

**DEVELOPMENT OF SENSORLESS SPEED CONTROL BASED
ON BACK-EMF ZERO CROSSING FOR THREE-PHASE
BRUSHLESS DC MOTOR**

By

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ABSTRAK

PEMBANGUNAN KAWALAN KELAJUAN TANPA PENGESAN BERDASARKAN DAYA ELEKTROMOTIF LINTASAN SIFAR UNTUK MOTOR ARUS TERUS TANPA BERUS TIGA-FASA

Penyelidikan ini memfokuskan kepada rekabentuk perisian dan implementasi perkakasan bagi operasi tanpa pengesan untuk memacu motor 16-kutup arus terus tanpa berus tiga-fasa. Operasi yang dicadangkan ini menggunakan pengawal isyarat digital dsPIC30F3010 yang dikeluarkan oleh Microchip Technology Inc. Pengawal isyarat digital ini mempunyai beberapa kelebihan seperti implementasi rekabentuk kos rendah, faktor saiz yang kecil dan padat, dan keperluan perkakasan yang minimum. Papan perkakasan yang digunakan di dalam penyelidikan ini adalah papan PICDEM MC LV yang dihasilkan oleh Microchip Technology Inc. Papan perkakasan ini menyediakan kaedah yang kos efektif dalam membangunkan dan menilai aplikasi motor tanpa pengesan. Dengan menggunakan papan ini bersama pengawal isyarat digital, aplikasi motor tanpa pengesan menggunakan teknik daya elektromotif lintasan sifar dapat dilaksanakan dan digunakan untuk mendapatkan turutan pembalikan motor. Keputusan eksperimen tanpa beban menunjukkan pada 50% kitaran kerja, kelajuan motor adalah lebih kurang 2393 pusingan seminit dengan voltan terminal 10.08V, dan pada 80% kitaran kerja, kelajuan motor maksimum mencapai 4110 pusingan seminit dengan voltan terminal 11.98V. Kawalan kelajuan ini adalah berkadar terus dengan voltan terminal. Oleh yang demikian, keputusan ini bertepatan dengan teori operasi motor arus terus tanpa berus.

ABSTRACT

DEVELOPMENT OF SENSORLESS SPEED CONTROL BASED ON BACK-EMF ZERO CROSSING FOR THREE-PHASE BRUSHLESS DC MOTOR

This research focuses on design development and hardware implementation for a sensorless operation to drive a 16-pole, three-phase Brushless DC Motor. The proposed operation adopted a dsPIC30F3010 digital signal controller developed by Microchip Technology Inc. The digital signal controller has the advantage of low-cost implementation, small and compact size factors and minimum hardware requirements. The development board used in this research is PICDEM MC LV development board produced by Microchip Technology Inc. The development board provides a cost-effective method in developing and evaluating a sensorless motor application. By using this board together with the digital signal controller, a sensorless motor application using Back-EMF zero-crossing technique is implemented and used to derive the commutation sequence. The no-load experimental results shows that at 50% duty cycle, the motor speed is about 2393 rpm with terminal voltage 10.08V, and at 80% duty cycle, the maximum motor speed is about 4110 rpm with terminal voltage 11.98V. The speed controller produces motor speed that is proportional to terminal voltage supply. Therefore, it confirms the theoretical principle of BLDC motor operation.

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LIST OF ABBREVIATIONS

AC	Alternating Current
BLDC	Three Phase Brushless Direct Current
DC	Direct Current
DSC	Digital Signal Controller
DSP	Digital Signal Processing
EMF	Electronic Magnetic Field
FPGA	Field Programmable Gate Array
HDL	Hardware Description Language
IDE	Integrated Development Environment
I/O	Input/Output
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Nd	Neodymium
PIC	Peripheral Interface Controller
PID	Proportional Integral Derivative
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation

RPM	Revolution per Minute
SmCo	Samarium Cobalt
USB	Universal Serial Bus

CHAPTER 1

INTRODUCTION

1.1 Background

Three-Phase Brushless Direct Current (BLDC) motors have become very popular and widely used in many applications such as automotive, aerospace and consumer due to its high efficiency, reliable operation, long operating life and compact construction. The BLDC motor uses an electronic commutator rather than a mechanical commutator, thus, compared to a DC motor, it is more reliable than a standard DC motor.

