MODIFIED PWM TECHNIQUE FOR TORQUE RIPPLES REDUCTION IN THREE PHASE PM BLDC MOTORS

by

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LIST OF SYMBOLS

v_a, v_b, v_c	phase voltages
i_a, i_b, i_c	phase currents
ψ_a, ψ_b, ψ_c	phase flux linkages
R	phase winding resistance
L	self-inductance
M	mutual inductance between pair of phases
e_a, e_b, e_c	phase back-EMF
L_a, L_b, L_c, L	phase inductance
R_a, R_b, R_c, R	phase resistances
L_{ab}, L_{ba}, L_{ac}, L_{ca}, L_{bc}, L_{cb}	mutual inductance between phases
K_T	torque constant
k	EMF constant
ϕ	permanent magnet flux
ω_m	mechanical speed
T_e	output torque
I	the amplitude of the phase current
E	back-EMF
P_o	output power
θ	rotor position angle
ω_e	electrical speed

p	number of poles
f_e	electrical frequency
T_L	load torque
B	damping constant
J	moment of inertia of the rotor shaft and the load
t_f	phase current fall time during commutation time
t_{fH}	phase current fall time during commutation time at high speed
t_{fL}	phase current fall time during commutation time at low speed
t_r	phase current rise time during commutation time
t_{rH}	phase current rise time during commutation time at high speed
t_{rL}	phase current rise time during commutation time at low speed
t_{com}	commutation time
t_{cond}	conduction time
t_{total}	total conduction time
T_{RF}	motor torque ripple factor
T_{PR}	torque ripple factor reduction percentage

LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
BLDC	Brushless DC
PM	Permanent Magnet
back-EMF	back electromotive force
PWM	Pulse Width Modulation
MPWM	Modified Pulse Width Modulation
MMF	Magnetomotive Force
PT	Pulsating Torque
TR	Torque Ripples
DTC	Direct Torque Control
GA	Genetic Algorithm
SPA	Space Vector Analysis
MCU	Microcontroller Unit
ADC	Analog to Digital Converter
IDE	Integrated Development Environment
ICD	In-Circuit Debugger/Programmer
RF	Ripple Factor
THD	Total Harmonic Distortion

LIST OF PUBLICATIONS

Wael. A. Salah, Dahaman Ishak and Khaleel J. Hammadi, 2011, Minimization of torque ripples in BLDC motors due to phase commutation - a review, *Electrical Review Journal*, vol. 87, Issue 1, pp. 182-188, [**ISI indexed**].

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TEKNIK PEMODULATAN LEBAR DENYUT TERUBAHSUAI UNTUK PENGURANGAN RIAK TORK PADA MOTOR TIGA FASA MAGNET KEKAL TANPA BERUS ARUS TERUS

ABSTRAK

Motor magnet kekal tanpa berus arus terus digunakan secara meluas dalam pelbagai aplikasi disebabkan kecekapannya yang tinggi, ketumpatan torknya yang tinggi dan saiznya yang kecil, yang menyebabkan motor jenis ini lebih popular berbanding motor elektrik yang lain. Fokus penyelidikan ini ialah penambahbaikan tork motor magnet kekal tanpa berus arus terus dengan meminimumkan riak tork yang terhasil semasa penukartertiban. Pendekatan dan kaedah yang digunapakai dalam projek ini dibentangkan secara menyeluruh berserta dengan analisa matematik dan pemodelan menggunakan perisian Matlab-Simulink. Riak tork yang dihasilkan oleh pemacu motor magnet kekal tanpa berus arus terus biasanya berasal daripada struktur reka bentuk motor dan juga daripada bahagian kawalan dalam bentuk riak arus. Riak tork yang disebabkan oleh bahagian kawalan muncul dalam bentuk pepaku dan celupan pada tork keluaran. Ia berlaku kerana kesan ketidakpadanan arus fasa semasa penukartertiban arus fasa. Secara praktikal, kadar peningkatan dan penurunan arus antara fasa ini adalah tidak sepadan, di mana arus pada fasa yang dikuasai mencapai nilai maksimumnya sebelum atau selepas arus fasa yang dinyah-kuasai itu menurun hingga ke sifar. Maka, objektif utama kajian ini ialah untuk menganggarkan dan mengawal kadar kuasaan arus fasa untuk dipadankan dengan kadar penidakuasaan arus fasa semasa penukartertiban arus. Hasilnya, riak tork diminimumkan. Untuk melaksanakannya, satu strategi pemodulatan lebar denyut yang diubahsuai digunakan pada fasa kuasaan untuk melambatkan fasa arus pada kelajuan rendah dan mempercepatkan fasa arus pada kelajuan tinggi.

Perbandingan antara teknik pemodulatan lebar denyut yang diubahsuai dengan teknik kawalan konvensional menunjukkan 45% purata pengurangan pada riak tork apabila teknik yang dicadangkan diaplikasikan pada keadaan bebanan yang berbeza dan pada kelajuan yang berbeza. Hasil eksperimen daripada teknik yang dicadangkan, secara umumnya, menunjukkan penurunan faktor riak tork (RF) apabila dibandingkan dengan kawalan pemodulatan lebar denyut konvensional. Sebagai kesimpulannya, keputusan menunjukkan bahawa riak tork secara efektifnya berkurangan apabila motor magnet kekal tanpa berus arus terus beroperasi dalam kawasan operasi tork malar. Oleh itu, keputusan eksperimen dan keputusan pemodelan untuk teknik pengubahsuaian pemodulatan lebar denyut mengesahkan dan membenarkan fungsi strategi yang dicadangkan.

MODIFIED PWM TECHNIQUE FOR TORQUE RIPPLES REDUCTION IN THREE PHASE PM BLDC MOTORS

ABSTRACT

Permanent magnet (PM) brushless DC motors are used in many applications due to their high efficiency, high torque density, and compact sizes, which make this type of motors more popular over the other types. This research work focused on torque improvement of PM brushless DC motors by minimizing the generated torque ripples during the commutation period. The approaches and methods adopted in this project are presented thoroughly, along with the mathematical analysis and Matlab-Simulink modeling. Torque ripples in PM brushless DC motor drives usually originate from the motor design structure and from the control side in the form of current ripples. The torque ripples coming from the control side appear in the form of spikes and dips on the output torque. They occur because of phase current rate mismatch during the phase current commutation period. Practically, the current rise and decay rates between the phases are not equal, where the current in the energized phase reaches its maximum value before or after the de-energized phase current reaches zero. Hence, the main objective of this research is to estimate and control the rate of the energized phase current to match approximately the de-energized phase current rate during the current commutation period. As a result, the torque ripples are minimized. To accomplish this objective, a modified pulse-width modulation (PWM) strategy is applied to the energized phase to slow down the phase current at low speed and to speed up the phase current at high speed. A comparison between the modified PWM and the conventional control techniques showed a 45% average reduction in torque ripples when the proposed technique was applied under different loading conditions and at different speeds. Experimental results of the proposed technique, in general, indicated a torque ripple factor reduction compared with conventional PWM control. To summarize, results indicated that torque ripples are effectively reduced when the PM brushless DC motor drive operates within the constant-torque operating region. Therefore, the experimental and simulation results of the modified PWM technique validated and verified the functionality of the proposed strategy.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Electric motors are among the most essential components and the driving force in today's industry. In general, motors are classified into two types, namely, AC and DC. AC motors are relatively inexpensive, rugged, and entail low maintenance cost, but their control is complex. On the other hand, DC motors are more expensive but have an easy and simple control.

