining the two schemes, smooth commutation is achieved and current ripples are minimized during commutation interval.

Joong-Ho [25] proposed a method using a single DC current sensor. The method is based on a strategy, in which the current slopes of incoming and outgoing phases during the commutation interval can be equalized by proper duty-ratio control. The method shows a suppression of the spikes and dips superimposed on the current and torque responses during the commutation intervals [25]. A simple current control algorithm for torque ripple reduction of a BLDC motor using a four-switch three-phase inverter has been proposed [26]. This method compensates for the commutation current slopes of the incoming and outgoing phases during the commutation interval of the phase currents in various speeds based on generation of a current reference.

A current control strategy for BLDC motors based on a common DC signal has also been proposed by [27]. The proposed drive is based on the generation of quasi-square wave currents using a single current controller for the three phases. Another study [28] proposed a current control method for torque improvement of high-speed BLDC motor drive. The proposed method is based on the adjustment phase advance angle control method. The proposed method improved output torque and speed response characteristics and transformed the current waveform shape to a rectangular one.

A method for touque ripple reduction using repetitive current control has been proposed by Mattavelli [29]. The proposed method is based on tracking a modified current reference by the parallel of a PI and a repetitive controller. Another study [30] presented a novel current prediction control method. The current in the non-commutation phase can be compensated quickly in the commutation interval. Meanwhile, another study [31] provided and analyzed torque ripples due to phase commutation in BLDC machines. It has demonstrated that commutation torque ripples can be minimized during low speed through the introduction of direct current sensing with hysteresis current controller.

Current tracking vector of electromotive force has been proposed by [32] for high efficiency and low torque ripple control of PM synchronous motor. The proposed method is based on making armature current tracking vector of distorted electromotive force. A proposed method with an underlying principle of direct measure of commutation interval from motor terminal voltage waveforms has been presented by [33]. Synchronization of the commutation points at the starting point of a PWM carrier signal reduced the pulsating currents and the total vibrations for the BLDC motor by 31%, according to [33]. An analysis study of torque ripple in BLDC motor based on commutation time has been conducted by [34]. The study proposed theoretical background to reduce torque ripples in BLDC.

4. Torque Control Techniques

A. Direct Torque Control (DTC)

The electromagnetic torque in a PMSM is proportional to the angle between the stator and rotor flux linkages. Therefore, high dynamic response can be achieved using DTC. The DTC mainly has advantages in terms of structure simplicity, especially since no coordinate transformations and no PWM generation are needed [35]. Zhu [36] provided a comparison of the performance of BLDC drives under DTC and PWM current control. In Zhu's work, the DTC-controlled BLDC drive exhibited significantly less low-frequency torque ripples than the PWM current-controlled BLDC drive without current shaping. Another study [37] proposed a technique for commutation-torque-ripple minimization in DTC PM BLDC drives. The technique is based on minimizing the error between commanded and estimated torque. The technique adaptively adjusts the phase-current waveform to maintain constant electromagnetic torque, so that commutation torque ripples, particularly at high rotational speeds, are effectively eliminated.

A DTC of BLDC drives with reduced torque ripple has been produced by Yong [38]. The principle of the proposed DTC is to estimate the torque and to represent the inverter voltage space vectors. A direct torque control of BLDC motor with non-sinusoidal BEMF has been proposed by Ozturk [39], [40] using a four-switch inverter. The proposed method produced faster torque response and eliminated the low-frequency torque oscillations caused by the non-ideal trapezoidal shape of the BEMF waveform. In [41], a direct torque control of BLDC motor with non-ideal trapezoidal back EMF has been presented. The method is based on the calculation of applied output voltage from the reference and the previous step torques in the two-phase conducting and commutation periods. An improved PMSM direct torque control DTC scheme using an active-null vector modulation strategy has been presented by Romeral [35]. The strategy is based on the minimization of the rms value of torque ripple, which is predicted using the time derivatives of the torque and the corresponding slopes under either active or null vector voltage application. An intelligent neural network-based DTC for a BLDC motor has been proposed by Gupta [42]. MATLAB simulation is used to verify the proposed approach and the results indicate that the intelligent controller significantly reduced the torque pulsation.

B. Torque Control Method

A new torque control method for torque ripple minimization of BLDC motors with non-ideal BEMF has been proposed by

[43]. The method entails calculating the time pulses that are computed in the torque controller by referring to the actual back EMF waveforms in both normal conduction and commutation periods. A high-performance torque control system for BLDC motors has been presented by [44]. The proposed design aimed to achieve continuously variable transmissions when applied to electric scooters. The control scheme uses only a single current sensor to measure the DC bus current to achieve torque control instead of two current sensors for three phase currents. By using close-loop torque control with phase advance and field weakening, constant torque and constant power for mechanical variable transmission system were attained.

5. Phase Conduction Methods

A. Conduction Overlap

Two types of switching methods have been proposed by [6] for torque ripple improvement of BLDC miniature motors. One method is overlapping and the other is PWM chopping method. In that study, computation work was carried out by digital simulation techniques, and the torque ripples were evaluated using a ripple index. A current overlapping method has been proposed to suppress the torque ripple presented by [45] to reduce noise in BLDC motor drive. Based on conventional overlap method, a research of a novel commutation control strategy of BLDC motor has been presented by [46]. The principle is based on dynamic commutation during the stop interval commutation.