BLDC motors do not use any brushes and it converts more electrical power into mechanical power than a brushed motor due to the absence of brush friction. There are several other advantages of BLDC motors over standard brushed DC motor which are listed below. [1]

- (i) Higher speed range due to no mechanical limitation imposed by brushed and commutator;
- (ii) High efficiency due to no voltage drop across the brushes;
- (iii) Size reduction due to superior thermal characteristics. The heat dissipation in BLDC is better since the source of thermal heat is only in the windings of the stator;

In a BLDC motor, the rotor incorporates the magnets and the stator contains the windings. The BLDC motor's commutation is implemented electronically using a power converter which converts voltage and current from DC to AC. An electronic controller is

also used to continuously switch the phase of the windings which will keep the motor spinning.

There are few types of power electronic converter such as [2]:

- (i) Converter/rectifier: Converts AC voltage/current into DC voltage/current
- (ii) Inverter: Converts DC voltage/current into AC voltage/current
- (iii) Chopper/ Switch Mode Power Supply: Steps up/down voltage/current level

Inverter is one of the common types of power electronics converter. In brushless DC motor (BLDC) application, the inverter is used to change the DC signal to AC signal required by the brushless DC motors.

The systematic conversion of voltage from DC to AC in an inverter circuit is implemented using a controller. There are several controllers in current market such as microcontrollers, digital signal controllers, Digital Signal Processing (DSP), dedicated chips and Field Programmable Gate Array (FPGA). A microcontroller and digital signal controller are popularly used as BLDC controller due to its flexibility and low cost for implementing control algorithms. It also has low power consumption, flexible programming, shorter development cycle and easier to be integrated. Generally, the functions of the microcontrollers or digital signal controllers is to produce the desired pulse width modulation (PWM) signals. The PWM signals generated by the controllers are fed to integrated power module and this combination drives the brushless DC (BLDC) motors in forward rotation, reverse rotations as well as speed control.

This project focuses on the implementations of the brushless DC (BLDC) motor controller using Microchip digital signal controllers dsPIC30F3010 on a PICDEM MC LV development board with a 16-Pole BLDC motor by Nanotech.

1.2 Problem Statement

The BLDC motor has the advantages of simple construction, high torque capability, low noise and long life operation. A BLDC motor is usually operated with one or more rotor position sensors since the electrical excitation must be synchronous to the rotor position. [3] However, in some motor application such as motor pump immersed underwater, it is desirable to run the motor without position sensors (sensorless operation). Thus, in this project, a sensorless motor control using a zero-crossing Back EMF technique is designed and tested.

The motor is started in open-loop which is an operation mode that is often used to control BLDC motor without rotor position sensors when the back EMF is too weak due to very low rotor velocity [4]. Once the speed is ramp up to a value that produces enough back-EMF voltage, the motor controller begins operation using the sensorless algorithm in a closed-loop running.

The sensorless operation for BLDC motor control requires fast interrupt response to handle PWM updates in real time. Therefore, the use of a high performance 16-bit digital signal controller embedded into a PICDEM MC LV development kit makes them as an ideal hardware to implement sensorless motor controlling system.

1.3 Aim and Objectives

The main aim of this project is to design and develop in software environment, and finally to implement a sensorless operation for a BLDC motor using a digital signal controller to drive and control the speed of brushless DC (BLDC) motor. The specific objectives of this research are:

- (i) To develop a sensorless motor control system based on zero-crossing back-EMF theoretical technique in a low cost digital controller
- (ii) To implement the sensorless motor control application in hardware and validation using a 16-pole, three-phase BLDC motor

1.4 Scope of Project

This project involves mainly in software development and implementation of the source code using C programming language. The development environment used is MPLAB® X IDE software tools and the Microchip C30 compiler software is used for compilation. The program is loaded into the digital signal controller dsPIC30F3010 using PICKit™ 3 Programmer together with AC164110 adapter (RJ11 to ICSP adapter) to connect the PICKit™ 3 with the ICD header on the board.

The source code is validated in PICDEM MC LV development board with a 16-pole Nanotec BLDC motor. This combination is expected to drive the brushless DC (BLDC) motor in a sensorless operation at various speed control.

1.5 Structure of Thesis

This thesis is organized into five main chapters. The first chapter briefly covers the background information, aim and objectives, problem statement, scope of research and the report outline.

Chapter 2 describes the literature review on the operating principle of 3-phase brushless DC (BLDC) motor covering switching and control technique. This chapter also describes the overview of the digital signal controller.

