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v_a,v_b, and v_c... Motor phase voltages.

R.. Stator phase resistance.

L_{aa}, L_{bb}, and L_{cc}.. Phase inductances.

L_{ab}, L_{bc}, and L_{ac}.. Mutual inductances.

e_a, e_b, and e_c .... Instantaneous back emfs.

P.. Derivative operator.

δ... Torque angle.

i_a,i_b, and i_c... Motor phase currents.

θ_{ol}... Overlap angle.

θ_a... Phase advance angle.

θ.. Rotor position.

EMF... Electro motive force.

BLDC.. Brushless DC.

V_{a1}... Fundamental component of phase voltage.

e_a... stator Back emf of phase A.

E_b... Back emf maximum value.

K_e... Voltage constant.

f(θ) .... Represent the per unit shape of the back EMF.

P.. Motor output power.

T_l... Load torque.

T_e... Electromagnetic torque.

J.. Inertia of the system.

B.. Damping constant.

V_s... DC bus voltage.

V_l... Line voltage of the main source.

α.. Firing angle.

N (RPM) ………………………………………..	Speed (revolution per minute).
ΔN………………………………………………	Speed ripple.
ΔT………………………………………………	Torque ripple.
VSI…………………………………………...	Voltage source inverter.
CSI…………………………………………...	Current source inverter.
IPM…………………………………………..	Intelligent power module.
PA………………………………………………	Phase advance technique.
OL………………………………………………	Overlap technique.
PAO…………………………………………..	Combination between phase advance and overlap.
OCPA……………………………………………	Overlap and chopping during phase advance period.

Abstract

The high spread of the brushless DC (BLDC) motor and its unique properties makes it a good competitor to the induction motor and the DC motor in many applications. The BLDC motor is outperforming in many aspects but it loses in driving critical load applications due to its torque ripple.

Nowadays, the torque ripple minimization represents one of the main research points. Some researchers produced different motor design techniques to overcome the torque ripples and others produced control algorithms to overcome these ripples. However these new control algorithms are complicated and require many sensors, thus the complexity and cost of the system increase.

A simple, torque ripple minimization, high speed bandwidth and low cost drive are the main scope of this thesis. This is achieved by studying the different driver's techniques and different converters that feed the BLDC motor. Analytical analysis and simulation for a novel switching technique is presented.

The work in this thesis is introduced in six chapters:

Chapter one is divided into three sections. Firstly, provides introductory information about the brushless dc motor (BLDC) and its benefits over the permanent magnet synchronous motor (PMSM). Secondly, the conventional drives associated with torque ripples are illustrated. Finally, the different suggested solutions for output torque ripple minimization in literature are reviewed.

Chapter two studies the complete model of the brushless dc motor (BLDC) drive system and different drive techniques. Firstly, motor modeling, sensor, voltage source inverter, and the current source inverter are illustrated. Secondly, the switching patterns, the basic idea for many drive techniques and novel drive technique are presented.

Chapter three analytical analysis of torque ripple during normal and commutation periods is presented, this analysis contains both torque spikes and torque dips during commutation intervals. The equalization between the current for the incoming and outgoing phases by pulse width modulation, phase advance angle, overlapping technique, and combinations between these techniques are produced. Finally, the conclusion about the best method for minimum torque ripples and speed fluctuation is presented.

Chapter four Illustrate the simulation results of each part of the system discussed above. The simulations are conducted under the same operating point and different drive techniques. The

search for optimum variables to reach minimum ripples is occurred. Then the novel technique with optimum variables is tested under wide speed range.

Chapter five Validates the analysis and the simulation of each detection technique through the experimental results.

Chapter six Concludes the thesis and identifies some areas for future researches.

Chapter 1. Introduction

1.1. Introduction

Pneumatic and hydraulic transmission devices are replaced by electric motors in many applications as electric vehicles and aerospace. Superiority of electric motors over hydraulic and pneumatic systems comes from simplicity, low maintenance, and higher power to weight ratio, small size, low price and ease of control. The dc motor achieves all of these requirements besides excellent output characteristics but the maintenance of commutators and brushes is still a problem. Permanent magnet synchronous machine overcome this problem by replacing the mechanical commutator with an electronic one.

The permanent magnet synchronous machines are produced in two main configurations, where the back emf of the machine may be sinusoidal or trapezoidal. Some scholars define permanent magnet synchronous motor with trapezoidal back emf as Brushless DC motor (BLDC) and permanent magnet synchronous motor with sinusoidal back emf as (PMSM). Other researchers refer BLDC for both types of permanent magnet synchronous machines as in the NEMA Standard MG7-1987, a BLDC motor is defined as " a type of self-synchronous rotary motor controlled by electronic commutation, where the rotor is a permanent magnet with rotor-position sensors, and the related commutation circuit could be either independent or integrated to the motor". The first definition is considered in this thesis

The sinusoidal or trapezoidal back emf waveform comes from the stator distributed winding or concentrated winding respectively. The main benefit of BLDC motor over PMSM is that the power output from the BLDC motor is greater than that of the PMSM with 15% [1]. A comparison between BLDC and PMSM is illustrated in Table 1-1.