B. Conduction Angle Control (120°,180°)

Reduction of commutation torque ripple in a BLDC motor drive based on changing the electrical degree of switching mode has been proposed by [47]. The study presented an analytical study of torque ripples due to commutation of phase currents in a BLDC motor for both 120° and 180° conduction modes. Kwok [48] presented a study on reducing the torque ripples of BLDC motor speed control system. The proposed method had two switching modes, and of the two, the 180° continuous switching system appeared to be more practical. A novel control strategy for BLDC Motor has been proposed by Wu [49] based on wide-angle wave control method for reduction of torque ripple. The proposed control strategy minimized torque ripple and increased the torque; the method also obtained sensorless control for BLDC motor.

C. Switching Angle

Generalized techniques of reducing torque ripples in BLDC motor drives have been proposed by [50]. The technique is based on reducing the torque ripple components by switching angles per half cycle of the inverter. The developed technique reduced the torque ripples and improved the performance of the system.

6. Compensation

A cascade modified model reference compensator has been proposed by [51] for torque ripple reduction in BLDC motor. The proposed method used cascade compensator to derive a correction signal from the inverse or the difference of the Park's transform of the original control signal. A concept for the compensation of torque ripple by a self commissioning and adaptive control system has been presented by Holtz [52]. Identification and compensation of torque ripple in high-precision permanent magnet motor drives are presented, and a fast current control system is employed to produce high frequency electromagnetic torque components for compensation. A compensation method and an algorithm to minimize the commutation torque ripple in trapezoidal BLDC motor with sensorless drive have been presented in previous studies [53], [54]. The proposed method compensated the commutation torque ripple of the trapezoidal BLDC motor by controlling the time and degree of compensation.

7. Other Techniques

The d-q-0 Reference Frame: A novel approach to achieve the ripple-free torque control with maximum efficiency based on the d-q-0 reference frame has been presented [55], [56] for pulsating torque minimization of brushless PM motor. An optimal current excitation scheme proposed by [57], which produces loss-minimized ripple-free torque of a BLDC motor, is based on the d–q–0 reference frame.

Optimal current excitation: An analytical study for minimum torque ripple and maximum efficiency excitation of brushless permanent magnet motors has been presented by [58]. It demonstrated the relationships between motor current and back EMF, and identified minimum torque ripple and maximum efficiency current excitations that can be implemented with finite bandwidth power electronics.

Fourier Series Coefficients Current Control: A current control algorithm based on Fourier series coefficients for torque ripple reduction of BLDC motors has been proposed by [59].

Adaptive Control: An adaptive controller has been presented by [60] for torque ripple minimization in PM synchronous machines. That study proposed an adaptive feedback structure as a solution model. Other adaptive torque ripple control of permanent magnet BLDC motors has been presented by [61]. For this technique, the coordination of an outer speed loop with an inner current loop is required. An adaptive solution to suppression of vibrations has been presented by Hillerstrom [62]. The approach approach is derived from repetitive control based on models of isolated frequencies.

Fuzzy Control: Wang [63] presented a complex fuzzy controller, which comprises two controllers. The first controller is designed to select correct voltage vector according to the torque error, stator flux-linkage error, and electric angle of stator flux-linkage. The second fuzzy controller with adjustable factor is designed to regulate the action time of voltage vector according to the torque error and torque error differential. Based on fuzzy logic control, Yaya [64] presented an approach for minimizing torque ripple in BLDC motor due to phase commutation using fuzzy control. The proposed fuzzy logic control uses double close-loops with current hysteresis and speed fuzzy logic control. The traditional speed PID controller is replaced by fuzzy PI-like controller to improve the performance of the BLDC motor drive system. Results demonstrated a viable suppression of the spikes on the current and torque responses during the commutation intervals.

Harmonic Elimination: A selective harmonics elimination technique for torque ripple minimization in BLDC motor drives and its effectiveness has been studied and evaluated by [65].

Harmonic Current Injection: The principle of harmonic is that, the torque harmonics serve as the integer multiples of the lowest common multiple (LCM) of stator and rotor pole number. Torque ripple reduction of interior PMSM (IPMSM) has been proposed by [66] to reduce torque ripple using harmonic injected current. Using the proposed method, average torque is increased by 20% and torque ripple is decreased from 84.6% to 48.1%.

Digital Observer Controller: A previous study [67] presented the digital observer controller, which is applied to the surface-mounted permanent magnet synchronous motors to minimize the ripple torque.

Flux/Torque Estimator: A control method for reducing pulsating torque for PMAC machines based on estimator control has been proposed by [68]. Based on the results, the influence of the cogging torque was considerably reduced at lower motor speed using internal model principle and adaptive feed forward compensation technique.

Conclusion

This paper has presented the techniques applied for minimizing the torque ripples in BLDC motor from the control side. Control techniques for minimizing pulsating torque could apply advanced methods, depending on the accurate information of machine parameters.

In conclusion, the demand in BLDC motor is to produce a BLDC drive with smooth operation to suit any application where needed. This paper addresses the issue of torque ripples associated to machine control and drives that could be minimized through different control techniques. Suppression of the ripples basically depends on the controller part of the drive system, and the techniques that can be used entail a variety of configurations to be arranged. Some techniques require hardware modification or add-on stages, whereas other schemes are algorithm-based techniques.

Despite the number of techniques that have been reported for minimizing pulsating torque production, the effective solution mainly depends on the application limitation and applied controller. Some advance control techniques that can be used include fuzzy, adaptive, control, and neural networks. The complexity of the system techniques vary depending on inputs and outputs to the system and signals to be processed to validate the selected topology. Hardware modification and addition also become issues when selecting the proper method and system requirements. Several methods have been applied throughout the modeling process. However, the case is highly sensitive during implementation. Other factors, therefore, have to be considered in choosing the proper method. The cost should also be addressed, especially when it is required to implement a control using a high-performance controllers, such as digital signal controller and DSPs. This paper procduces an extensive review of torque ripples minimization in BLDC motors through different control techniques.

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