Chapter 3 discusses the methodology implemented in this project. It consists of theoretical concepts, operating principles and speed control design aspects of both software and hardware implementation. The design flow chart is included to assist the understanding of the overall design and implementation processes that had taken place.

Chapter 4 focuses on results and discussions from the experiments and tests performed in terms of functionality of the sensorless controller system with the BLDC motor.

Chapter 5 details out conclusions and future development. The overall project findings will be summarized together. This chapter also covers system performance and improvements that could be revisited.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discussed the fundamental and operating information required to understand the hardware and software design implementation for developing the brushless DC (BLDC) motor controller application using microchip PICDEM MC LV Development Board.

2.2 BLDC Motor

A Brushless Direct Current (BLDC) motors was introduced since 1950s and is one of the most popular motor type used in the industries such as home appliances, automotive, aerospace, medical, industrial automation equipment and instrumentation [5].

As the name implies, BLDC motors do not use brushes for commutation; instead they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few are the following [6][7][8][9]:

- High power density, low inertia and high dynamic response due to small rotor size, low weight and high flux density neodymium-iron-boron permanent magnet rotor
- High efficiency due to low rotor losses because of the absence of current carrying conductors on the rotor and reduced friction and windage losses in the rotor

- Long operating life and high reliability due to the absence of brushed and metallic commutators
- Clean operation due to the absence of brushes, resulting in no brush dust during operation and allowing for clean room applications
- Low audible noise operation due to the absence of brushes and mechanical commutators
- High speed operation is possible since these motor are electronically commutated and are not subjected to the limitations of conventional commutations

Generally, a BLDC motor is conventionally defined as a Permanent Magnet Synchronous Motor (PMSM) type because of the rotating magnetic field generated by the stator and the rotor revolves at the same speed. The magnetic fields are uniformly distributed in the air gap and the motor running at constant speed, thus, resulting in a back-EMF that has trapezoidal shape in time. Hence, the BLDC motor is also normally called as trapezoidal back-EMF motor.

2.3 Motor Construction

A BLDC motor is an AC synchronous motor with permanent magnets on the rotor (rotating part) and windings on the stator (stationary part). The rotor flux is created by the permanent magnets on the rotor, and the electromagnet poles is created by the windings on the stator. When a three phase AC supply is supplied to its stator windings, the electrical energy changes to mechanical energy due to the magnetic attracted forces

between the permanent magnets on the rotor and the rotating magnetic field created in the stator poles.

Figure 2.1 and figure 2.2 show the illustrations of BLDC motor construction with the permanent magnet rotor and wire wound stator poles.

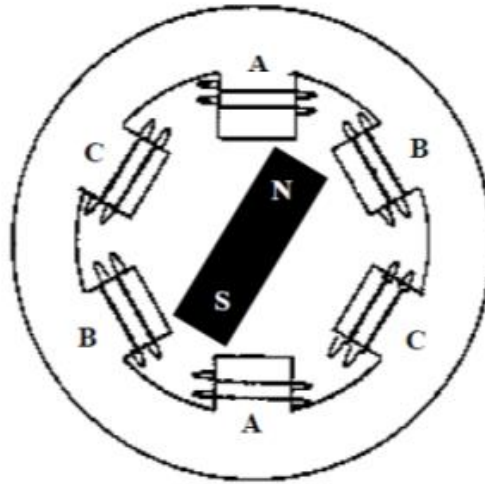


Figure 2.1 BLDC Motor Construction (Top) [10]