Conventional DC motors are moderately efficient, and their features make them suitable for different applications. However, one of their drawbacks is the need for commutator and brushes, which are regularly subject to wear and tear; hence, periodic maintenance is required. If the function of the commutator and the brushes are replaced by solid-state switches, then brushless DC motors could be realized. These motors would then be almost maintenance-free.

In a conventional brushed DC motor, the brushes make mechanical contact with the commutator, creating an electrical circuit between the motor armature coil windings and the DC supply. Rotation of the armature causes the stationary brushes to contact with different segments of the rotating commutator. The set of electrical switches formed by the commutator and the brush system ensures a repetitive sequential firing in which electrical power flows through the next closest armature coil to the stationary permanent magnet (PM) stator.

On the other hand, a PM brushless DC motor is an AC synchronous electric motor seen from the modeling perspective as very similar to a DC motor. The difference is only apparent when the commutation system is electronically controlled, instead of using a mechanical commutation control system. Physically however, the two motors are completely different. In PM brushless DC motor, the electromagnet coils are stationary because they are wound at the stator core, and the PMs are mounted on the rotor. The brushed commutation system is replaced by an intelligent electronic controller that performs power distribution similar to a brushed DC motor.

The PM brushless DC motor can be potentially applied in a wide range of power and speed and can be manufactured in different shapes and geometries. PM brushless DC motors are also one of the motor types that rapidly gains popularity over other types of electric motors. PM brushless DC motors are used in different industrial applications, such as automotive, aerospace, home and office appliances, and in many industrial equipment and instrumentation. Their small sizes and external rotor designs enable wide applications where such properties are required, such as in audio equipment, computer disk drives, and other consumer home and office equipment (Matsuoka and Obata, 1989).

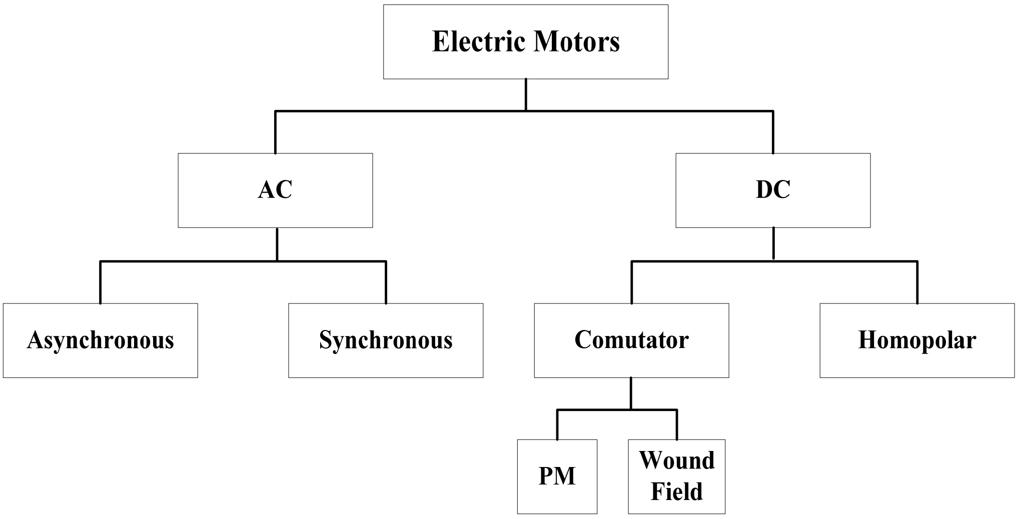


Figure 1.1 General classification of electric motors (Hanselman, 2003).

In general, electric motors are classified into two main categories relative to the power supply, namely AC or DC current, as shown in Figure 1.1. Brushless DC motors are PM synchronous motors (PMSMs). Each type of these motors possesses its own advantages and disadvantages. However, present interests are more focused on AC than DC drives. AC motors have become a more attractive solution for variable-speed applications and have recorded a steady growth since 1990 because of the rapid technological advancement in power electronic converters, as shown in Figure 1.2. This demand is a major shift from the traditional variable-speed brushed DC motors, which have been used for decades (Boldea and Nasar, 2006; Mohan et al., 2007).

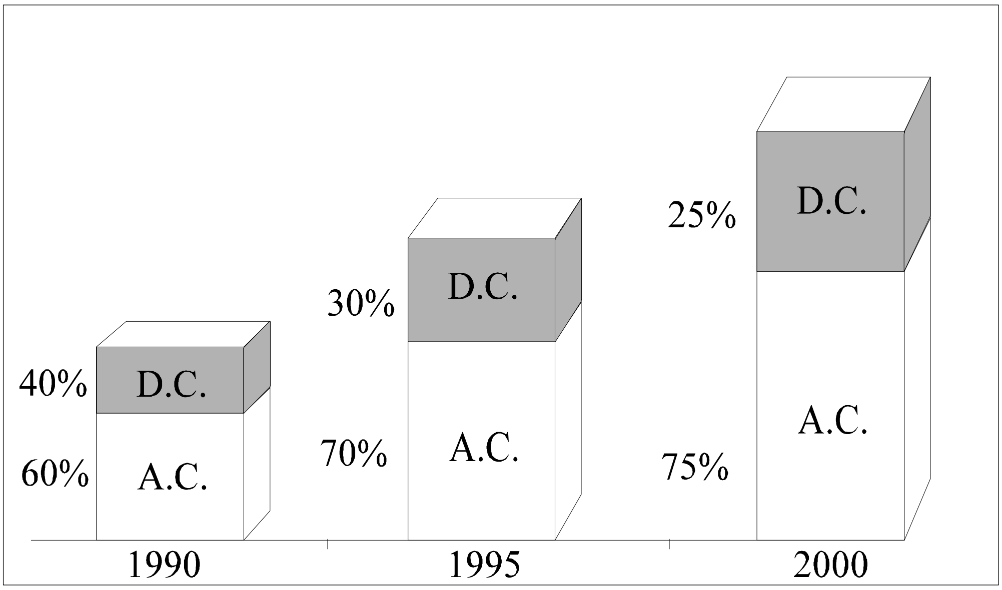


Figure 1.2 AC versus DC electric drive market dynamics (Boldea and Nasar, 2006).

The demand for motion control products has shown a steady growth in the past few years, as shown in Figure 1.3. During this period, the annual demand for DC commutator motor drive sales has decreased in contrast to the significant increase in the demand for AC motor drives (Gieras, 2008).

