SENSORLESS OPERATION OF PERMANENT MAGNET BRUSHLESS DC MOTOR BASED ON INFINITE IMPULSE RESPONSE DIGITAL FILTER

by

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Thesis submitted in fulfillment of the requirements
for the degree of
Doctor of Philosophy

October 2010

ACKNOWLEDGMENTS

"All praises and thanks to ALLAH"

I would like to express my sincere gratitude to my main supervisor Dr. Dahaman Ishak for his valuable guidance and dedicated support throughout my PhD study. Without his patience, guidance and constant supports, this work would not have been possible. Many thanks are also due to many staffs in School of Electrical and Electronic Engineering and Institute of Postgraduate Students, Universiti Sains Malaysia for numerous assistance and help given to me. I also wish to express my token of appreciation to the technical staff in Electrical power Lab USM, En. Ahmad Shaukhi Noor and En. Jamaludin Che Mat for their kind assistance during my test and experiment work.

I would like to express my respect, honor and warmest thanks to both of my parents for their prayers, continuous support and true love showered upon me even though we are geographically thousand miles apart. Finally, Warmest and heartfelt thanks to my lovely wife and my children Tanya and Yosef, for their understanding, patience and undivided support throughout the period of my research.

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
BLDC	Brushless DC Motor
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processors
EMF	Electromotive Force
FFT	Fast Fourier Transforms
IIR	Infinite Impulse Response
ISR	Interrupt Service Routine
LPF	Low-Pass Filter
MMF	Magnetomotive Force
PID	Proportional Integral Derivative
PM	Permanent Magnet
PWM	Pulse width Modulation
rpm	Revolution Per Minute
ZCP	Zero-Crossing Point

LIST OF SYMBOLS

λ_s	Flux linkage of single turns coil
l	Rotor length
B	Airgap flux density
θ	Rotor position
ω_r	Rotor speed
N_s	Number of turns in phase winding
e_a	Phase A back-EMF
i_b	Phase A current
t_{on}	On-time
t_{off}	Off-time
D	Duty cycle
T_s	Time period
V_0	Output voltage
V_{dc}	Direct current voltage
V_L	Inductor voltage
i_L	Inductor current
L	Inductance
v_n	Neutral voltage
T_m	Electromagnetic torque
B	Viscous friction constant
J	Rotor moment of inertia
T_L	Load torque

K_e	Back-EMF constant
P	Number of poles
$y(n)$	Discrete output signal at instant n
$y(n-1)$	Discrete output signal at instant (n-1)
$x(n)$	Discrete input signal at instant n
$x(n-1)$	Discrete input signal at instant (n-1)
ω_{racce}	Acceleration rate of the rotor
ω_{rsyn0}	Initial rotor speed
α	Phase advance angle

OPERASI TANPA PENDERIA UNTUK MOTOR ARUS TERUS MAGNET KEKAL TANPA BERUS BERASASKAN PADA SAMBUTAN DEDENYUT TAK TERHINGGA PENAPIS DIGIT

ABSTRAK

Disertasi ini membentangkan operasi baru tanpa penderia bagi motor arus terus magnet kekal tanpa berus (BLDC) berasaskan pada penapisan digit gelombang daya gerak elektrik balik dengan menggunakan dsPIC30F6010 mikropengawal. Dari segi motor pacuan, teknik pemodulatan lebar denyut (PWM) biasanya digunakan untuk mengubah voltan yang dikenakan pada pangkalan motor supaya dapat mengendalikan kelajuan motornya. Secara umumnya, isyarat daya gerak elektrik balik daripada belitan fasa yang tiada tenaga mempunyai hingar cerapan daripada fasa-fasa motor yang bertenaga. Namun, kebiasaannya adalah amat sukar untuk mengesan peristiwa lintasan sifar daripada gelombang daya gerak elektrik balik disebabkan oleh hingar PWM terganding. Dengan menggunakan pendekatan yang sesuai, suatu isyarat daya gerak elektrik balik yang telah ditapis dapat dihasilkan daripada gelombang yang telah diukur di mana gelombang tersebut lebih mirip suatu isyarat yang unggul. Dengan demikian, proses untuk mengesan peristiwa lintasan sifar akan lebih berjaya. Suatu asas teori yang pertama kali terorak adalah mempertimbangkan aspek dinamik dari segi elektrikal dan mekanikal bagi magnet kekal tanpa berus mesin dalam model Matlab Simulink dengan menggunakan pengawal kelajuan tradisional PI. Dua model simulasi bagi operasi dengan penderia dan tanpa penderia dilakukan dengan langkah penapisan digit pada isyarat-isyarat voltan pangkalan dan hasilnya dibahaskan. Butiran spektrum-spektrum daripada gelombang daya gerak elektrik balik terbenam dengan PWM terpenggal yang dikira oleh jelmaan Fourier pantas juga akan diberikan. Rekabentuk yang sesuai bagi optimum penapis digit rendah yang diperlukan boleh didapati apabila menganalisis