Due to PMSM design, torque ripples are produced as cogging torque. Skewing and fractional slot pitch windings are known methods to overcome this ripples. In BLDC, the commutation torque ripple with frequency six times the fundamental frequency is produced besides the cogging torque. This commutation torque ripple is the dominant source of torque ripple in BLDC motor.

The relative ripple is independent of load, varies with speed, and may reach fifty percentage of the average torque. Analytical analysis of commutation torque ripple will be done in chapter three.

Table 1-1Comparison between BLDC and PMSM.

PMSM	BLDC
• Distributed winding.	• Concentrated winding.
• Sinusoidal back EMF.	• Trapezoidal back EMF.
• Not self driven.	• Self driven.
• Power density is lower than BLDC.	• Power density is higher than PMSM.
• Continuous stator flux position variation.	• Stator Flux position commutation each 60°.
• Three phases conduction.	• Two phase conduction.
• No torque ripples at commutations.	• Torque ripple at commutations.
• Fewer harmonic due to sinusoidal excitation.	• Low order current harmonics.
• Lower core loss.	• Higher core losses due to harmonic content.
• Higher switching losses.	• Less switching losses.
• Control algorithms are mathematically intensive.	• Control algorithms are simple.
• High precision sensor as encoder.	• Low cost sensor (Hall Effect).

The BLDC motor has a trapezoidal back emf, for constant output power the square wave current is injected in the motor windings. The commutation between winding (ingoing and outgoing phases) occurs every 60º electrical using electronic switches. But due to the motor inductance the current cannot rise or vanish in no time, this time called commutation time. The different rate of rising and falling time produced torque ripple during this period. Beside the back EMF is not ideal and supply voltage limitations. Thus, commutation torque ripple causes can be summarized as:

- Rectangular current distortion.
- Trapezoidal back EMF distortion.
- Finite dc bus supply voltage.

The distorted back emf is not considered in this work. The work focus on the current distortion causes with assuming ideal back emf and overcoming the finite DC bus supply voltage by current source inverter.

Critical loads driven by BLDC as arm control not allow these ripples. Many researchers are producing different techniques to overcome this torque ripples. The first way is the machine design[2]. The control method, drive technique, and drive circuit are a second way after machine design to overcome the torque ripple. The voltage source inverter (VSI) and current source inverter (CSI) are alternatives to drive BLDC motor. As shown in the next sections.

In the following sections different BLDC driving modes (configurations) as voltage source inverter and current source inverter will be introduced. Moreover different control techniques in each mode are proposed.

1.2. Voltage Source Inverter (VSI) Fed BLDC

The first type of drivers is the VSI, will be discussed in this section. The electronic switches are used instead of commutator to transfer current from one phase to another. The transfer is occurred to maintain the 90º angle between the field magnetic axis and armature magnetic axis thus maximum torque production is occurred. Position sensor is required to know the field magnetic axis position. The main conduction modes are two phase conduction, three phase conduction, and hybrid between two and three phase conduction.

The two phase conduction mode is the first switching strategy for VSI switches. Only one switch is on from upper group (T1, T3, and T5) and one from the lower group (T2, T4, and T6) as shown in Table 1-2. Thus there are six possible switching combinations (commutation) in complete electric cycle, every 60º electrical commutation between phases are occurred. The commutation is occurred depending on the rotor magnetic axis and direction of rotation desired as shown in Table 1-2.

Table 1-2 Switching pattern for clock wise operation

Mode I	**Mode II**	**Mode III**	**Mode IV**	**Mode V**	**Mode VI**
$0^\circ<\theta\leq60^\circ$	$60^\circ<\theta\leq120^\circ$	$120^\circ<\theta\leq180^\circ$	$180^\circ<\theta\leq240^\circ$	$240^\circ<\theta\leq300^\circ$	$300^\circ<\theta\leq360^\circ$
s/w 1 &6	s/w 1 &2	s/w 3&2	s/w 3 &4	s/w 5 &4	s/w 5 &6

Thus, armature magnetic axis is transferred in steps instead of continuous one, causing output ripple torque.

The motor output torque is constant during normal and commutation periods assuming ideal trapezoidal back EMF and ideal square wave line current. However, the actual current does not penetrate the phase in no time and the back EMF is not ideal. Thus the torque ripples are appeared on the motor shaft. The low mechanical time constant, due to low inertia, causes greater speed fluctuation.

The commutation between phases is occurs every 60º as mentioned before. The current decays in same phase and rises up in another one, depend on mentioned sequence for clockwise or anti-clockwise operation, during commutation period. The current rise up rate and decaying rate may