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Sensorless Based Torque Ripple Reduction in Brushless DC Motor

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Abstract*: *Abstract— Brushless Direct Current Motor (BLDCM) has been commonly utilised in fields that necessitate high fidelity and specific control, owing to its simple structure, high power density, high efficiency, high starting torque, long operating life, and prolonged ranges of speed. While considering of the drive part of the motor, the most significant part is commutation control. During commutation, they generate some high torque ripples which is caused by non-ideal commutation currents in the stator windings which confines its application, exclusively at low-voltage fields. Some of the techniques for the mitigation of commutation torque ripples are reviewed here. A complete knowledge of commutation torque ripple was done by proposed phase advancing method for commutation control for diminishing torque pulsations for the complete ranges of speed. An analysis was made in order to design and implement an optimal current vector trajectory for reducing the torque pulsations for the complete speed range. This method utilises terminal voltage sensing technique and the terminal voltages are converted into d-q reference frame and hence those values are compared with specified values in order to generate the commutation signals. Initially the proposed system is simulated with Proportional Integral controller and then with Fuzzy Logic Controller. Simulation of the proposed system was done in MATLAB version 2013a and the results of comparison was made for both PI controller and fuzzy logic controller.

Keywords: Brushless Direct Current Motor (BLDCM), torque ripples, Phase Advancing method(PA), Proportional Integral controller(PI), Fuzzy Logic Controller.

I. INTRODUCTION

Brushless Direct Current Motors have several advantages over conventional DC motors and other AC motors. Conventional DC motors use mechanical commutator and brushes; hence they are subjected to wear and need frequent maintenance whereas brushless DC motors are electronically commutated which lead them effectively maintenance-free motor. These are mostly used for a wide range of applications such as fluctuating loads, continuous loads and position control in the fields of industrial control, automotive, fitness care apparatus, aviation, automation schemes etc.

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BLDC motor consists of three-phase distributed winding on the stator and permanent magnets on the rotor. Brushless DC motor (BLDCM) consists of a three-phase stator winding and a permanent magnet on the rotor. Commutation is carried out based on hall sensors inputs which are used to detect the position of the rotor. Unlike Conventional DC motors, rotor rotates and the stator windings remain stationary. Adjustable speed AC drives made possible with the advent of microelectronics and power switches. The principle of sensorless control strategy is that the error equals the difference between the reference speed and real motor speed of the drive. Torque ripples are primarily minimized by upgraded design structures and enhanced governing techniques. Upgraded motor design techniques for pulsating torque minimization mainly includes modifying structure of stator. Enhanced control schemes use advanced control schemes such as pre-programmed values and harmonics injection techniques, etc. High-speed and precision control applications require digital control in motor drive systems.

II. CONTROL STRATEGY FOR BLDC MOTOR

The effect of torque ripples includes speed fluctuations and causing of vibrations in drive side of the BLDC motor system which gives rise to acoustic noise and observable shaking forms in high-precision applications [1]. Therefore, reduction of noise and vibrations a significant problem in brushless DC motor system. The universal causes of torque ripples present in these motors comes under following general fields: a) Nature of Drive, b) Structure of Motor, and c) Control of Motor.

a) *Nature of Drive*: Here ripples are associated with the natural properties of drive's factory-made resources. Choice of good resources give rise to better improvement in the performance of motor.
b) *Structure of Motor:* In this case ripples are concerned with the design parameters of stator and rotor like dimensions and shape. For good performance design these parameters should be considered cautiously.
c) *Control of Motor*: Here torque ripples are originated while controlling the motor. Numerous techniques have been presented to minimize torque ripples. Here a novel scheme is presented for the reduction of commutation torque ripples in PMBLDC motors while controlling the same.

The interaction between the magnetic fields of the stator and the rotor by the repulsive forces produces torque.

In the case of BLDC motor six ripples are produced in torque output which happens at every electrical cycle. Since the frequency of the torque ripple is directly proportional to the speed of rotor it will affect motor speed. During high speeds, the effects of torque ripple can be neglected. Also, during less speeds, torque ripples can be diminished by using suitable controller for the motor. But the rotor speed is highly affected, when the frequency of the torque ripple is almost equal to the bandwidth of speed loop of the drive controller. The combination of cogging and ripple torque components give rise to pulsating torque. These ripples could be minimized by suitable structuring of drive and it is not involved with stator excitation [1]. The major disadvantage the brushless DC motor is the ripples of toque produced in the commutation period of stator windings, which worsens its performance at large speeds. One of the major technique to reduce these torque ripples is by proper designing of motor structure and the other method is the application of various controller approaches. This paper emphases on mitigation technique for commutation torque ripples in a PMBLDC drive by improving the controller performance.