spektrum-spektrum dengan lebih lanjut. Pengubahan struktur-struktur dan pelaksanaan praktikal bagi penapis digit sambutan dedenyut tak terhingga (IIR) telah diperiksa dan dipertimbangkan. Namun, penapis digit IIR yang dialih lata daripada bentuk langsung II telah dipilih untuk memudahkan pelaksanaan praktikal dan kepekaan yang lebih rendah bagi pengkuantuman parameter. Untuk mengesahkan kaedah operasi kurang deria dengan penapis digit IIR, suatu ujian dibinakan dan prestasi bagi operasi tanpa penderia daripada motor arus terus magnet kekal tanpa berus juga diuji. Daripada hasil-hasil ujikaji, prestasi yang sangat baik di kawasan-kawasan torsi malar telah diperolehi dengan operasi kitar tugas PWM 100%. Selain itu, skim pergantian fasa sebelumnya yang telah termasuk dalam kawalan algoritma telah diuji bagi motor yang beroperasi dalam julat operasi kelajuan tinggi. Keputusan-keputusan ujikaji yang telah diperolehi menunjukkan prestasi pacuan motor yang memuaskan semasa operasi dalam keadaan-keadaan mantap untuk kedua-dua kawasan torsi malar dan kuasa malar.

SENSORLESS OPERATION OF PERMANENT MAGNET BRUSHLESS DC MOTOR BASED ON INFINITE IMPULSE RESPONSE DIGITAL FILTER

ABSTRACT

This dissertation presents a new sensorless operation for permanent magnet brushless DC motor based on digital filtering of back-EMF waveform using dsPIC30F6010 microcontroller. In motor drives, PWM technique is normally used to vary the voltage imposed on the motor terminals, and therefore controlling the speed of the motor. Generally, the back-EMF signal of the un-energized phase winding has noise imparted from the driven motor phases. However, it is relatively difficult to detect the zero-crossing event of the back-EMF waveform due to the coupled PWM noise. With appropriate approach, a filtered back-EMF signal can be generated from the measured waveform which looks more like an ideal signal. Thus, the process of detecting zero-crossing event will be more successful. A theoretical basis is first developed and presented, considering the electrical and mechanical dynamic aspects of the permanent magnet brushless machine in Matlab Simulink model with traditional PI speed controller. Two simulation models for sensor and sensorless operations respectively are first performed with digital filtering step on the terminal voltage signals and their results are discussed. Also given are details spectrums of the back-EMF waveforms embedded with PWM chopping as computed by Fast Fourier Transform. Analyzing the spectrums further could lead to appropriate design of an optimal low digital filter required. Varying structures and practical implementation of infinite impulse response (IIR) digital filter has been examined and considered. However, the IIR digital filter with cascade transposed direct form II is chosen for its easier practical implementation and low

sensitivity to parameter quantization. To verify the proposed sensorless operation method with IIR digital filter, an experimental test-bed is built and the performance of the sensorless operation of the permanent magnet brushless dc motor is tested. From the experimental results, very good performance in constant torque region is obtained with 100% PWM duty cycle operation. Additionally, phase advance commutation scheme which has been included in the control algorithm is tested for the motor to operate in high speed operation range. The experimental results obtained show satisfactory motor drive performance at steady-state operations for both constant torque and constant power regions.

CHAPTER I

GENERAL INTRODUCTION

1.1 Introduction

Permanent magnet brushless DC (BLDC) motor is increasingly being used in computer, aerospace, military, automotive, industrial and household products because of its high torque, compactness, and high efficiency. The BLDC motor is inherently electronically controlled and requires rotor position information for proper commutation of currents. However, the problems of cost and reliability of rotor position sensors have motivated research into sensorless control of BLDC motor drives. Solving this problem effectively will open the way for full penetration of this motor drive into all low-cost, high reliability, and large volume applications.