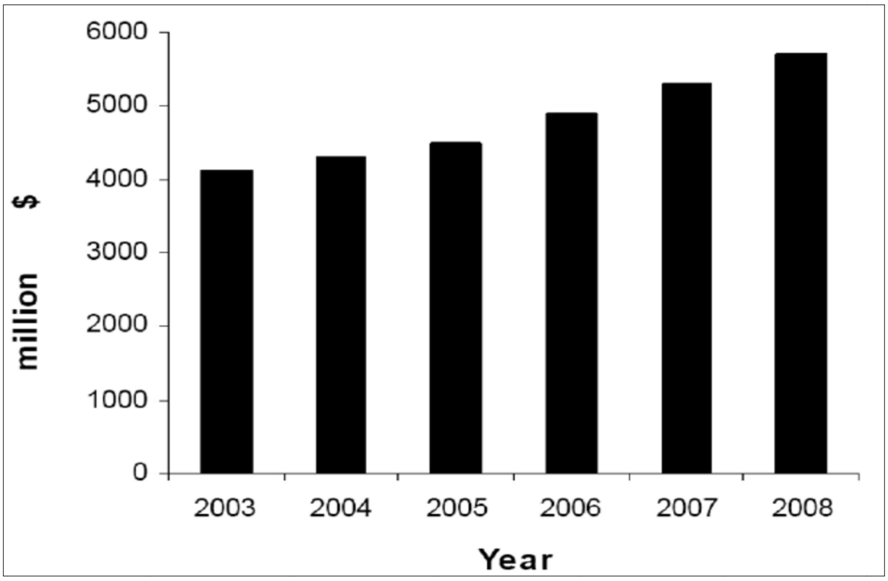


Figure 1.3 Motion control market growth (Gieras, 2008)

1.2 Problem Statement

The use of PM brushless DC motor in different applications necessitates studying its characteristics to develop a motor drive that can operate properly with a smoother torque, lower noise, and lower vibration.

A rectangular current excitation for the PM brushless DC motor windings ideally generates zero torque ripples if the motor's back electromotive force (back-EMF) is purely trapezoidal. However, typical PM brushless DC motor has a phase back-EMF waveform that can be quite far from an ideal trapezoidal shape. Hence, the motor can potentially generate significant torque ripples.

Torque ripples occurs because of many factors, with some related to the machine itself and others related to the supply and control system of the motor drive. Ripples coming from the machine are cogging torque and non-ideal trapezoidal-shaped EMF waveforms; those originating from the supply inverter are current ripples resulting from the control technique and phase current commutation.

From the motor design perspective, many methods, such as slot skewing and changing the magnet's dimensions or position, are proposed to minimize torque ripples. Further, many studies on the minimization of torque ripples arising from the supply inverter and control system have been presented. Therefore, the present research focused on the technique of reducing torque ripples originating from the control side by modeling and implementation of a proposed modified pulse-width modulation (PWM) control strategy.

1.3 Scope of research

The generation of ripple-free torque in brushless PM motors depends on the exact match between the motor phase back-EMF and the controller current waveforms. This thesis mainly concentrates on the torque ripples generated in three-phase PM brushless DC motors arising from current commutation. Therefore, it principally focuses on the torque ripple reduction methods used to overcome this issue through the development of a proper control technique.

An extensive review of the applied control techniques for torque ripple minimization is presented. Further, an analysis of the torque and current characteristics during current commutation is conducted for the development of a proposed modified PWM control technique to reduce torque ripples generated in PM brushless DC motors.

Torque ripples in PM brushless DC motors occur during current commutation because of time mismatch of the falling and rising phase currents. Torque ripples can therefore be minimized by controlling the energized phase current rate to match the de-energized phase current rate during the commutation time. To achieve this objective, a modified PWM strategy is applied to the energized phase to slow down the phase current at low speed and to speed up the phase current at high speed.

The proposed strategy is applied to each energized phase during the current commutation period so that the fall time of the de-energized phase current matches with that of the current of the energized phase when attains its maximum value.

Therefore, the proposed modified PWM is applied six times per electrical revolution for the positive and negative phase currents in a typical three-phase PM brushless DC motor. The high- and low-side switches of the inverter bridge operate in PWM hard-switching mode. Simulation and experimental results of the proposed control technique validated the effectiveness of the proposed modified PWM technique, with obvious reduction in torque ripples.

1.4 Research Objectives

The aim of this PhD work is to minimize the output torque ripples in PM brushless DC motors caused by the inequality between the energized and the de-energized phase current rates during the commutation period. Therefore, the main objectives of this research can be summarized as follows:

- To propose a control technique that minimizes the output torque ripples during current commutation periods.
- To model the proposed modified PWM technique in the Matlab-Simulink software.
- To develop motor controller using PIC18F4431 microcontroller for a PM brushless DC motor for experimental test and measurement.
- To validate the modified PWM technique for PM brushless DC drive in the experiment.

1.5 Research Contributions

Minimization of the torque ripples in PM brushless DC motors results in smoother motor operation. Therefore, improvement of the output torque by minimizing the generated torque ripples is significant, which can increase the applications of PM brushless DC motors.

The research contributions of this PhD thesis are summarized as follows:

(a) Proposal of a modified PWM technique applied to the energized phase using a duty cycle that can control the rise and fall rates of the phase current to be approximately equal so that torque ripples are minimized

(b) Implementation of the modified PWM strategy using a low-cost microcontroller from Microchip without the need of high-speed dsPIC microcontroller

(c) Development of a Matlab-Simulink model for PM brushless DC motor PWM control and modified PWM control technique

1.6 Research Methodology and Flowchart

Smooth output torque operation in electric drives is an important issue, as presented earlier. A profound study must be conducted so that measures can be developed to improve the performance of PM brushless DC drives.

A review of the sources of torque ripples is made to achieve the main objective of this research. In addition, an extensive review of the techniques applied for minimization of torque ripples and improving output performance has been conducted.

Software deployment and implementation of a control technique for minimizing the output torque ripples from the control side were also the major task of a recent project, which disregarded the factors related to the motor design. The implemented hardware and software were built and tested to validate the effectiveness of the proposed modified PWM technique.

Comparison of experimental and simulated results were conducted and presented, as well as comparison with other researchers' findings. Finally, based on the measured and simulated results, the overall conclusion for the current research is summarized and reported.

The research flowchart is shown in Figure 1.4, which summarizes the main flow of the current research project.

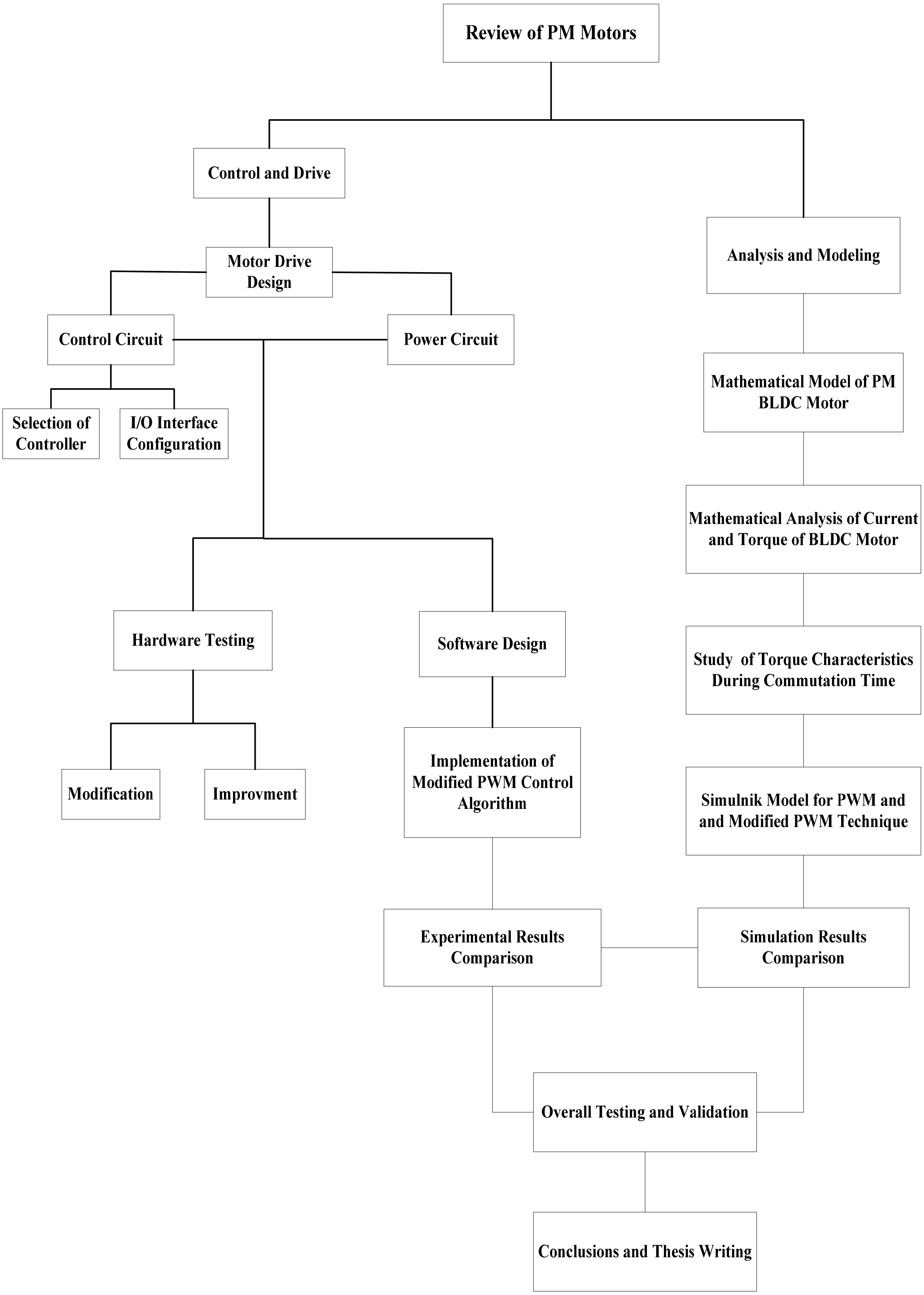


Figure 1.4 Research methodology and flowchart

1.7 Outlines of the Thesis

This thesis is organized into seven chapters, namely:

Chapter 1—An introduction about three-phase PM brushless DC motors is presented, followed by the problem statement of this research. The research scope, research methodology, objectives, and research contributions are also presented.

Chapter 2—Review of the sources of torque ripples in PM brushless DC motors, the methods, and the parameters that affect these ripples are discussed. From the literature survey, an extensive review of the control techniques proposed and implemented for the reduction of the torque ripples in PM brushless motors is presented. In addition, the basic operation and drive techniques of PM brushless DC motors are presented, as well as the comparison of PM brushless DC motor with other types of electric motors.

Chapter 3—The analysis of PM brushless DC motor drive parameters is presented. Further, the behavior of the motor torque and current is discussed and analyzed. Detailed analysis of the current and torque during commutation period is also carried out. The approaches and methods for the proposed modified PWM technique to reduce torque ripples are described and discussed thoroughly in this chapter. A mathematical model is presented, along with the developed Simulink blocks, followed by the complete Simulink model and simulation results. For qualitative comparison, the conventional and modified PWM controller models are presented in details. Finally, the results of both control techniques are compared.

Chapter 4—The development of the modified PWM technique, detailed switching, timing charts, and switching signals are presented. Further, generation of PWM and modified PWM switching signals are laid out. In addition, hardware implementation details of the proposed technique are presented. The references and parameters are explained using timing charts.

Chapter 5—Hardware implementations are presented in details, and the ratings and parameters used in the experimental setup are introduced. Software development for the PM brushless DC control algorithm is discussed with the aid of the algorithm sequence flowcharts.

Chapter 6—Details of the experimental results are presented in figures and waveforms. Experiments are conducted on different setups to test the various motor load levels and speeds. The results are discussed, analyzed, and compared to highlight the effectiveness of the proposed modified PWM technique. Results of the proposed technique verified and validated its functionality.

Chapter 7—The summary of the present work is presented, which concludes the outcome of this research, along with recommendations and suggestions for future research work. This chapter presents the overall findings of the conducted research referring to the minimization of the torque ripples in three-phase PM brushless DC motors.

CHAPTER 2

LITERATURE REVIEW

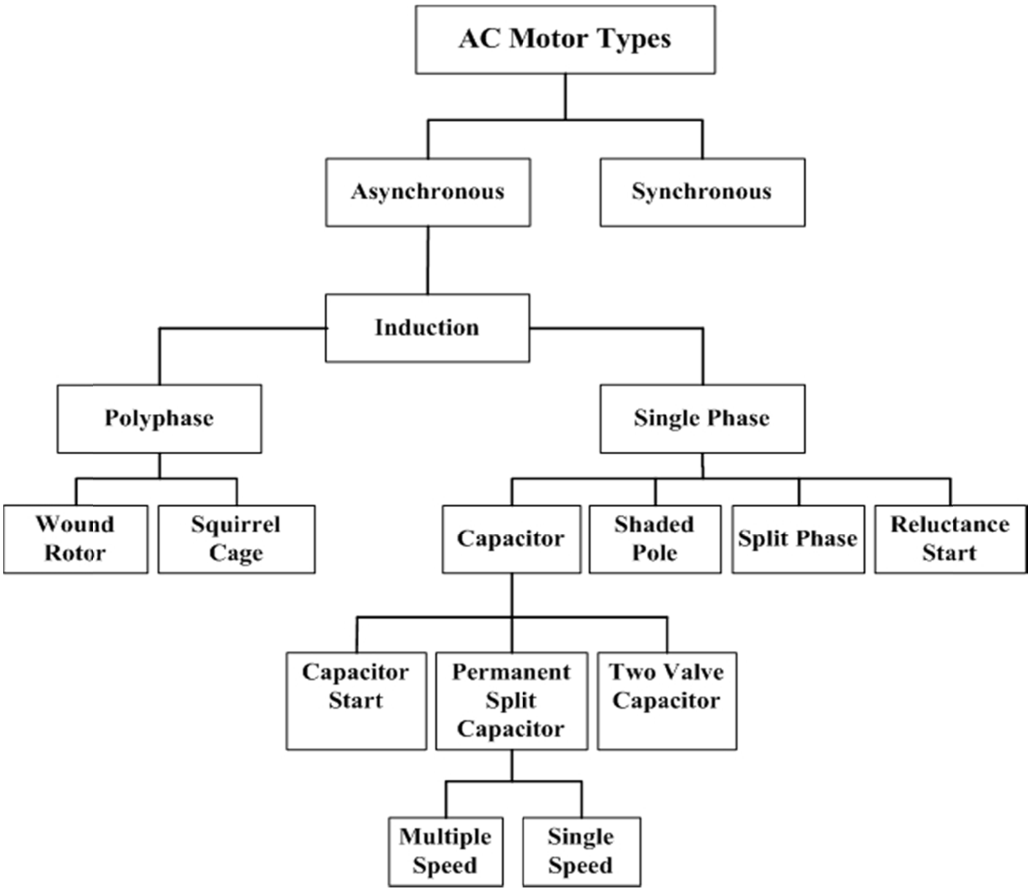
2.1 Introduction

AC motors can be categorized into two major groups, namely, synchronous and asynchronous motors. Each group consists of different types of motors, which vary in characteristics and structures. Figure 2.1(a) shows the types of asynchronous motors, and Figure 2.1(b) shows the synchronous motor types.

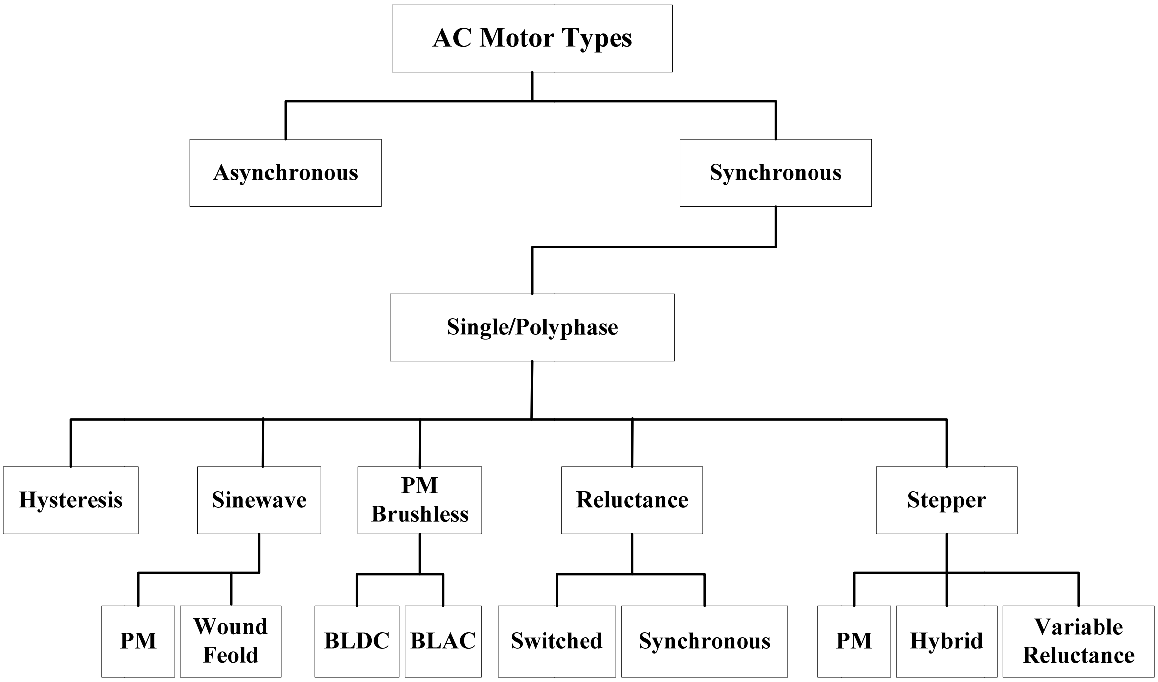
Unlike brushed DC motors, AC motors, such as PM AC and induction motors, are more rugged because they are lighter and have lower inertia than brushed DC motors. Electrical connection between the stationary and the rotating parts are not required in AC motors, resulting in maintenance-free motors. AC motors also have higher efficiency compared with brushed DC motors, as well as higher overload capability.

Figure 2.1(b) shows that the PM brushless DC motor is a type of synchronous AC motors with PMs, where the magnetic fields generated by the stator and the rotor rotate at the same frequency. The rotor magnets can be either surface- or interior-mounted magnets.

In conventional PM brushed DC motors, the electromagnetic field generated by the PM is on the stator and armature windings of the rotor. These motors are expensive and require regular maintenance because of the brushes and the accumulation of brush debris, dust, commutator surface wear, and arcing. PM brushless DC motors can overcome these issues by replacing the mechanical switching components with electronic semiconductor switches. The PM brushless DC motor has a PM rotor and a wound field stator connected to a power electronic switching circuit.



(a) Asynchronous motors



(b) Synchronous motors

Figure 2.1 AC motor types

2.1.1 PM Brushless DC Motors

Smoothness of the variable-speed drive operation is a critical and important criterion applied in the design and development of motion control. The torque produced in a PM brushless DC motor with trapezoidal-shaped back-EMF is constant under ideal conditions. However, in practice, torque ripples appear on the produced output torque. Some ripples result from the natural structure of the motor, whereas others are related to the motor design parameters. These torque ripples can be minimized within the machine design process.

Another source of torque ripples is related to the control and drive side of the motor. The literature review in this chapter is focused on the torque ripples associated with machine control and drives that can be minimized with the application of different control techniques. The various applied techniques to minimize the torque ripples in PM brushless DC reviewed here are focused on the motor control side.

PM brushless DC motor drives have high efficiency, low maintenance cost, long life, low noise, simple control, lesser weight, and compact construction. Therefore, due to these features, PM brushless DC motors have become very popular and viable products in the market. They offer more advantages than other types of AC motors, resulting in phenomenal market growth for PM brushless DC motors, as shown in Figure 2.2 (Gieras, 2008).

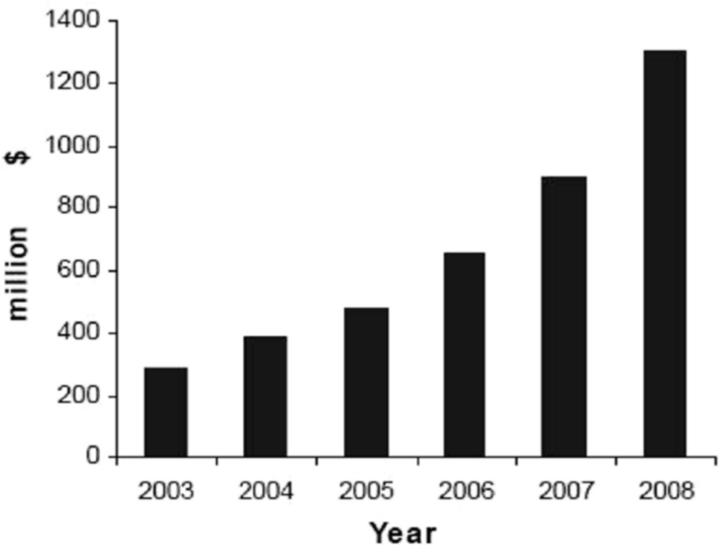


Figure 2.2 Growth of PM brushless DC motor market (Gieras, 2008)

2.1.2 Classifications of PM Brushless DC Motor

PM brushless DC motors are classified according to the flux direction, magnet position in the rotor structure, rotor position, and induced back-EMF waveforms, as shown in Figure 2.3.

Based on the field flux direction, PM brushless DC motors are classified as radial-and axial-field. For the radial field, the main flux direction is along the radius of the machine, whereas for the axial field, the main flux direction is parallel to the rotor shaft. Although radial-field PM brushless DC motors are commonly used in industries, axial-field machines play a significant role in some applications because of their compact shape, smaller axial length, higher power density, and higher acceleration.

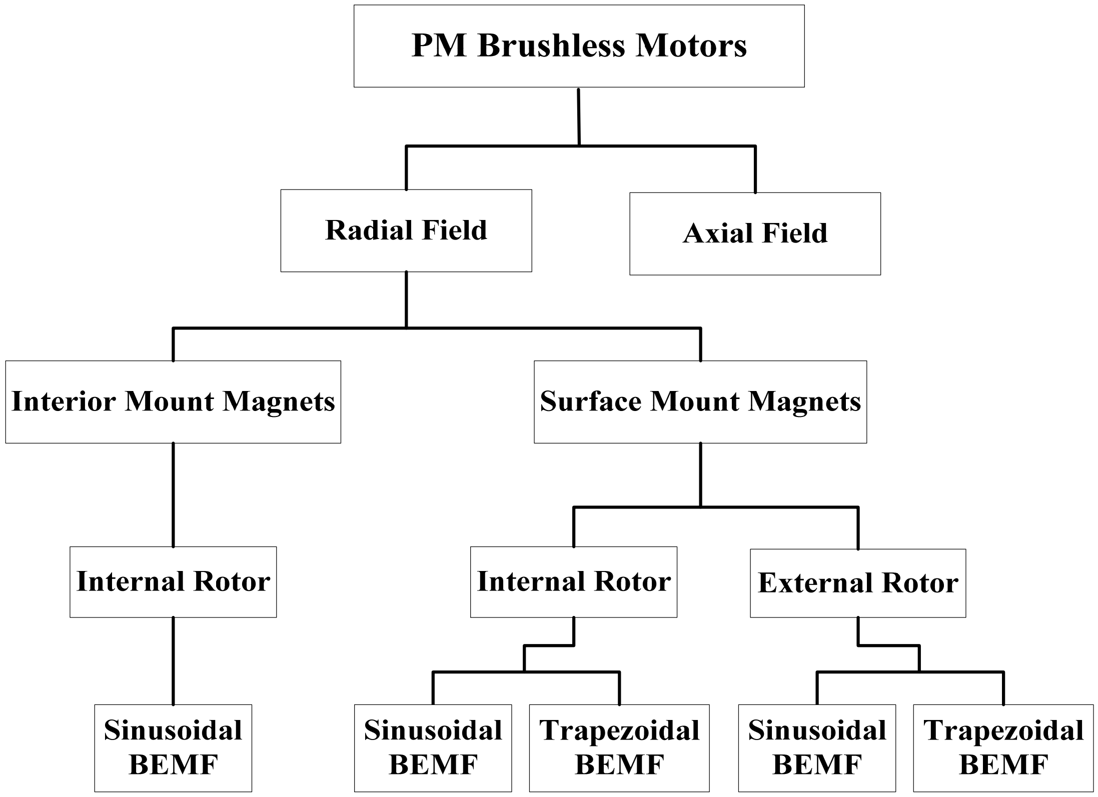


Figure 2.3 Classification of PM brushless motor drives

PM brushless motors are classified according to the shape of the back-EMF, i.e., trapezoidal (brushless DC) or sinusoidal (brushless AC) back-EMF. Figure 2.4 shows the motor phase current and the back-EMF of the trapezoidal-shaped type. In PM brushless DC motors, PMs produce a trapezoidal air-gap flux density distribution, which results in trapezoidal back-EMF waveforms.

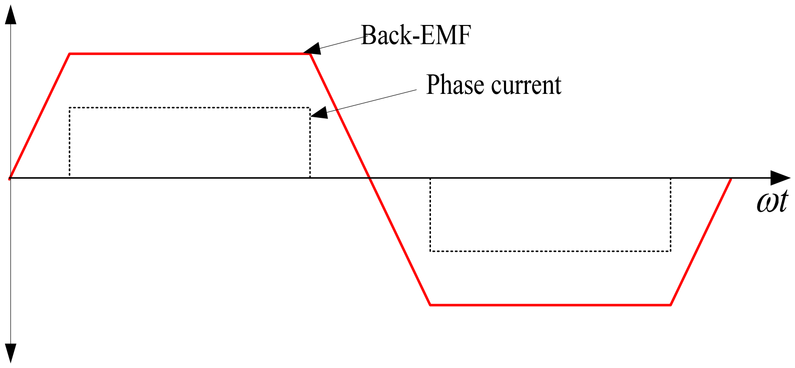


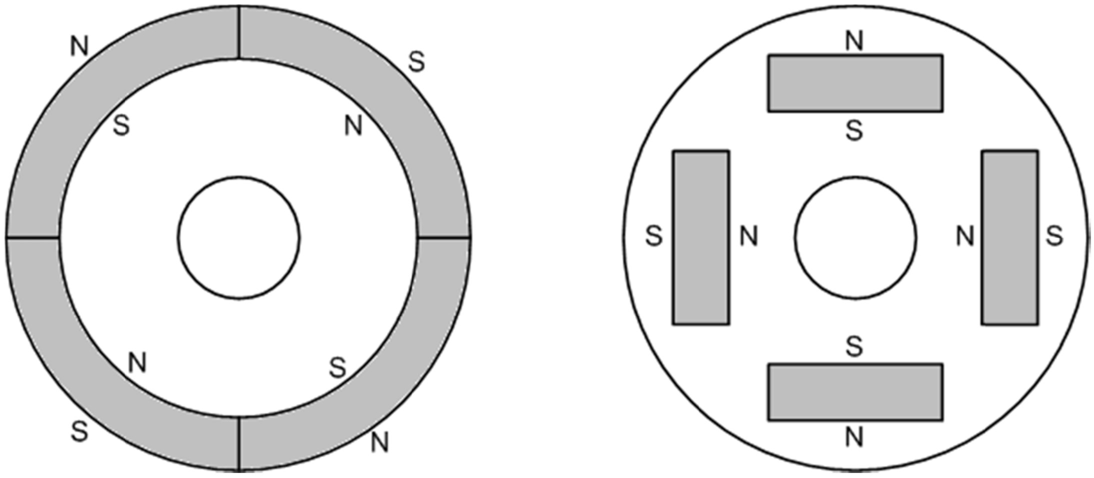
Fig 2.4 Induced back-EMF with a trapezoidal shape

2.1.3 Structure of the PM Brushless DC Motor

A PM brushless DC motor is a type of PM motors whose PMs are located in the rotor structure. The stator has laminated steels to reduce eddy current losses, and the rotor has PMs that eliminate the heat source coming from the winding in conventional brushed DC motors. Fig 2.5 shows the PM brushless DC motors categorized according to the mounting of PMs on the rotor, that is, either surface- or interior-mounted rotors (Gieras and Wing, 2002, Toliyat and Campbell, 2004).

In the surface-mounted PM motor type, each PM is mounted on the round surface of the rotor. This type is easy to build, but the attached PM can possibly fly apart during high-speed operation.

In the interior-mounted PM motor type, each PM is mounted inside the rotor. Surface-mounted motors are more commonly used than interior-mounted PM motors. However, interior-mounted PM motors are more suited for high-speed operations. In addition, an inductance variation due to the effective air-gap variations with rotor position occurs in interior-mounted PM motor types (Gieras and Wing, 2002; Toliyat and Campbell, 2004).



(a) Surface-mounted PM rotor

(b) Interior-mounted PM rotor

Figure 2.5 Classifications of PM brushless DC motors based on magnet location

2.1.4 PM Brushless DC Motors and PM Brushless AC Motor (PM BLACs)

Generally, PM brushless motors are classified according to the induced back-EMFs, which can be either a sinusoidal or a trapezoidal waveform. The PM brushless motor with trapezoidal back-EMF is known as PM BLDC. On the other hand, those with sinusoidal back-EMF are known as PMSMs or PM BLAC. Trapezoidal back-EMF implies that the mutual inductance between the stator and the rotor is non-sinusoidal (Gieras and Wing, 2002; Pillay and Krishnan, 1989a; Pillay and Krishnan, 1988).

a. Trapezoidal Back-EMF

The induced trapezoidal back-EMF is the main feature of the PM brushless DC motor. PM brushless DC motors with trapezoidal-shaped back-EMF are characterized by rectangular distribution of magnetic flux in the air gap and concentric stator windings. Therefore, a quasi-square current excitation is required. Furthermore, this trapezoidal back-EMF type of motor has lower manufacturing cost and simple control strategy compared with the sinusoidal back-EMF type of motor. The currents in the three-phase motor windings are ideally rectangular and are in phase with the corresponding back-EMF waveforms, synchronized with the instantaneous rotor position (Gieras and Wing, 2002; Pillay and Krishnan, 1989b; Krause et al., 2002).

b. Sinusoidal Back-EMF

The most fundamental characteristic of the induced sinusoidal back-EMF type of brushless motor is that the back-EMF generated by the rotation of the magnet in each phase winding is a sinusoidal wave function of the rotor angle (Gieras and

Wing, 2002). The basic operation of a sinusoidal back-EMF type of brushless motor is very much similar to that of the AC synchronous motor. PMSM is similar to the wound-rotor synchronous motor except that PMSM is used for servo applications (Pillay and Krishnan, 1988). The typical characteristics of the PMSM are the sinusoidal distribution of magnetic flux in the air gap, sinusoidal distribution of stator conductors, sinusoidal current excitation, and higher manufacturing cost (Gieras and Wing, 2002; Pillay and Krishnan, 1989a; Krause et al., 2002).

2.1.5 Output Torque Characteristics of PM Brushless DC Motors

Smoothness in motor operation is an important consideration in any implemented system. When PM brushless DC motors are introduced in many industrial applications, the torque pulsation delivered by these motors limits their usage. Therefore, improving the performance of PM brushless DC motors by minimizing the torque ripples is very important to obtain smoother operation of the motor drive system.

Torque pulsations in PM brushless DC motors are generated due to the deviation from ideal conditions, either related to design factors of the motor or to the power inverter supply, resulting in non-ideal current waveforms (Jahns and Soong, 1996). Undesirable torque pulsation in the PM brushless DC 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 (Singh, 1997). PM brushless DC motor torque pulsations produce noise and vibration in the system. Therefore, minimization or elimination of noise and vibration is a significant issue in PM brushless DC motor drive.

Torque pulsations can be principally minimized by two techniques: improved motor designs and improved control schemes. Improved motor design techniques for pulsating-torque (PT) minimization include skewing, fractional slot winding, short-pitch winding, increased number of phases, air-gap windings, adjusting the stator slot opening and wedges (Jahns and Soong, 1996), and rotor magnetic design through magnet pole arc, width, and positions (Holtz and Springob, 1996b).

With regard to the minimization of torque pulsations using improved motor control schemes, digital control-based techniques can be used and are discussed in details in this chapter. These techniques include the adaptive technique, preprogrammed current, harmonic injection, estimator and observer technique, speed-loop disturbance rejection technique, high-speed current regulator, commutation-torque minimization (Jahns and Soong, 1996), (Holtz and Springob, 1996b), and other techniques.

2.2 PM Brushless DC Motor Drive System

2.2.1 PM Brushless DC Drive Components

PM brushless DC control drive system is based on the feedback of the rotor position obtained at fixed points, typically every 60° electrical, for six-step commutation of the phase currents (Toliyat and Campbell, 2004). The PM brushless DC drive system consists of PM brushless DC motor, power electronic converter, sensor, and controller, as shown in Figure 2.6.

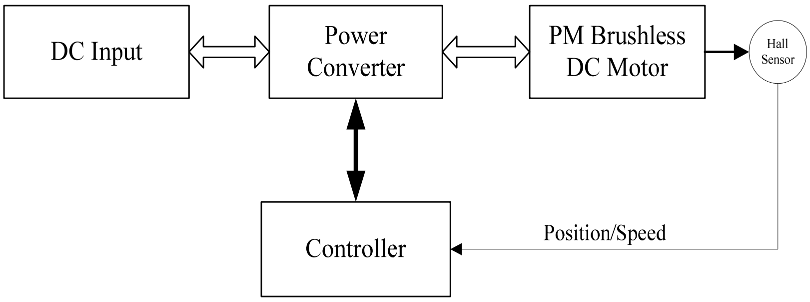


Figure 2.6 PM Brushless DC drive system components

To switch the motor stator coils to 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 using Hall effect sensors or encoders. Rotor position is required for appropriate commutation of PM brushless DC motors, which can be detected using Hall effect position sensors or encoders or can be estimated using sensorless motor control.

The controller switches the appropriate currents in the right stator coil at the right time, sequence them by obtaining the information supplied by the position sensor, and process them with preprogrammed commands to achieve the desired motor performance. Digital control can be found in many applications, including motor drive systems, where high-speed and precision are a critical requirement. Advanced microprocessors, microcontrollers, and digital signal processors (DSPs) are used to generate and analyze drive system signals, as well as to detect and protect the system from abnormal conditions, such as overvoltage and overcurrent.

The availability of high energy density PM materials at competitive prices, the commercial availability of low-cost microcontrollers, and the reduction in cost of powerful and fast DSPs, along with the advances in semiconductor power switches, have opened up a wider area for PM brushless DC motor drives to be a competitive solution in meeting market demands. A typical three-phase inverter is used to drive PM brushless DC motor. The switches used in the inverter can be IGBTs or MOSFETs, depending on the application requirement. However, IGBTs provide higher power capability than MOSFETs.

PM brushless DC motors are very popular for home appliance applications because of its higher power density, higher efficiency, and lower acoustic noise compared with induction motor and switched reluctance motor. Speed control can be achieved by changing the average applied voltage across the motor phases, which can be done by the following techniques (Yen-Shin et al., 2007):

1. Pulse amplitude modulation (PAM) with 120° electrical commutation control

2. PWM control with fixed DC-link voltage

3. Hysteresis control method.

2.2.2 PM Brushless DC Drive Six-Step Commutations

For the PM brushless DC motor drive with a 120° electrical conduction time, the current produces a torque spike every 60° electrical, causing the rotor to pulsate at a frequency six times the fundamental one. As torque is produced by induced voltage and current, these spikes are mainly produced by the rapid transition of the current with a slight delay at the switching instants (Murai et al., 1989).

To obtain a constant output power and a relatively constant output torque, the current is driven through a motor winding during the flat portion of the back-EMF waveform. To drive the PM brushless DC motor, only two switches are turned on at a time: one on the high side and the other on the low side of the inverter bridge.

For a star-connected motor winding, two phases are connected in series across the DC bus, and the third phase is floating. Each phase carries current only during the 120° electrical period of conduction when the back-EMF is constant. Thus, a commutation event between phases occurs every 60° electrical, and this action produces a current transition every 60° electrical.

2.2.3 Rectangular and Sinusoidal Current Excitations of PM Brushless Motors

Some similarities may exist in terms of motor constructions for both PMSM and PM brushless DC motors. Nevertheless, both motors are operated differently. PMSM requires sinusoidal current excitations, whereas PM brushless DC motor employed rectangular current excitations. As the motor used in this project is a PM brushless DC type, the required current excitation is rectangular.

a. Rectangular Current Excitation

PM brushless DC motor has generally trapezoidal back-EMF waveforms; thus, rectangular stator current is required to produce constant output torque (Pillay and Krishnan, 1988; Karthikeyan and Dhana Sekaran, 2011). In addition, rectangular current excitations in PM brushless DC motor also require the rotor position signals, often detected using Hall effect sensors. Depending on the rotor position, only two phase windings are energized, whereas the third phase is completely switched OFF during each commutation sequence. This condition lasts for 60° electrical duration. In one electrical cycle, six commutation sequences or intervals occur. Hence, this operation is also known as six-step switching operation. Therefore, PM brushless DC motor drives are simpler and cheaper than PMSM drives (Gieras and Wing, 2002; Pillay and Krishnan, 1989b).

b. Sinusoidal Current Excitation

The operating principle of PMSMs is based on rotating magnetic field, similar to other types of synchronous motors. Sinusoidal currents are applied to the PMSM stator windings to produce constant torque (Gieras and Wing, 2002). A PMSM has a sinusoidal back-EMF; therefore, it has to be excited with a sinusoidal stator current to produce constant output torque (Pillay and Krishnan, 1988). Sinusoidal current waveform requires continuous rotor position information, which can be obtained using an encoder or a resolver. The motor control algorithm is more involved and complex, for example, vector control or direct torque control (DTC), for this type of motor. However, in general, PMSMs have better dynamic performance, such as fast response and smooth output torque (Pillay and Krishnan, 1989b). In PM brushless AC motors with sinusoidal current excitation, all stator winding phases carry current at any instant (Gieras and Wing, 2002; Karthikeyan and Dhana Sekaran, 2011).

2.3 Sources of Torque Ripples in PM Brushless DC Motors

Figure 2.7 shows that the general sources of torque ripples in PM brushless DC motors fall into 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 materials. Selection of better materials leads to better performance.

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

c. Motor control: Torque ripples related to motor control are those ripples associated to hysteresis and PWM switching of the inverter. Inverter design and component selection can also affect the output current supplied to drive the motor. Many techniques have been introduced to minimize torque ripples (Salah et al., 2011). This research highlighted the minimization of torque ripples in PM brushless DC motors from the motor control side, specifically the torque ripples due to phase current commutation.

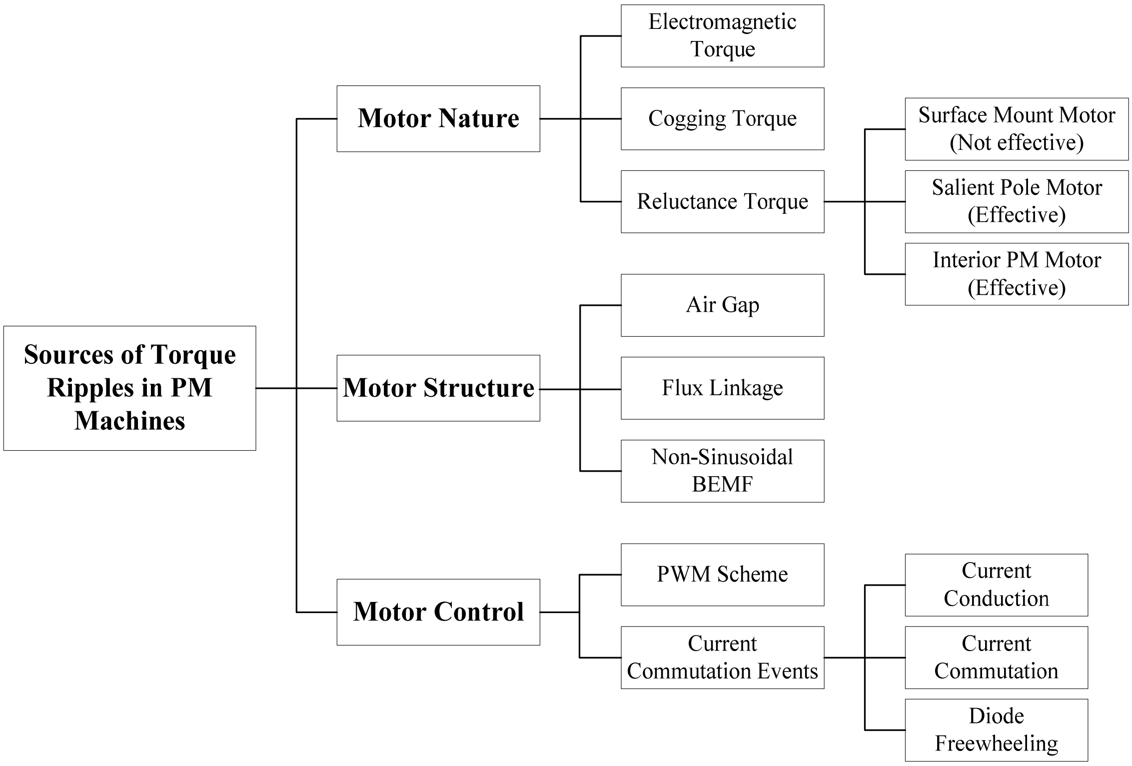


Figure 2.7 Sources of torque ripples in PM brushless DC motors (Salah et al., 2011)

As stated by Jahns and Soong (1996), PT refers to any source of divergence from ideal conditions in either the motor or the associated power converter in a PM AC motor drive, which produces undesired torque pulsations.

Torque ripple components are generated by the interaction of the stator current magnetomotive forces (MMFs), which can be the mutual or alignment and reluctance torques. Mutual torque results from the interaction of the phase current's MMFs with