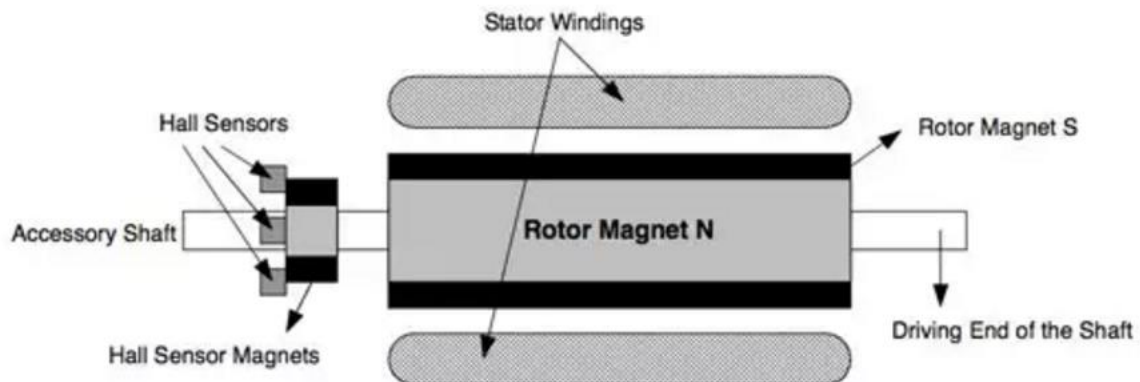
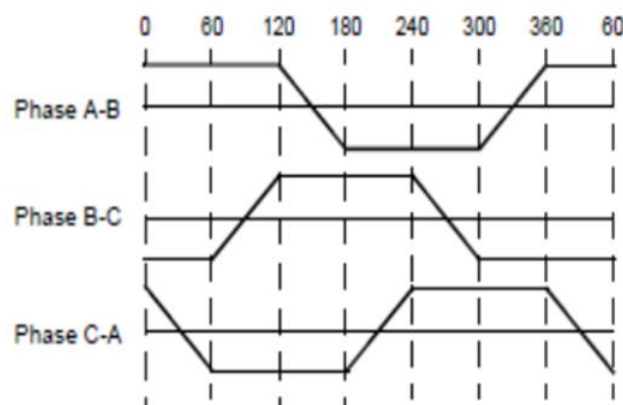


Figure 2.2 BLDC motor construction(cross section) [11]

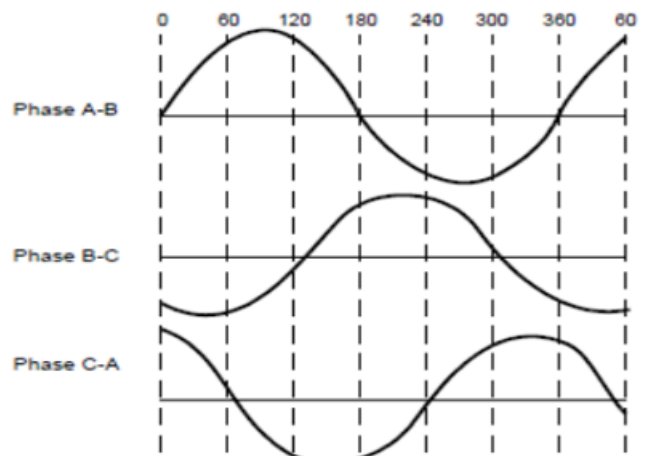
The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery [1]. Most BLDC motors have three stator windings connected in star fashion and these windings are constructed with numerous coils interconnected to form a phase winding. Each of these windings is distributed over the stator periphery to form an even number of poles.

As shown in Figure 2.1, stator phase A winding is first fed with a DC pulse which magnetizes coil A1 as a south pole and coil A2 as a north pole drawing the magnet into its initial position. As the magnet passes the excited phase A windings, in this case coils A1 and A2, the current to phase A is switched off and the next phase B windings are fed with a similar DC pulse causing coil B1 to be magnetized as a south pole and coil B2 to be a north pole. The magnet will rotate clockwise to align itself with phase B. By pulsing the stator pole pairs in sequence the magnet will continue to rotate clockwise to keep itself aligned with the energized pole pair.

BLDC motor can be classified based on few characteristics such as the shape of back-EMF waveform. The different basis of interconnection of the coils in the stator windings creates a different type of back electromotive force (back-EMF). Figure 2.3 shows the shape of back-EMF which can be either trapezoidal or sinusoidal [1].



(a) Trapezoidal



(b) sinusoidal

Figure 2.3 Trapezoidal and Sinusoidal Back-EMF

As their name indicate, the trapezoidal motor gives a back-EMF in trapezoidal shape and the sinusoidal motor's back-EMF is sinusoidal. In addition, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor which influences the torque ripple of the BLDC motor. For trapezoidal back-EMF type, it has higher torque and larger torque ripples while in sinusoidal back-EMF shape BLDC motor, the torque ripple is smaller and smoother [12].

2.4 Rotor construction

The rotor of a BLDC motor is normally constructed of permanent magnets which varies from 2 to 8 pole pairs with each alternate North (N) and South (S) poles. The permanent magnets are mounted on the rotor with the armature windings being housed on the stator with a laminated steel core, as shows in Figure 2.4.