In the last two decades, many sensorless drive solutions have been offered to eliminate the costly and fragile position sensor for BLDC motors which have trapezoidal back-EMF. In back-EMF voltage sensing approach, current commutation point can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30^o phase shift. To detect the ZCPs, the phase back-EMF should be monitored on the unenergized phase by subjecting the terminal voltages to a low-pass filtered first (Vas, 1998)

Three low-pass filters (LPFs) are utilized to eliminate harmonics caused by inverter switching, the time delay of LPFs will limit the high speed operation capability of the BLDC machines. In back-EMF integration method the commutation instant is determined by integration of the unenergized phase's back-EMF (Becerra et al., 1991). The basic idea of this method is that the integrated area of the back-EMFs is approximately the same at all speeds. The integration starts when the unenergized phase's back-EMF crosses zero. When the integrated value reaches a pre-defined threshold value, which corresponds to a commutation point, the phase current is commutated. The integration approach is less sensitive to switching noise and automatically adjusts for speed changes. But at low speed operation, it performs poorly due to the error accumulation and offset voltage problems from the integration.

Another sensorless method is by a detection of the freewheeling diodes conduction (Ogasawara and Akagi, 1991). This method utilizes current flowing through a freewheeling diode in unenergized phase. Right after the ZCP of the back-EMF in the unenergized phase, a tiny current is flowing through the freewheeling diode during the active phase switches are turned off under alternate chopper control. This unenergized phase current starts to flow approximately at the time where the back-EMF of the open phase crosses zero. This method also has a position error of commutation points in the transient state as other back-EMF based methods. The most serious drawback of this method is the use of six isolated power supplies for the comparator circuitry to detect current flowing in each freewheeling diode. The drawback prohibits this method from practical applications.

(Ertugrul and Acarnley, 1994) introduced the flux linkage estimation from measured voltages and currents and then the position is predicted by polynomial curve fitting. The fundamental idea is to take the voltage equation of the machine. Then the flux linkage can be calculated as the integration of this voltage equation with respect to time. This method also has an error accumulation problem for integration at low speeds. The method involves lots of computation and is sensitive to the parameter variation.

Another method for sensorless drive of BLDC motor is based on the third harmonic of the back-EMF sensing. This method utilizes the third harmonic of the back-EMF to determine the commutation instants of the BLDC motors (Moreira, 1996). Since the third harmonic of the back-EMF has three times greater frequency, this method is not as sensitive to time delay of a LPF, which is a problem of the terminal voltage sensing method. The back-EMF terms can be represented using the Fourier series. The summed terminal voltage includes only the triplen harmonics since the summations of the three phase fundamental currents is zero. The third harmonic term dominates the summed voltage, and to obtain commutation instants, the summed voltage is integrated, and then the zero crossings of the integrated third harmonic flux linkage are used for commutation points. However, to sense the third harmonic of the back-EMF, an external hardware circuit is required.

The third harmonic-based method has a wider speed range and smaller phase delay than the terminal voltage sensing method. However, at low speed, the integration process can cause a serious position error, as noise and offset error from sensing can be accumulated for a relatively long period of time (Shen et al., 2004; Shen and Iwasaki, 2006).

Observers have also been implemented in sensorless PM motor drive systems (Seniyu et al., 1995), for example the reduced-order observers (Solsona et al., 1996) also, sliding-mode observers are applied to estimate the rotor position utilising d and q axes. The fundamental idea is that a mathematical model of the machine is utilized and it takes measured inputs of the actual system and produces estimated outputs. Then, the error between the estimated outputs and measured quantities is fed back into the system model to correct the estimated values. The biggest advantage of using observers is that all of the states in the system model can be estimated including states that are difficult to obtain by measurements.

Most of the observer-based methods are used for PM AC motors, which have sinusoidal back-EMF and need continuous rotor position. Typically, for the BLDC motors, which require just six position points for one electrical cycle, the continuous position information from the observer is not necessary. But, for special purposes such as flux weakening operation based on advanced angle control, the positions between commutation points will be required.

These are the main categories of the past sensorless solutions for permanent magnet BLDC motors. However, none has worked arguably well at all speeds without accuracy, reliability, and complexity problems, especially at low speed range. Typically, practical minimum speed of the conventional sensorless drive is around 10% of the rated speed. Also, the position error from a phase shifter in transient state deteriorates the performance of sensorless drive (Vas, 1998). In addition, normally at high speed the motor commutation is significantly retarded and the average torque falls rapidly as the rotor speed increases above the base speed, hence the motor will frequently be found to have insufficient torque at higher speed. These are drawbacks of sensorless BLDC motor drives which have been an obstacle for the wide spread use of this motor in various industrial applications (Safi et al.,1995 ; Shen and Iwasaki, 2004) .

1.2 Problem Statement

The most popular category of the sensorless operation is based on detection of back-EMF zero crossing point (ZCP). The current commutation can be estimated by the zero crossing point of back-EMF and a 30 phase shift. Unfortunately in this scheme the position error from a phase shifter and requirement of virtual motor neutral point deteriorate the performance of sensorless drive. It may not be easy to identify the zero-crossing position because high frequency components due to pulse width modulation (PWM) switching are involved in the terminal voltage. This method generally uses hardware low pass filter to remove high frequency component of the terminal voltage due to PWM pulses. Also at high speed torque is deteriorate and the current delayed due to influence of winding inductance. Therefore, a controller that has the feature of advanced commutation is required.

1.3 Scope Of Research

This research work presents an improved sensorless position detection based on a digitally filtering back-EMF and improved zero-crossing detection of the filtered phase with field weakening capability to counter the problem of torque deterioration at high speed. Also enhanced starting procedure is set forth. The commutation instants can be estimated from low speed to full speed; it provides a precise commutation pulse at steady state as well as a 100% duty cycle can be achieved which is one limitation in traditional back-EMF zero crossing methods (Shao, 2006). The proposed method does not require any external hardware circuitry for sensing terminal voltages.

Moreover, the proposed sensorless algorithm is very suitable for implementation in low cost, fixed point Digital Signal Processors (DSPs). Simulation model for the sensorless BLDC motor drive has been developed to validate the proposed methods, and experimental results obtained are in agreement with the proposed methods. Furthermore, the accuracy of the proposed sensorless method is analyzed and simulated to investigate the impact of digital filter of back-EMF on real experimental systems.

1.4 Research Objectives

The main aim of this research is to develop a reliable sensorless control method for the BLDC motor drive over a wide speed range without using additional hardware and large memory space and with improved torque production at full speed. In order to achieve this, an improved sensorless operation based on zero crossing of unexcited phase with digitally filtering back-emf is presented. Therefore, the research objectives are:

- To study theory for a direct back–EMF estimation based on a function of rotor position and develop an efficient MATLAB/Simulink model for permanent magnet BLDC motor operation and control.
- To develop reliable sensorless algorithm for BLDC motor based infinite impulse response digital filter which excludes the need for analog low–pass filtering hardware, off-chip comparator and with 100% PWM duty cycle operation capability.

- To improve starting operation of the motor with possible maximum developed torque. A simulation model is used to verify the validity and to evaluate the performance of the proposed sensorless control methods.
- To maximize torque production at high speed operation by implementing phase advance commutation at high speed. The proposed sensorless method is tested on the experimental test-bed in order to verify the theory and simulation model.

1.5 Research Methodology and Flow Chart

The first step in this work is to conduct an in-depth study of the mathematical model and dynamic behavior of permanent magnet BLDC motor; this is done in order to facilitate the developed Matlab simulink model to simulate traditional hall sensor and sensorless back-EMF with terminal voltage filtering as well as efficient dynamic behavior study. Analyses of the back-EMF signal spectrum using FFT algorithm is carried out to design digital IIR filter and to simulate the digital filter operation on back-EMF. In experimental part, the first step is to operate of BLDC motor using traditional Hall Effect sensor, after which it is compared the experimental signal with simulation. Developing and test-improving the starting sequence is the first step in sensorless operation; this is followed by the Experimental test for sensorless operation of the BLDC motor with digitally back-EMF filtering and improved starting sequence. The final step is the Experimental test of the same sensorless operation with phase advance commutation scheme. Figure 1.1 illustrates the research methodology undertaken in this research work.

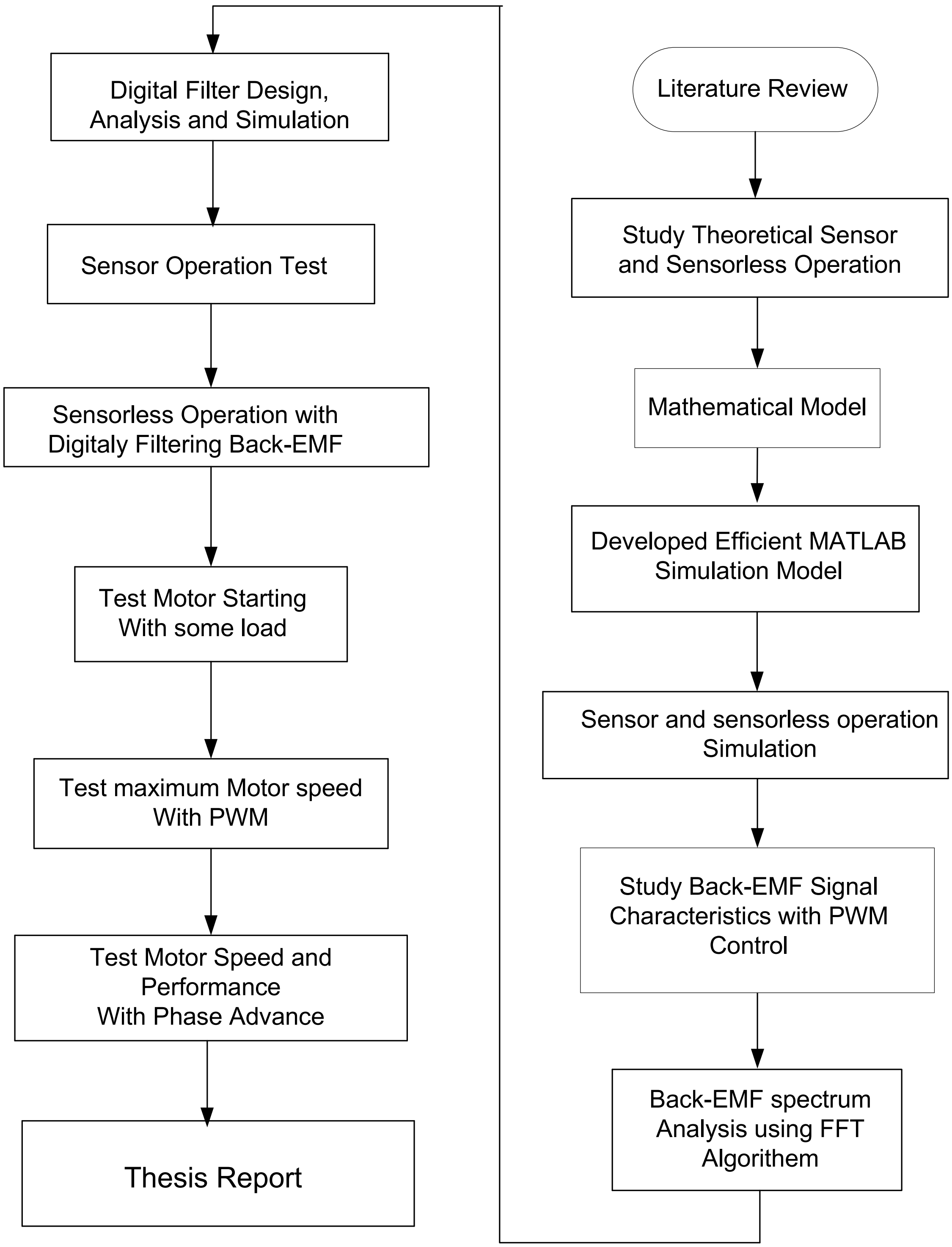


Figure 1.1 Research flowchart

1.6 Contributions of PhD thesis

The contributions of the thesis can be summarized as follows:

(a) Investigation of back-EMF characteristics for different operating speed and load conditions, and design an optimized digital IIR filter based on FFT analysis of back-EMF coupled with PWM noise. The various structures for practical realization of IIR are investigated with particular focusing to cascade transposed structure based on direct form II sections

(b) Digitally filtering the terminal voltage, this leads to a significant reduction in the component count of sensing circuit with single-chip DSP and 100% duty cycle operation can be achieved. In addition, the software compensation for signal delay can reduce torque ripple by maintaining the motor current in phase with the back-EMF and extend control into significantly lower speed operation.

(c) Propose new phase advance scheme for a specific load. By automatically imposing phase advanced commutation when the speed reaches near rated speed. The value of this phase advance angle is determined upfront depending on the load and motor parameter.

(d) This thesis develops an efficient MATLAB/Simulink modeling method for a BLDC motor especially for trapezoidal waveform constructed. Unlike traditional inefficient look-up table, a sine function is followed by a saturated block which generates a wide range of trapezoidal waveform shape from ideal to one which is very close to sinusoidal is proposed. In addition the S-R flip flop is used for hysteresis current controller. This simulation model can be used to study any type of controller applied to a BLDC motor.

1.7 Dissertation Outline

Chapter 1: The basic sensorless operations of permanent magnet brushless motor topologies are reviewed.

Chapter 2: Brief description of the permanent magnet motor types from the view of back-EMF shape as sinusoidal back-EMF and trapezoidal back-EMF are presented, after which the merits and demerits of each type are discussed. Torque production mechanism is discussed based on single turn coil. A typical drive system of the BLDC motor with Hall Effect sensor for rotor position detection and six step commutation technique is discussed in details as well as a voltage control using PWM and hysteresis current controller are presented. Given that the back-EMF waveform of the motor varies as both a function of the rotor's position and speed, therefore the rotor position can be extracted from detection the back-EMF of unenergized phase (for permanent magnet brushless DC motor only two phases are excited at any time leaving the third phase floating). Sensorless operation based back- EMF voltage zero-crossing point can be detected by different methods. This thesis describes three:

1- comparing the BEMF voltage to half the DC bus voltage

2- comparing the BEMF voltage to the motor neutral point; and

3- detecting the BEMF zero-crossing point from the terminal line voltage.

All of these methods have advantages and drawbacks; these will be discussed in the next chapter. The method of flux calculation and observer are discussed as well.

Chapter 3: The mathematical model of the BLDC motor and its drives are presented. Using powerful MATLAB/Simulink software for modeling and simulation non-linear dynamic differential equation and state space equation can be solved precisely. Thus, the operation in sensor and sensorless with terminal voltage filtering, the dynamic behavior of BLDC motor (response to step load change), torque production mechanism and power converter used for current commutation, are all effectively modeled and simulated.

Unlike the traditional method used for trapezoidal back-EMF constructed using the look-up table, a new and smart efficient method is presented in this thesis using sine function and saturated block which that can handle a wide range of trapezoidal waveform shape from an ideal trapezoidal to one which is very close to sinusoidal waveform; this is very important for study the effect of harmonics in machines performance.

Chapter 4: The characteristics of back-EMF at high and low speed and as well as its spectrum are set forth. FFT is used to analyse the spectrum of back-EMF which has high frequency harmonic due to PWM switching. Depending on this analysis, a digital infinite impulse response filter is designed and practical implementation and realization structure is studied with particular reference to cascade transposed direct form II structure due to its low sensitive poles and zero change when being implemented with finite-precision arithmetic.

The matlab digital filter design tools provides several graph showing the response of the filter; of special interest to the algorithm in this thesis is the group delay vs frequency graph. The group delay graph shows how much delay (in sample) the filtered signal will have compared with the actual back-EMF signal. A simulation result for back-EMF digital filtering is presented.

Chapter 5: Experimental results for sensorless operation with digitally filtering back-EMF are described in this chapter. The potential modes of algorithm are the starting mode, sensorless operation mode and phase advance feature for high speed operation.

Chapter 6 Conclusions of this thesis on the research work are presented here. Further improvements on this research are also considered for future works

CHAPTER 2

OPERATING PRINCIPLES OF PERMANENT MAGNET BLDC MOTOR DRIVES

2.1 Introduction

BLDC motors are basically inside-out DC motors. In a DC motor the stator is a permanent magnet. The rotor has the windings, which are excited with a current. The current in the rotor is reversed to create a rotating or moving electric field by means of a split commutator and brushes. On the other hand, in a BLDC motor the windings are on the stator and the rotor is a permanent magnet. Hence the term inside-out DC motor. To make the rotor turn, there must be a rotating electric field. Typically a three-phase BLDC motor has three stator phases that are excited two at a time to create a rotating electric field. This method is fairly easy to implement, but to prevent the permanent magnet rotor from getting locked with the stator, the excitation on the stator must be sequenced in a specific manner while knowing the exact position of the rotor magnets. Position information can be gotten by either a shaft encoder or, more often, by Hall effect sensors that detect the rotor magnet position. For a typical three phase, sensored BLDC motor there are six distinct regions or sectors in which two specific windings are excited(D'Souza,S, 2005). Technology advances in the development of fast semiconductor switches and cost-effective DSP processors have revolutionized the adjustable speed motor drives. These new opportunities have tremendously contributed to the field of motor drives by introducing novel configurations for electric machines in which the burden is shifted from complicated hardware structures onto software and control algorithms. In turn this results in considerable reduction in cost and upgrading in the performance of the overall drive system. The BLDC motor drive system is the most illustrative example of this trend. Very compact geometry and impressive efficiency, along with a very simple control are among the main attractions for replacing many adjustable speed applications with this emerging technology.

The detailed structure of the BLDC motor, the advantages and disadvantages of the motor, control strategy and power converters for the BLDC motor drive, torque generation mechanism, and dynamics of the BLDC motor are described in the preceding section as well.

2.2 Synchronous Machines with Permanent Magnet

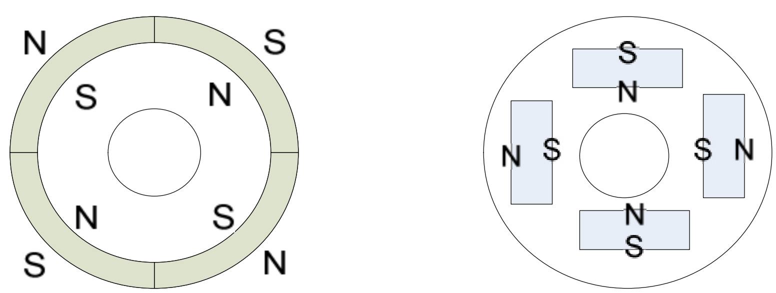
The permanent magnet BLDC motor is a rotating self-synchronous machine with a permanent magnet rotor and with known rotor shaft positions for electronic commutation. In a brushed DC motor, the polarity reversal is performed mechanically by the commutator and brushes. Given that the mechanical commutator is fixed to the rotor, the switching instants are automatically synchronized with the alternating polarity of the magnetic field. However, in the permanent magnet BLDC motor, the polarity reversal is performed electronically by power electronic switches. The resulting performance equations and speed/torque characteristics for BLDC motors are almost identical with those of DC motors (Hanselman, 2003). The permanent magnet BLDC motors can be categorized according to the way the permanent magnets are mounted on the rotor and in accordance with the shape of the back-EMF. The permanent magnets can either be surface mounted or interior mounted and the back-EMF shape can either be sinusoidal or trapezoidal.

2.2.1 Surface-Mounted Permanent Magnet Motors

Figure 2.1(a) shows the surface-mounted permanent magnet rotor. Each permanent magnet (PM) is mounted on the round surface of the rotor. It is easy to build and, in the machine design point of view, skewed poles can be easily magnetized on this round rotor to minimize cogging torque. Although there is a possibility that the attached PM can fly apart during high-speed operation, this can be prevented by using carbon fiber tape or non-magnetic sleeves. Typically, for this type of motor, the inductance variation by rotor position is negligibly small (Krishnan, 2010).

2.2.2 Interior-Mounted Permanent Magnet Motors

Figure 2.1(b) shows the interior-mounted PM rotor. Each permanent magnet is mounted inside the rotor. The use of the interior-mounted PM is not as common as the surface-mounted type, this construction is mechanically robust and therefore suited for high-speed application. The manufacturing of this arrangement is more complex than for the surface-mount synchronous machine. There is an inductance variation for this type of motor because the effective air-gap varies with rotor position (Krishnan 2001; Vas, 1998).



(a) Surface mounted PM rotor.

(b) Interior mounted PM rotor.

Figure 2.1 Cross sectional view of the permanent magnet rotor.

2.3 Trapezoidal Shape Back-EMF Motors

The trapezoidal back-EMF type of motor is designed to utilize the trapezoidal back-EMFs with square wave currents to generate constant torque. It has the following characteristics:

- Rectangular distribution of magnetic flux in the air gap.
- Quasi-square current waveform.
- Concentrated stator windings.
- Lower manufacturing cost.
- Simple controller.
- Six commutation intervals are required for one electrical cycle.
- Commutation torque ripple occurs.
- Hall effect sensors are required for rotor position detection.

For this type of BLDC motor, the excited current takes the form of quasi-square current waveform with two 60° electrical intervals of zero current excitation per cycle. The nature of the excitation waveforms for trapezoidal back-EMF allows some important system simplifications compared to sinusoidal back-EMF machine. In particular, the resolution requirements for the rotor position sensor are much lower since only six commutation intervals are necessary for one electrical cycle. Figure 2.2 shows the winding configuration of the trapezoidal back-EMF type of the BLDC machine (Yedamale, 2003; Su and McKeever, 2004).

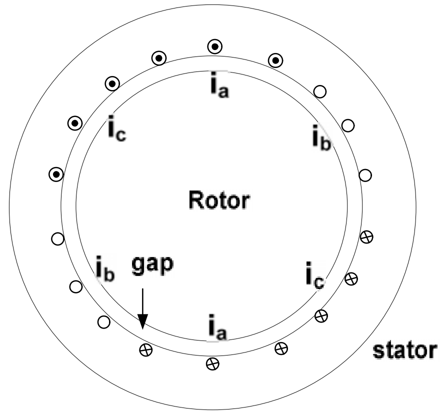


Figure 2.2 Structure of the trapezoidal back-EMF type of BLDC motor.

2.4 Sinusoidal Shape Back-EMF Motors

Figure 2.3 shows the winding configuration of the sinusoidal back-EMF type of motors. They have the following characteristics:

- Sinusoidal distribution of magnetic flux in the air gap.
- Sinusoidal current waveforms excitation.
- Sinusoidal distribution of stator conductors.
- Used for servo applications.
- Smaller commutation torque ripples.
- Higher manufacturing cost.
- Optical encoder or resolver is usually required as a position sensor.
- Sophistical control algorithm is required.

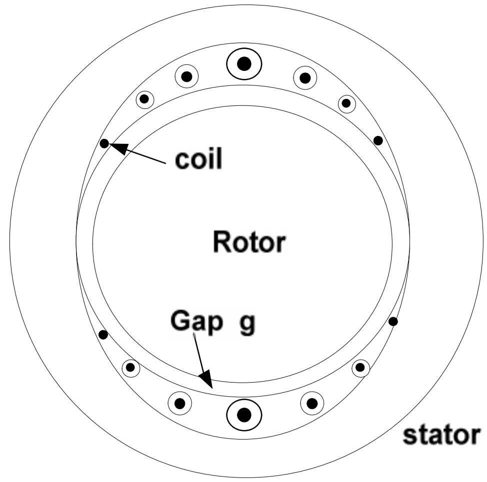


Figure 2.3 Structure of the two-pole, sinusoidal back-EMF type of BLDC motor.

The most fundamental aspect of the sinusoidal back-EMF type motor is that the back-EMF generated in each phase winding by the rotation of the magnet should be a sinusoidal wave function of the rotor angle. The basic operation of a sinusoidal back-EMF type BLDC motor is very similar to the AC synchronous motor, it has a rotating stator MMF wave which is similar to a synchronous motor, and can thus be analyzed with a phasor diagram (Paul et al., 2002). Typically, the sinusoidal back-EMF type of a motor is not considered as a BLDC, rather a PMSM (permanent magnet synchronous machine).

2.5 Advantages and Disadvantages of the BLDC Motor

The BLDC motor offers many advantages, such as those listed below (Crowder, 2006; Kim and Ehsani, 2004):

- High efficiency: BLDC motors are the most efficient of all electric motors. This is due to the use of permanent magnets for rotor excitation, which consumes no power. The absence of mechanical commutator and brushes means low mechanical friction losses.

- Compactness: The recent introduction of high-energy density magnets (e.g., NdFeB and smco magnets) has allowed the achievement of very high flux densities in the motor airgap (Hendershot and Miller, 1994). This allows higher torques per unit volume, which in turns allows for a motor with a smaller and lighter design.
- Ease of control: The BLDC motor can be controlled as easily as a DC motor because the control variables are easily accessible and constant throughout the operation of the motor.
- Ease of cooling: There is no current circulation in the rotor; thus the rotor of a BLDC motor does not heat up. The only heat production is on the stator, which is easier to cool than the rotor because it is static and is located on the periphery of the motor.
- Low maintenance, great longevity, and reliability: The absence of brushes and mechanical commutator suppresses the need for associated regular maintenance and suppresses the risk of failure associated with these elements. The longevity is based only on the winding insulation, bearing, and magnet life-length.
- Low noise: There is no noise associated with the commutation because it is electronic and not mechanical. The driving converter switching frequency is high enough so that the harmonics are not audible.

Apart from these advantages, however, the BLDC motor also has some inherent disadvantages such as those listed below:

- Cost: Rare-earth magnets are much more expensive than other magnets ,resulting in an increased motor cost. The cost of higher energy density magnets prohibits their use in applications where the initial cost is a major concern.

- Limited constant power range: The field weakening operation for the BLDC motor is somewhat difficult due to the use of permanent magnets. A large constant power range is crucial for several applications. The permanent magnet BLDC motor is incapable of achieving a maximum speed greater than twice the base speed.
- Demagnetization of the permanent magnet: Magnets can be demagnetized due to presence of large opposing magnetomotive forces and high temperatures. The critical demagnetization force is different for each magnet material. Extreme care must be taken to cool the motor, especially if it is built compact.
- High-speed capability: The surface-mounted permanent magnet motors cannot reach high speed levels because of the limited mechanical strength of the assembly between the rotor yoke and the permanent magnets.
- Inverter failures in the BLDC motor drives: Due to the permanent magnets on the rotor, BLDC motors present major risks in case of short circuit failures of the inverter. Indeed, the rotating rotor is always energized and constantly induces an electromotive force in the short-circuited windings. A very large current circulates in those windings, and large torque tends to block the rotor. Especially for vehicle applications, the dangers of blocking one or several wheels of a vehicle are non-negligible.

Table (2.1) illustrate the comparison between the BLDC motor and Induction motor drive.