Methods for the mitigation of torque ripples in PMBLDC machines

In several applications brushless DC motors are utilized and the torque ripples cause major impact on the performance of those applications. Previously numerous methods are used to improve the controller performance by reducing the ripples in BLDC motors.

A. Different PWM control techniques

Since the stator windings of PMBLDC motors commutate every 60 degrees, the magnetic flux lines unevenly circulate and jumps for each sixty degrees, hence creating irregular torque. Cunshan proposes a pulse width modulation (PWM) control technique for the minimization of ripples of torque produced by uneven jumping stator magnetic field during commutation of stator windings [2]. A novel PWM strategy proposed by [3] for eliminating the ripple currents formed by freewheeling diode in the nonconductive phase of the stator winding. In this new PWM mode the freewheeling diode is completely eliminated during non -commutation period in the stator winding of BLDC motor. This literature [4] proposes the different types of PWM modes applied stator windings of sensorless brushless DC motor under sensorless scheme and investigates their impact on the ripples of torque during commutation. Out of the four PWM modes, the optimum one is selected and applied for the reduction of ripples at the time of commutation of stator phases. This paper [5] analyses 5 cases of PWM modes for sensorless scheme of control. This scheme is proposed based on back electro motive force current and the optimum Pulse Width Modulation mode is chosen to minimize torque ripples at commutation control.

This paper [6] examines the constant commutation technique with PWM mode, and hence the implementation of control of compensation for minimizing commutation torque ripple overall speed range. The proposed technique studies the impact of pulse width modulation mode on a three-phase inverter with 120° conduction mode operation of permanent magnet brushless DC motor and also provides mitigation control ripples of commutation torque at the time of non-commutation.

B. DC bus voltage control

This literature discusses a technique for the minimization of torque ripples by controlling input DC voltage by Laplace transformation method in BLDC motor [7]. Jin-soek Jang [8] proposes a new voltage control technique for reducing cogging torque ripple components of brushless DC drive which is excited by square wave voltage and the torque characteristics of motor is analyzed by analytic calculation and it is validated by finite element analysis. The main interest of this literature is to reduce the current harmonics for the particular BLDC motor and analytical computation of harmonics of currents done by neglecting third harmonics. This literature [9] introduces a new DC link multilevel inverter for low inductance PMBLDC motors in order to decrease the current ripples.

C. Techniques based on controlling current

This literature focuses a brushless DC motor which consists of only a current sensor with PID controller for the minimization of torque pulsations which samples the phase current at any instant without knowing the recent pulse width modulation switching technique at a low cost with improved performance [10-11]. Gate signals of the inverter circuit are generated by Model predictive control (MPC) in order to improve the stator currents and thereby reducing ripples of torque. In this technique quasi-square wave currents are generated by a single controller considering all phases of stator. This technique [11] uses a dc current sensor for BLDC motor for the minimization of commutation torque ripples during intervals of commutation of each current phase. Based on the information a new duty ratio control technique is implemented in order to normalize the two different intervals of commutation time which enables effective destruction of the torque pulsations covered on the current and torque outputs at the periods of commutation during low and high speeds. In order to obtain improved motor performance characteristics a new technique based on reference current generation scheme is designed and implemented in the three-phase inverter circuit which consists of only four switches instead of six switches. This system contributes to the minimization of commutation torque ripples in several applications in industries. In industries which requires wide range of operating speeds, this proposed method is utilized which enables a control technique by changing phase advance angle which improves the characteristics of speed and torque outputs. This scheme also enables forward and reverse motoring modes of operations even at high speeds. This paper focuses on control of PMSM with distorted EMF utilising basic 3-phase inverter and coordinates of d-q reference frame in order to get no-toque ripple and less copper loss. In this literature [12] commutation interval is calculated in terms of voltage of terminal in a brushless DC motor and duty cycle is calculated from the measured commutation intervals which is applied to the control driver for reducing the ripples of commutation torque.

D. Direct Torque Control (DTC)

This technique [13] uses the value of error between the reference torque and the actual torque which need not depends on the period of conduction at the switching period of three phase inverter circuit of PMBLDC motor. This technique also facilitates the steady electromagnetic torque by adjusting the stator current and thereby eliminating torque ripples at the time of commutation even at high speeds.

E. Phase-Advancing and Overlapping Control

In general, the brushless DC motor is energized by 120◦ mode of conduction at which two phases are conducting at each 60 degrees, which is known as the six-step commutation technique. This scheme with the commutation in terms of six steps which goes along with counter electro motive force suitable for the applications which requires high efficiency along with reduced torque ripples. Phase Advancing technique is just equal to the conventional field-weakening control in the PMSM drive during above the rated speed, is a best choice get a broader speed ranges. And also, the other method for wider speed range is referred as overlapping technique which improves the conducting interval beyond 120◦ and so on. The proposed commutation control method gives rises to reduce pulsations of torque in PMBLDC motors under sensorless control. These are mainly suitable for economic applications due to its high efficiency and less budget of manufacturing. The main drawback is, they contribute more pulsations of torque characteristics produced by non-sinusoidal stator currents at commutation interval which confines their use, specifically for limited voltage fields [14-15].

III. PROPOSED FUZZY LOGIC CONTROLLER BASED TORQUE RIPPLE MINIMIZATION

Many sensorless driving techniques have been proposed for improving the characteristics of PMBLDCM among them the techniques based on back EMF detection is dominated and selected due to its simple nature. In the Fig.1, three-phase inverter fed brushless DC motor is shown. DC supply is given to the three-phase voltage fed inverter as shown. In this scheme, control strategy consists of only speed controller. Then real speed is measured and equated with specified one, hence control signals are generated in order to adjust duty ratio α to PWM module, i.e., α ∈ [0,1]. Sensorless control of the motor is enabled by the commutation detection block. In order to found the commutation of particular stator winding status, a mode number m is shifted to the Pulse Width Modulation module.

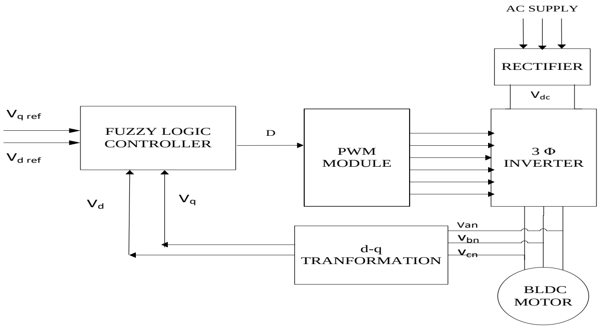

Fig. 1 Proposed BLDC motor drives system with sensorless control

Phase Advancing Method for Commutation Control

The Phase advancing technique is carried out by shifting in terms of advancing the voltage applied originally to particular value of phase angle which is done by current injection in prior to the earlier from the counter electro motive force. Fig .2. shows brushless DC motor circuit which consists of three-phase, voltage-fed inverter (VFI) topology for the proposed system. Regeneration is possible inherently by the bypass diodes of the voltage-fed inverter configuration which also contributes two unwanted effects. The first effect is, in any case of deviation occurrence at the power supply of direct current, the motor will continue the current flow through the outage until the rotor is continuing its rotation. The other effect is, the firing signals for the switches will be lost during at high operating speeds of motor which contributes to undesirable regenerative braking. In this case the motor runs at very slow speed at which the magnitude of the counter electro motive force drips under the value in direct current power supply which give rise to additional components requirement for the protection against any failures.

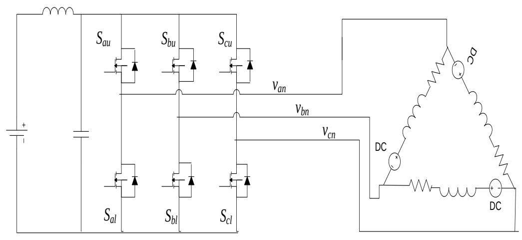

Fig.2. Voltage-fed inverter topology and BLDC motor model

Strategy for FLC

In this strategy, linguistic variables are used to generate the fuzzy controller rules which is referred as fuzzification. Then the conversion of fuzzy variables into crisp values is referred as defuzzification.

Table -I:Fuzzy Logic Control Parameters

Input Variables				Output Variables			
E_q	E_d	E_{qref}	E_{dref}	Error E_q	Error E_d	Error E_{qref}	Error E_{dref}
L	A	H	L	L	L	L	L
L	H	H	L	L	L	L	L
L	H	L	-	L	L	L	L
L	H	-	L	L	L	L	L
L	H	A	-	L	L	L	L
L	H	-	H	L	L	L	L
L	H	-	H	A	L	L	L
L	H	-	H	H	L	L	L
L	H	H	H	H	H	L	L
L	H	-	H	H	H	H	L
L	H	-	H	H	H	H	A
L	H	-	H	H	H	H	H
L	H	-	H	H	A	H	H
L	H	-	H	H	A	H	L
L	H	-	H	H	A	L	L
L	H	-	H	H	H	L	L
L	H	-	H	H	L	L	L
L	H	-	H	A	L	L	L

In this strategy all membership functions are connected with each linguistic variable which is given in the above table as four inputs and four outputs. Here the inputs were denoted as E_q, E_d, E_{dref}, E_{qref} and the corresponding output variables were denoted as $ErrorE_q$, $ErrorE_d$, $ErrorE_{qref}$, $ErrorE_{dref}$. Linguistic variables were classified as following categories: i) Low (L), ii) Average (A), iii) High (H). In this strategy a triangular function is chosen as membership function.

Table- II: Specifications of BLDC motor

Rated power	2.5 hp
Torque rating	1.2 Nm
Voltage rating	300 V
Current rating	6 A
Resistance of winding	0.08 Ω
Inductance of winding	1.15 H
Magnetic flux	0.014 weber
Pairs of pole	2
Moment of Inertia	0.08 kgm^2
Rated speed	1500 rpm

IV. RESULTS AND DISCUSSION

Simulation was done with specifications of BLDC motor shown in above Table II. Simulation analysis was carried out for torque outputs during different time ranges and it is recorded. Both Controllers (PI controller and FLC based torque controller) was simulated under MATLAB version 2013a environment and the results were compared.

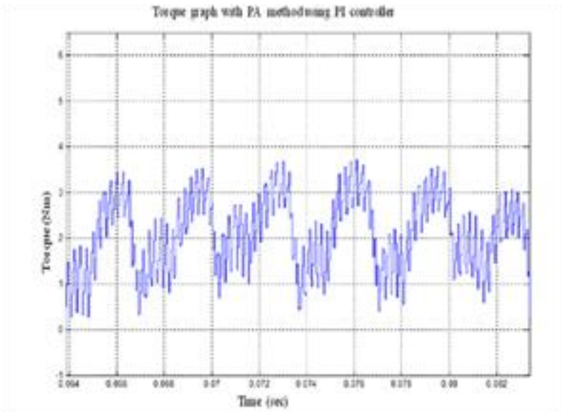

Fig.3 (a) Torque response of PMBLDC motor with PI

Observed torque responses are shown in Fig. 3(a) and 3(b). For both PI controller and FLC torque responses were taken and their magnitudes of commutation torque ripples are compared. It is shown that in Fig. 3(a), horizontal axis is meant for Time(s) and vertical axis is referred as Torque(Nm). The percentage torque ripple is expressed as the ratio of peak to peak torque to the value of torque rated. In the Table II the given rated torque is 1.2 Nm. By the analytical calculation, it was determined that the value of torque pulsation is 75% at commutation period when Proportional Integral controller is used. But with Fuzzy Logic Controller, it is found that the value of torque ripples of commutation is determined as 12.06% which is shown in Fig. 3(b). It is observed that commutation torque ripples are minimized about six times with Fuzzy Logic Controller method instead of PI controller.

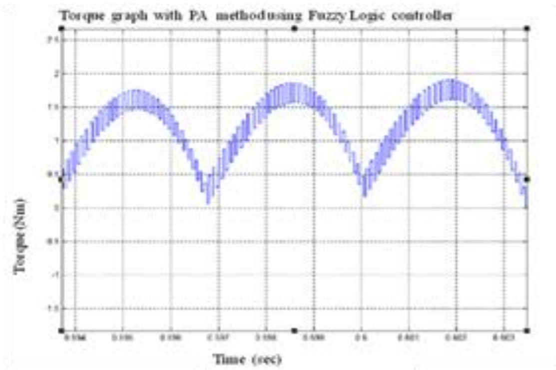

Fig.3(b) Torque waveform of BLDC motor with Fuzzy controller

V. CONCLUSION

The proposed technique is developed and implemented to obtain less pulsations of torque in PMBLDC motor by improving its controller performance. In general, for diminishing pulsating torque, specific methods of control are applied, which is depending on the precise information of the machine parameters. The major objective of this literature is to implement a brushless DC motor which will give smooth operation in order to suit all kinds of applications. This scheme is proposed to minimize the torque ripples during commutation period in the PMBLDC motor controller which was simulated in MATLAB version 2013a. A complete investigation of the ripples of torque at commutation period has been done which enables reduction of the same in the whole range of speed, based on the new phase advancing commutation control method. MATLAB Simulation was done to assess the performances of both PI controller and FLC based techniques for controlling commutation torque ripples. The torque outputs for different ranges of time were observed and recorded. By comparing the simulation results of both controllers, it is observed that torque response is better with reduced torque ripples once Fuzzy Logic Controller is implemented instead of PI controller. Hence the brushless DC motor shows better performance with fuzzy logic controlled, Phase advancing method.

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