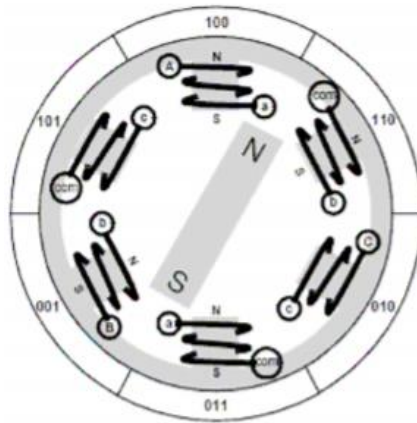


Figure 2.4 Permanent Magnet BLDC Construction [13]

The magnetic material of the permanent magnet determines the magnetic field density. There are two types of magnetic material used as the rotor permanent magnets which are the following:

- Ferrite magnets: Traditionally used as rotor's permanent magnet. This type of magnet is less expensive. However, it has low flux density which is one of the disadvantages.
- Rare earth alloy magnets: It has high magnetic density per volume, thus, it enables rotor size to be smaller and compact for the same torque. It gives higher torque for the same size motor using Ferrite. However, it is more expensive. Example of rare earth alloy magnets are Neodymium (Nd) and Samarium Cobalt (SmCo).

2.5 Hall Sensor

A basic mechanism of a BLDC motor is that it starts rotating once the stator winding is energized. Since the BLDC motor is controlled electronically, knowledge of rotor position is critical to correctly energize the windings to sustain rotating motion. Thus, a hall effect sensor which is embedded into the stationary part of the stator (non-driving end of the motor) is used to obtain the rotor position information and detect the energized stator winding.

The hall effect sensor is a sensing switch that outputs a logic level based on the detection of a magnetic field [14]. The hall effect sensor which is normally mounted in the motor measures the motor's position and the information is communicated to the electronic controller to rotate the motor at the right time and right orientation. The hall sensors are operated by a magnetic from a permanent magnet, responding to South (operate) and North (release) poles [15].

Figure 2.5 shows an example of eight-pole motor with a three-phase winding which uses three bipolar hall effect sensors to detect the position of the rotating motor.

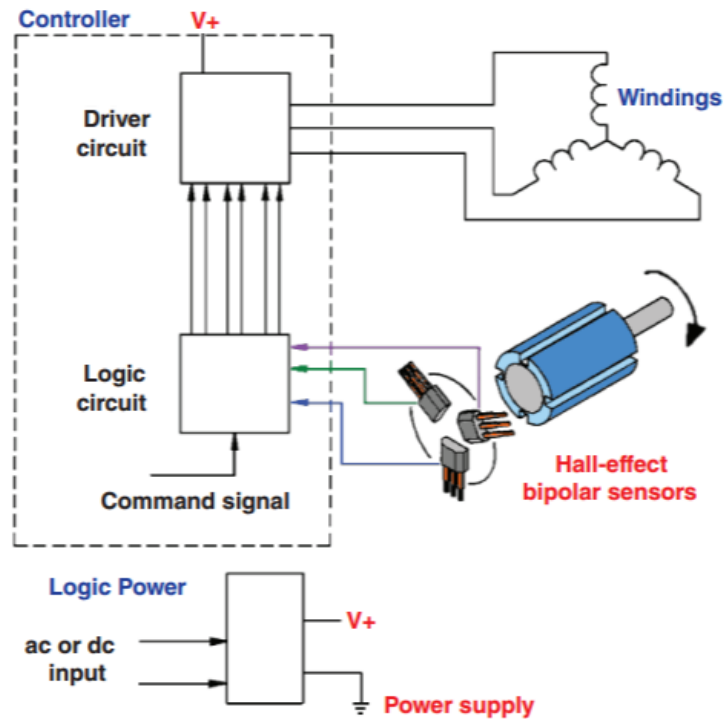


Figure 2.5 Hall effect sensor used in BLDC motor application [15]

The Hall Effect sensors produce a high signal (logic 1) or low signal (logic 0) to show the North (N) or South (S) poles of the rotor magnetic passing near the sensors. This allows exact commutation sequence to be detected based on the combination of 3 hall sensor signals as each sensors are 120 electrical degree separated from each other.

2.6 Back Electromotive Force (Back-EMF)

A Back-EMF is a magnetic field induces when a motor that has coils turning inside magnetic fields. When a motor rotates, each winding will produce a voltage and this voltage is known as Back-EMF voltage. The polarity is in opposite direction of the energized voltage. The Back-EMF depends on 3 main factors: