SIMULATION AND HARDWARE DEVELOPMENT OF PM BRUSHLESS DC MOTOR DRIVES

BY

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analogue-to-Digital-Converter
ASM	Assembly Language
Back-EMF	Back Electro-Motive-Force
BJT	Bipolar Junction Transistor
BLDC	Brushless DC Motor
DC	Direct Current
GTO	Gate Turn Off Transistor
H_a	Hall-sensor A
H_b	Hall-sensor B
H_c	Hall-sensor C
I_a	Reference Stator Current Phase A
I_b	Reference Stator Current Phase B
I_c	Reference Stator Current Phase C
IDE	Integrated Development Environment
IGBT	Insulated Gate Bipolar Transistor
I/O	Input Output
ICD	In-Circuit Debugger
IPM	Interior-Mounted Permanent Magnet
MCU	Microcontroller Unit
MCT	Metal-oxide Semiconductor-Controlled Thyristor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PC	Personal Computer
PCB	Printed Circuit Board
PIC	Peripheral Interface Controller
PI	Proportional Integral

PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
Q	Power Transistor
RAM	Random Access Memory
RPM	Revolution per Minute
SPM	Surface-Mounted Permanent Magnet
U, V, W	Phases in Three-Phase
VSM	Virtual System Modelling
V_{an}, V_{bn} and V_{cn}	Phase Voltage
e_a , e_b and e_c	Induced phase back-EMFs
i_a , i_b and i_c	actual phase currents
R_s	Stator resistance per phase
L	Stator inductance per phase
M	Mutual inductance
T_e	Electrical torque
T_L	Load torque
J	Moment of inertia
B	Friction coefficient
ω_{ref}	Reference Speed
ω_{act}	Actual Speed

SIMULASI DAN PEMBANGUNAN PERKAKASAN PEMACU MOTOR MAGNET KEKAL ARUS TERUS TANPA BERUS

ABSTRAK

Tesis ini membentangkan rekabentuk simulasi dan perkakasan litar kawalan untuk pemacu motor tiga-fasa magnet kekal arus terus tanpa berus dengan menggunakan kaedah kawalan 120-darjah, enam langkah penukartertiban kawalan arus. Pengawalmikro yang digunakan adalah PIC16F877 yang melakukan jujukan penukartertiban arus, kawalan arah pusingan, kawalan kelajuan dan bacaan isyarat yang dihasilkan oleh penderia Hall. Pengawalmikro ini merupakan pengawalmikro 40 pin yang biasa dan murah. Kaedah kawalan berderia dipilih kerana ianya kawalan yang ringkas sesuai untuk aplikasi kelajuan tinggi dan rendah. Untuk kaedah kawalan berderia, pengesanan kedudukan pemutar sangat penting untuk melakukan penukartertiban elektronik pada pemacu motor supaya arus yang mengalir pada tiga fasa belitan motor dapat dilakukan pada jujukan yang betul. Sebelum perkakasan dibina, model BLDC motor ini disimulasi dengan menggunakan dua perisian: Matlab Simulink dan Proteus VSM. Matlab Simulink menyediakan simulasi berasaskan persamaan matematik. Dari simulasi ini, parameter-parameter yang penting untuk motor ini seperti fasa arus, fasa voltan, daya gerak elektrik balik dan kelajuan boleh diperhatikan. Simulasi kedua telah dibangunkan dengan menggunakan Proteus VSM. Simulasi ini adalah berasaskan sifat komponen elektronik yang sebenar yang akan digunakan dalam peringkat membangunkan perkakasan tersebut. Daripada simulasi ini, jangkaan hasil keluaran dapat diperhatikan dan dianalisa secara maya. Karakter yang paling penting dalam perisian ini adalah kebolehannya memprogramkan pengawalmikro secara terus seperti yang dikehendaki. Untuk menyiapkan kajian ini, prototaip pemacu motor BLDC dibangunkan sama seperti model simulasi Proteus VSM. Daripada ujian dan pengukuran, ianya didapati bahawa keputusan-keputusan ujikaji adalah sangat sepadan dengan keputusan-keputusan simulasi.

SIMULATION AND HARDWARE DEVELOPMENT OF PM BRUSHLESS DC MOTOR DRIVES

ABSTRACT

This thesis presents simulation and hardware implementation of a 3-phase PM brushless DC (BLDC) motor drive using 120-degree, six-step current commutation control technique. The microcontroller used is PIC16F877 which functions to perform current commutation sequence, rotating direction control, speed control and reading Hall sensor signals. This microcontroller is a common and low-cost 40-pin MCU. The sensored type of controlling technique has been chosen in order to make this design suitable for both low speed and high speed applications plus control simplicity. For this controlling technique, the rotor position detection is crucial to perform electronic commutation of the motor drive so that the right sequence of current flowing in the three-phase motor windings can be made. Before the hardware is constructed, the BLDC motor model was simulated by using two software: Matlab Simulink and Proteus VSM software. The Matlab Simulink provides simulation based on mathematical equations. From here, important parameters of the motor such as phase current, phase voltage, back-EMF and speed can be monitored. The second simulation was performed by using Proteus VSM software. This software provides simulation based on real electronic components behavior that will be used in hardware development stage. Through this simulation, expected results can be monitored and analyzed virtually. The most important characteristic of this software is its ability to directly program the MCU as intended. To complete this research, the prototype for the BLDC motor drive has been developed following the circuit simulated in Proteus VSM software. From test and measurement conducted, it is found that the experimental results are in good agreement with the simulation results.

CHAPTER 1
INTRODUCTION TO BLDC MOTOR

1.1 Introduction

Permanent magnet (PM) synchronous machines with trapezoidal back-EMF are known as PM brushless DC machines. In-term of construction, BLDC (brushless direct current) motor is an inside–out brushed DC motor. This is because the armature is in the stator and the permanent magnets are in the rotor side (Krause, 2002). Basically the drive system of this motor consists of four main parts: a power converter, a permanent-magnet synchronous machine (PMSM), sensors and control algorithm (KIM, 2007) (Krause, 2002). The power converter used which is inverter transforms power from the source (such as DC supply bus) to the proper AC form to drive the permanent magnet synchronous machine, which in turn, converts electrical energy to mechanical energy. One of the important features of the brushless DC drive is to detect the rotor position. Two popular ways of controlling the BLDC motor are sensored method and sensorless method. The easiest way to know the proper instant to commutate the winding currents is by means of a position sensor; in this case Hall effect sensor. It is also possible to determine when to commutate the motor drive voltages by sensing the back-EMF on motor terminal during one of the drive phases in sensorless control. The obvious advantage that sensorless has over sensored type is cost reduction in which no Hall sensor is needed. However with this cost saving type, it comes with disadvantages over its performance such as:

- As it depends on back-EMF, the motor must be rotating at a minimum speed to generate sufficient back-EMF to be sensed which leads to non-applicable for very low speed applications.

- Abrupt changes to the motor load can cause the back-EMF drive loop to go out of lock (Brown, 2002).

In this project, sensored technique of 120-degree trapezoidal six-step control algorithms has been used to develop the BLDC motor drive both in simulation and hardware implementation. The target is to produce low power application of BLDC motor drive which can operate in high and low speed range with low-cost material and experiment set up. Simulation was performed in two modes by using two different software with different approaches. At first, Matlab Simulink is used to model the BLDC motor from the arrangement of mathematical equation based on phase analysis. Second simulation is then used for hardware development and for this reason, Proteus VSM software has been chosen. This software provides circuit simulation, animated components and microcontroller models to facilitate complete microcontroller based design.

The application of PIC16F877 as the brain of the whole system controller takes very important role. The MCU will operate based on source code flashed inside it. It will read the Hall sensor signal to determine which phases should be energized. For BLDC motor that operates on AC signal, power converter such an inverter need to be used to convert input DC bus supply to AC output supply. In this project, 3-phase bridge inverter has been designed to be interfaced with MCU and perform phase commutation based on MCU command. This project focuses on designing BLDC motor drive using sensored controlling method.

1.2 Problem statement

BLDC motor has become popular through its simple controlling technique and yet provides high torque to inertia ratio, high efficiency and long operating life. Simple controlling technique in this manner means it is easy to be controlled with the application of microcontroller where the rotor position information is used to perform electronic commutation process. Traditionally embedded designer in industries will set up experiment equipments and test procedures to flash the MCU with the source code, debug it, take it off from programmable development board, put it in intended test circuit and run it. If any error occurred, the process will be repeated until the design target is achieved. This is not just for the MCU itself, but also for external circuit built on PCB. It was impossible for the designer to develop and test the complete design before the construction of the physical prototype (Su, 2010). In order to shorten design cycles, reduce cost and risk, the BLDC motor system can first use modelling and simulation technology to establish its model. In this way, a lot of actual design time is effectively saved (Cai, 2010).

In designing stage, it is advisable to have simulation first before going to hardware development. So far, many researches on BLDC motor drive use only Matlab Simulink as the simulation platform. This powerful software provides good simulation results on the drive model but when comes to hardware implementation and hardware analysis, it cannot model the BLDC motor drive based on the real component performance and operations. In research environment, the low-cost prototype should also include reductions cost in research and development stage. Most of the time without any method to test the components behavior and performance, bench-test which takes significantly long period of time is used. For one application, sometime it requires to test 3 or 4 components, even more, before the design target is achieved. Worst case scenario, designer needs to revise PCB circuit over and over again when the design is a failure product which leads to waste of time and increase in designing cost. In industrial applications, low-cost still a dominant factor and become major consideration (Kim, 2007). For that reason, this research introduce the usage of Proteus VSM software to simulate every necessary components needed in order to come out with complete BLDC motor drive circuit before starting hardware construction. The virtual programming and debugging MCU and transient analysis capability offered by this software makes work easier for designer especially when it comes to MCU circuit-based design. From the transient analysis, the most important part which is the MCU can be confirmed working properly with the source code programmed inside it.

This research is an extended research work from researches made by Bo Su and Li Wang; “Application of Proteus Virtual System Modeling (VSM) in Teaching of Microcontroller” in 2010 and “The Construction of Single-chip Experiment Platform Based on Proteus” by Shi Wei and Liu Jianhui in 2009 . The papers introduce the use of Proteus VSM software in application using MCU. However this research takes one step further by using the software for BLDC motor drive embedded system application where PIC16F877 programmable MCU is used as the main controller.

1.3 Research Objectives

The aim of this research is to design, develop and build 3-phase PM BLDC motor drive. The main objectives are:

i) To build and simulate PM BLDC motor model in Matlab Simulink using 120-degree six-step switching technique by using related mathematical equations

ii) To build virtual prototype of the design system in Proteus VSM

iii) To construct BLDC driver’s hardware with efficient and cost saving method and compare the hardware results with simulation results.

1.4 Scope of Research

In this project, the research has been conducted starting from BDLC motor drive simulation using Matlab Simulink software. At this stage, PM BLDC motor drive is modelled from power electronic controller, BLDC motor and Hall sensor signal generation. The simulation is basically based on mathematical equations.

The second stage involves simulation in which Proteus VSM software has been introduced in this research. The software is different from Matlab Simulink simulation because it is based on hardware realization. Actual components intended to be used in hardware design are first simulated using this software. Its library provides thousands of components which also include programmable microcontrollers. PIC16F877 is one of MCU that can be programmed with source code within Proteus VSM environment. How the code is working when attached to this MCU can be monitored within this software. It provides real-time virtual hardware simulation and software debugging module. In this software environment, BLDC motor controller circuit using open-loop control mechanism with Hall effect as its rotor position detection sensor is developed. Other circuit such as over current, over voltage and over temperature protection circuit have also been built to complete one simple and low cost BLDC motor drive.

The third and final stage is to implement the complete BLDC motor drive circuit in Proteus VSM software into the real hardware design using the exact same component simulated previously. The MCU is later on programmed by using PICDEM 2 PLUS development board and ICD2 debugger through MPLAB IDE software provided by Microchip Corporation.

1.5 Research Methodology

In order to complete this project, the research and design steps have been planned carefully and each task were constructed systematically following the right sequence to avoid any major possible mistake that can lead to unsuccessful project result. Figure 1.1 shows the research methodology chart for this project. The project begins by literature review of the related projects performed by other researchers in order to get clearer picture of the theoretical information behind this project and to avoid any misconception. Plus, references through related engineering books, published papers and other trusted available sources have been made to strengthen the BLDC motor control algorithm understanding. Next, problem statement is identified to focus this project on solving the problem.

After defining what need to be done in this project and its research scope, simulation stage begins by constructing the BLDC motor drive model using Matlab Simulink program. This simulation software has been chosen as it is a dependable and widely used software in modelling motor drive and other systems. Simulink simulation strengthens the understanding of BLDC motor driving concept. In this software, BLDC motor has been modelled by using basic block-set including Hall effect sensor block representation. The simulation results are then compared with theoretical concept to ensure the simulated system produces accurate simulation results. Next simulation uses Proteus VSM software. This software offers hardware simulation for the electronic components used and source code simulation that flashed inside the MCU. At this simulation stage, various electronic components were tested in order to find lower cost devices yet fulfills design requirement in low-cost environment.

Once the BLDC motor drive simulation has been successfully designed, hardware implementation begins following the designed circuit in Proteus VSM. In this stage, the main controller which is PIC16F877 is used as the microcontroller that controls all system. The source code written in assembly language is then flashed into the MCU by using Development Board PICDEM 2

Plus along with ICD2 debugger through MPLAB IDE software. The following task is to determine and analyze the experimental results and compare them with simulation results.

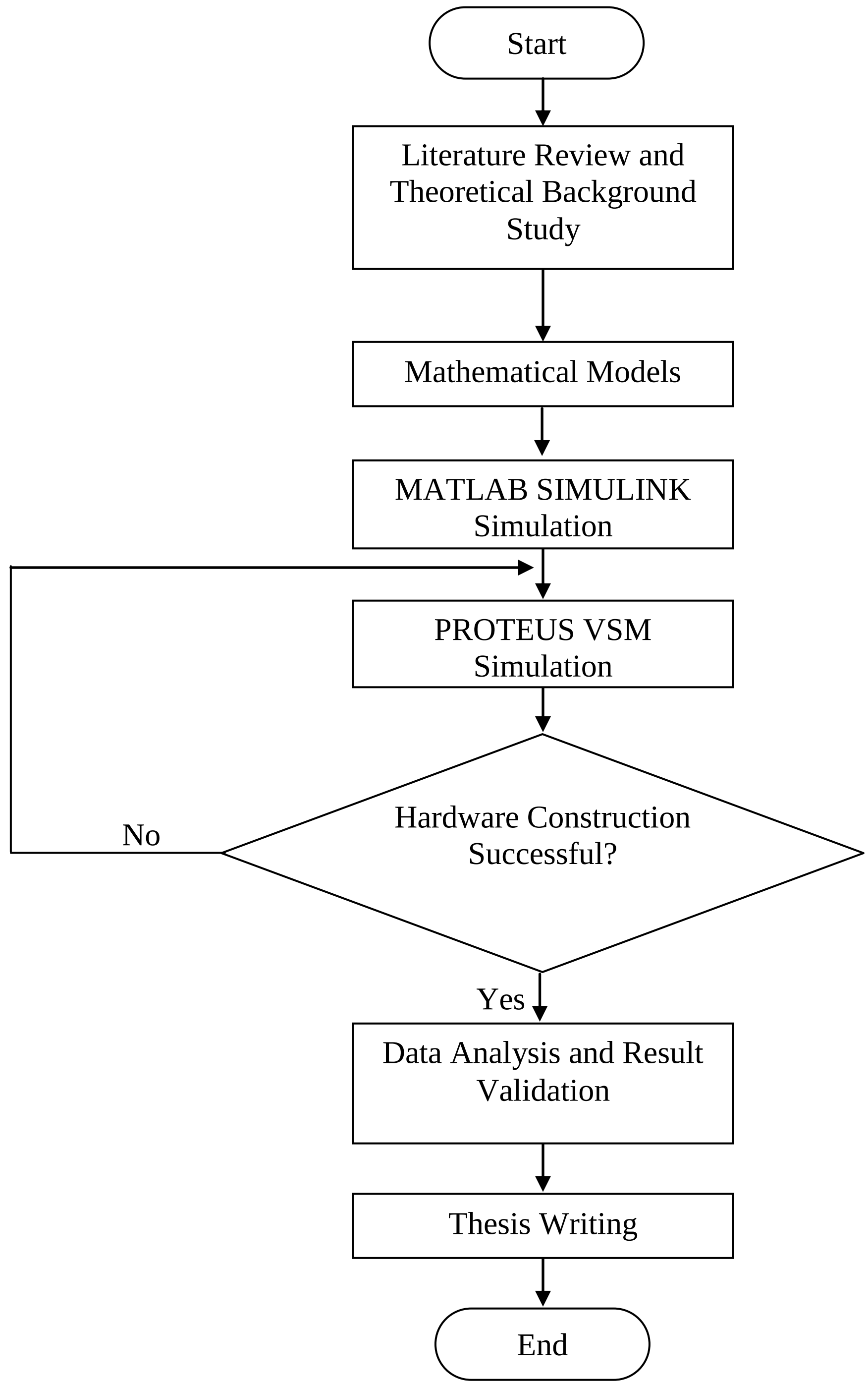


Figure 1.1 Project flow chart

1.6 Structure of the Thesis

This thesis is divided into six chapters as explained below:

Chapter 1:

This chapter introduces the research in this project. It contains problem statement, research objectives, research scope and research methodology.

Chapter 2:

Chapter two presents the introduction of PM BLDC motor both its hardware construction and controlling system. A few control methods are discussed and the control technique used in this project is explained in details.

Chapter 3:

This chapter is about simulation. PM BLDC motor drive system is modelled with Matlab Simulink and Proteus VSM softwares. Both have different approaches towards PM BLDC motor drive. The control model is using 120-degree trapezoidal six-step switching technique in open-loop mode. Analysis has been made by using transient analysis provided by the highly capable software.

Chapter 4:

After completing the simulation stage, hardware implementation and analysis are performed in this chapter. The exactly same circuit and components that are simulated in Proteus VSM software are used in hardware prototyping.

Chapter 5:

This chapter analyzes and compares the simulation results with the developed PM BLDC motor drive hardware.

Chapter 6:

This chapter presents thesis conclusions and future work for improvement.

CHAPTER 2

OPERATING PRINCIPLE OF PM BLDC MOTOR DRIVE

2.1 PM BLDC Motor

DC machine with Permanent Magnets (PM) field excitation has been introduced around 1950s. This introduction which replaces electromagnets, leads to the revolution in synchronous AC machine and DC machine. Using PM in synchronous machine eliminates its conventional field excitation at the rotor side. After the introduction of PM, later on switching power transistor and silicon-controlled-rectifier devices were developed and brings to the inverter invention, thus enables the mechanical commutator to be replaced with electronic commutator. These two findings contributed to the development of PM synchronous and brushless DC (BLDC) machines. For conventional DC machine, the armature winding is located at the rotor while field winding at stator side but with PM and electronic commutator, the armature now is located at stator side enabling better cooling condition. Moreover, the field winding is transferred to the rotor with the PM poles, therefore, PMBLDC motor is basically 'an inside out DC machine' (Krishnan, 2003).

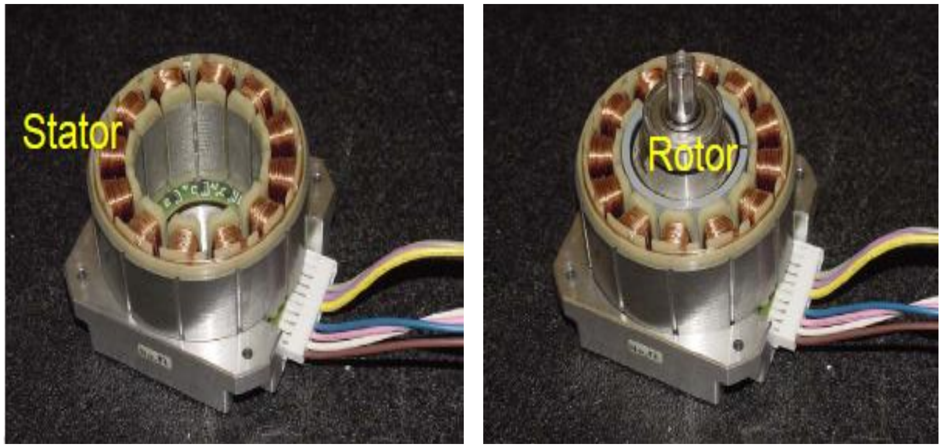
Brushless Direct Current Motor (BLDC) basically is a Permanent Magnet Synchronous Motor (PMSM). Despite the name "brushless DC motor", this is a PM synchronous machine where the magnetic fields are uniformly distributed in the air gap (rather than sinusoidally distributed). With the motor running at constant speed, this results in back-EMF that has trapezoidal shape in time, and hence the name trapezoidal back-EMF motor (Chiasson, 2005).

In terms of applications, BLDC motor has gained designer attention lately since it offers many advantages over other common motor. It is used in industries such as home appliances, automotive, aerospace, medical, industrial automation equipment and instrumentation (Han, 2008). In comparison to other types of motor, besides offering control simplicity, BLDC motor provides many advantages like (Hong, 2007) (Sathyan, 2009) (Krishnan, 2003) (Kim, 2007):

- 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 as a result 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 brushes 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
- Control simplicity over its counterparts. This is an important characteristic for industries application to counter back its high cost set up.

2.2 BLDC Motor Construction

BLDC motor basically is an AC motor despite its name. It consists of a permanent magnet synchronous machine (PMSM) with either sinusoidal or trapezoidal back-EMF driven by an inverter (Han, 2008). Three phase AC supply is supplied at its stator winding which also known as armature winding while its rotor is made from permanent magnet. Figure 2.1 shows example of stator coil and permanent magnet rotor of BLDC motor while Figure 2.2 shows cross section of BLDC motor physical construction.



(a) (b)

Figure 2.1 Stator and rotor of BLDC motor example (a) Stator (b) Rotor (Jani, 2006)

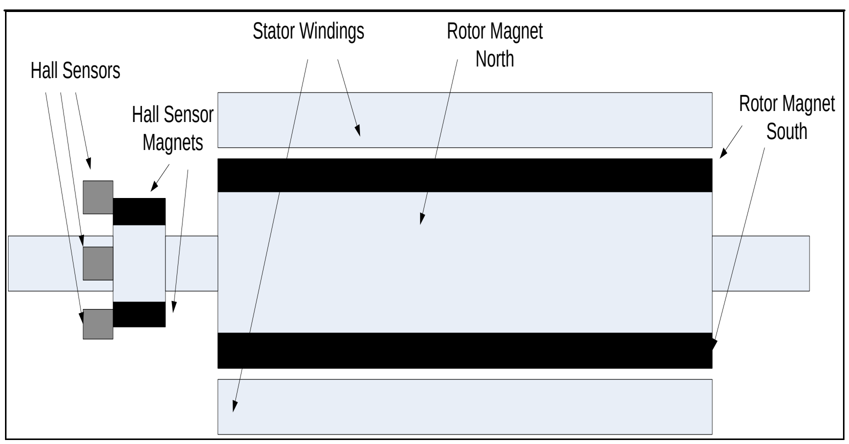
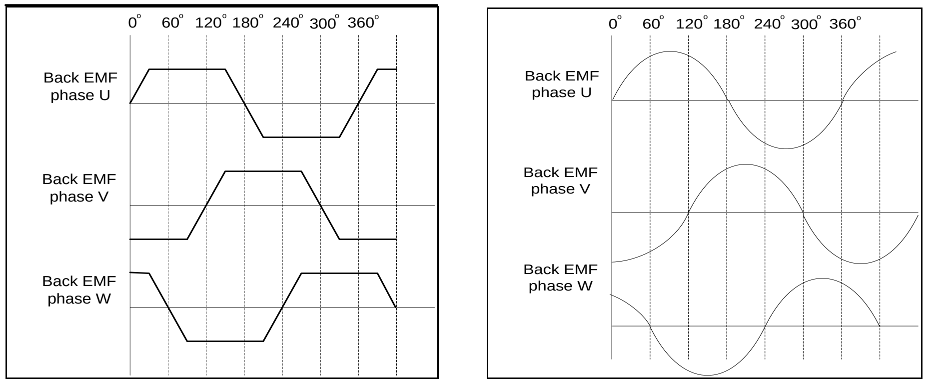


Figure 2.2 BLDC motor constructions (Yedamale, 2003)

BLDC motor can be classified based on a few characteristic such as the type of permanent magnet (ferrite, ceramic, alnico or rare earth), the placement of permanent magnet, the shape of back-EMF waveform and etc. Classification based on back-EMF waveform is shown in Figure 2.3. As can be seen the shape of the back-EMF can be either sinusoidal or trapezoidal (non-sinusoidal). A torque ripple of BLDC motor is mainly influenced by the electronically commutation and back-EMF (Hong, 2007). 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 (Emadi, 2005).

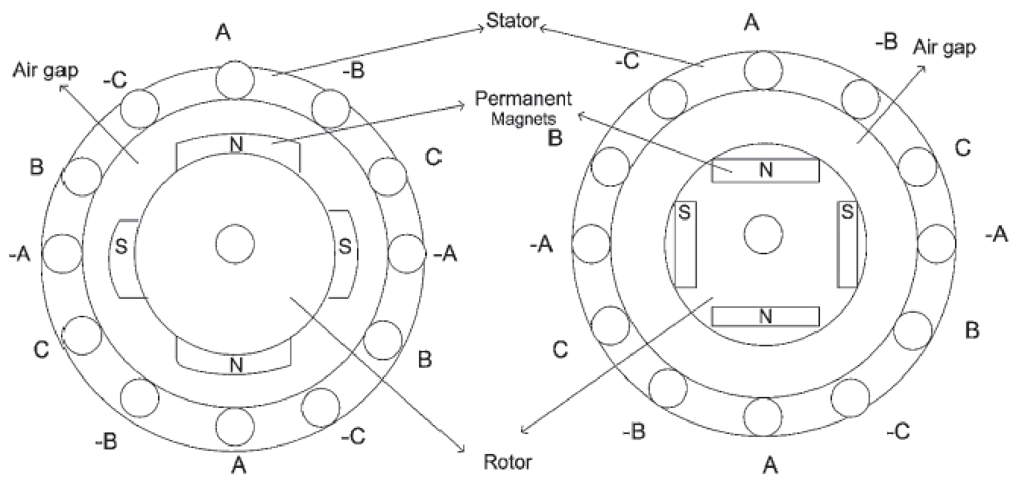


(a) (b)

Figure 2.3 Ideal back-EMF waveform of BLDC motor (a) Trapezoidal back-EMF (b) Sinusoidal back-EMF (Krishnan, 2003)

For trapezoidal type, its armature phases must be supplied with quasi-square currents for ripple free torque operation (refer Figure 2.5). In the other hand, for sinusoidal type, it requires sinusoidal phase armature currents for the same reason. High resolution position sensor is required in sinusoidal type as the rotor position need to be known at every instant of time for optimal operation and this leads to the complexity of hardware and software design. For this reason, trapezoidal type is much more attractive choice due to its simplicity, lower price and yet high efficiency and therefore it is generally used for low-cost industrial applications (Kim, 2007) (Sen, 1997).

For surface-mounted permanent magnet (SMPM) or interior-mounted permanent magnet (IPM) types of BLDC motors as shown in Figure 2.4, the permanent magnets are mounted either on surface or inside the rotor. In the surface-mounted machine, the air gap might be non-uniform, while for the interior mounted machine, the air gap is uniform (Emadi, 2005).



(a) (b)

Figure 2.4 Rotor construction (a) Surface-mounted permanent magnet (b) Interior-mounted permanent magnet

There are three types of permanent magnet materials used for PM DC motor which is Alnicos, ferrites and rare-earth materials. Ferrites type is the most common PM used in fractional kW motors while alnico type are used in applications up to 200kW. In the other hand, rare-earth materials are very costly but it is the most economic choice in very small motors (Kothari, 2010).

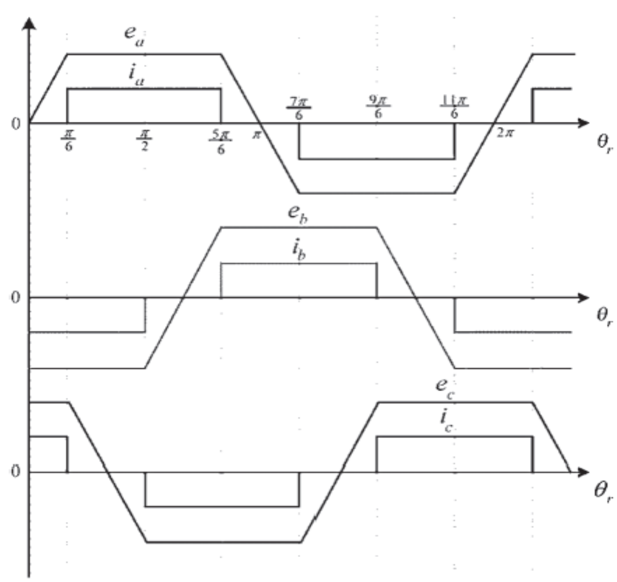


Figure 2.5 Relationship of phase current and phase trapezoidal back-EMF

2.3 Control Algorithm for BLDC Motor

This motor basically is a new type of DC motor which uses the electronic commutation technology instead of mechanical commutation, with operation high efficiency, high starting torque, wide speed range, simple structure and reliable operation (Cai, 2010). The control algorithm must provide basic three things:

- PWM (Pulse Width Modulation) voltage to control the motor speed
- Mechanism to commutate the motor
- Method to estimate the rotor position using the back-EMF or sensor

BLDC motor rotates caused by the commutation of stator current. Thus by changing the applied voltage across the motor phases, the speed can be varied. This can be done by using sensored method based on the concept of PWM (Sathyan, 2009).

PWM serves to control the average output voltage given a fixed input voltage. This is achieved by using power switches to vary the time for which DC input is supplied to the load (Sathyan, 2009). PWM determines how long each cycle the transistors in bridge inverter are ON sending energy to the load (Jacob, 2002). It is basically a rectangular DC waveform which contains ON state side and OFF state side. The ratio of ON state over the period for one cycle is called duty cycle. Duty cycle can be varied from 0% to 100%. For 100% duty cycle meaning it always turn ON. The amplitude of PWM waveform commonly 5 V for microcontroller applications. Figure 2.6 shows example of PWM with different percentage of duty cycle.

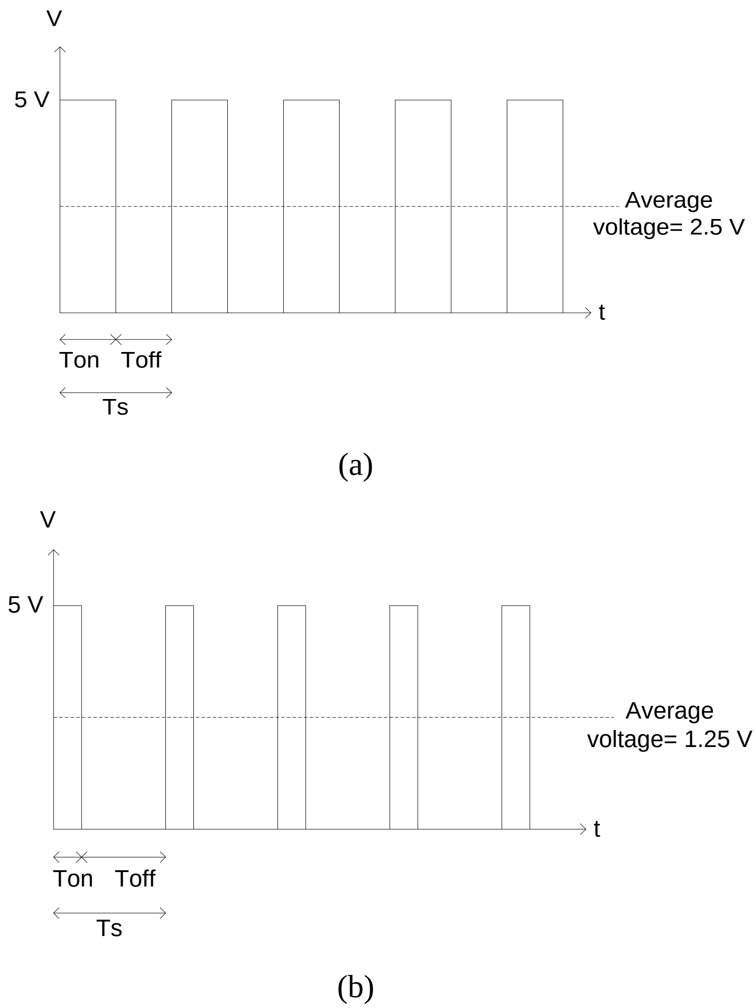


Figure 2.6 Pulse Width Modulation (a) PWM with 50% duty cycle
(b) PWM with 25% duty cycle

PWM is very useful and an effective way in controlling electrical motor speed. Motor speed will increase when applied voltage is increased. By controlling the duty cycle of PWM waveform, average voltage sent to connected motor is controlled. The higher duty cycle percentage, the higher average voltage received by the motor. For example, PWM of 5 V amplitude and 50% duty cycle will supply average voltage of 2.5 V for every cycle. For continuous PWM supply, the motor are receiving 2.5 V constant. By multiplying duty cycle percentage with PWM magnitude, will result average voltage per cycle.

2.3.1 Sensored and Sensorless Control

Controlling BLDC motor can be narrowed down to two major types which is sensored and sensorless. Sensored operation technique is useable for low speed and high speed applications. In this operation method, sensor needs to be used to detect rotor position so that commutation sequence can be performed accurately. Rotor position information can be provided by either a shaft encoder or, more often, by Hall effect sensors that detect rotor magnet position. Former method is fairly easy to implement but excitation on the stator phase winding must be done in correct manner so that the permanent magnet rotor will rotate smoothly without significant torque ripple and speed ripple that can affect motor performance. BLDC motor is commutated electronically where the stator windings are energized in sequence.

Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnet on the rotor side. To keep the rotor rotating, magnetic field at the stator winding should also rotate by following clock wise or anti clock wise commutation sequence. Figure 2.7 shows the block diagram of sensored BLDC motor controlling technique. As can be seen, the Hall sensor signals come from the motor into the MCU.

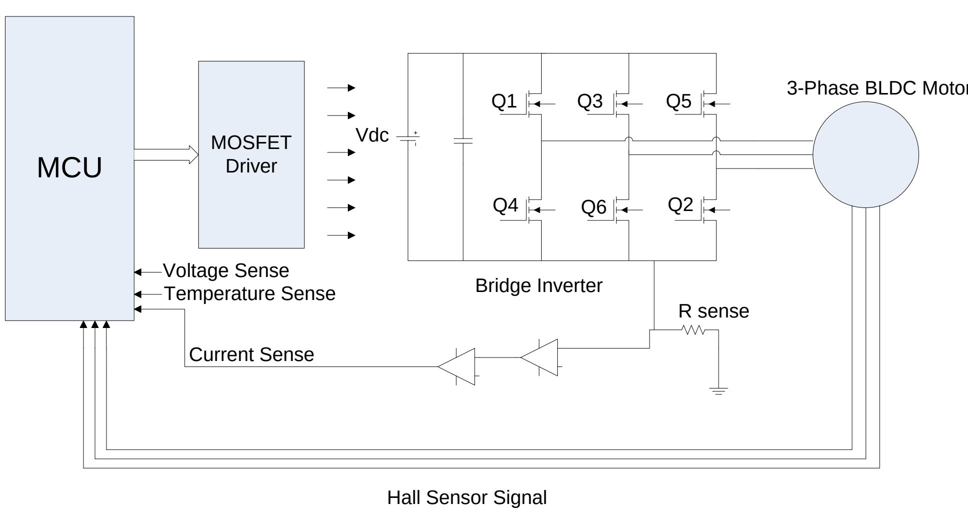


Figure 2.7 Sensored BLDC motor control block diagram

For sensorless controlling technique, the commutation timing comes from back-EMF detection on the floating windings of the motor. The back-EMF on the unconnected winding is a direct indication of the rotor position. If the zero crossing of the phase back-EMF is detected, then the commutation of the appropriate stator winding can be implemented. Since only two phases are conducting current at one instant time, and the third winding is open, this feature enables the back-EMF detection in the floating winding (Karunakaran, 2009).

In sensorless method, the rotor position estimation faces difficulty in precisely detecting rotor position that leads to rotor position error which will greatly reduce motor efficiency and produces torque pulsation. Speed dependent back-EMF is a popular method in sensorless control algorithm but it is still impossible to use the back-EMF sensing method in low speed application as the back-EMF is zero or undetectably small when the motor is standstill or rotating at very low speed (Kim, 2003). However recently many researches have come out with solutions how to solve this problem which will not be discussed in details here as this project concentrates in sensored type motor control. In designing driver for PM BLDC motor, rotor position detection plays important role as the motor is electronically controlled to produce proper commutation of currents in its three-phase windings. Although sensorless control method brings in cost reduction, the inaccurate rotor position estimation has become major problem for this control technique which can decrease its performances (Kim, 2003). Moreover, it faces serious problem when the motor is running at very low speed. As the back-EMF is proportional to the speed, low speed will cause low back-EMF generated to detect zero-crossing. To overcome this problem, usually the motor will be started in open-loop control manner from static until it reaches certain speed that back-EMF is built sufficiently to detect the zero-crossing point, and then the control algorithm will be switch to back-EMF sensing method (Yedamale, 2003). In term of cost reduction, cost saving in eliminating the position sensor does not balance back the extra cost needed as the method demand high-performance processors, large program codes and large memory. Therefore, it is very difficult to decrease the total motor drive cost (Kim, 2007). It is however a technique that gains popularity among researchers as the ability to eliminate any position sensor and it opens wider research area in BLDC motor drive system.

In sensored controlling technique, rotor position is detected using signal generated from sensor. The common sensor used is Hall effect sensor which normally mounted on a PC board and are fixed to the enclosure cap on the non driving-end of the motor (Yedamale, 2005). Three Hall sensor will be used as a feedback to the MCU and each of the sensors are out of phase by 120-degrees to each other. Each Hall sensor will provides either a High or Low output signal based on the polarity of magnetic pole close to it indicating that the north or south pole is passing near. At every 60-degrees, one of the Hall sensors makes transition as shown in Figure 2.8.

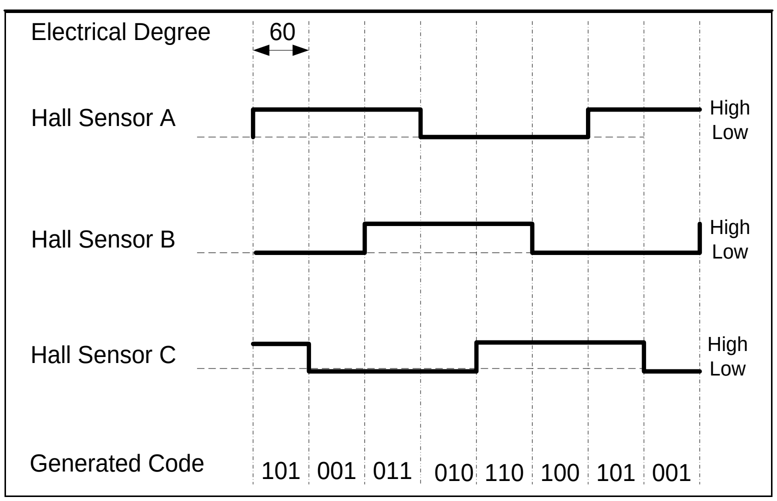


Figure 2.8 Hall sensor signals

Signal from Hall sensors will be fed to microcontroller to perform electronic commutation based on sequence declared inside its memory. From here, the two stator windings will be energized while the third will be left floating. This mechanism is shown in Figure 2.9. Each Hall sensor is High for 180-degree and after 120-degree, second Hall sensor starts to be High as the displacement is 120-degree.

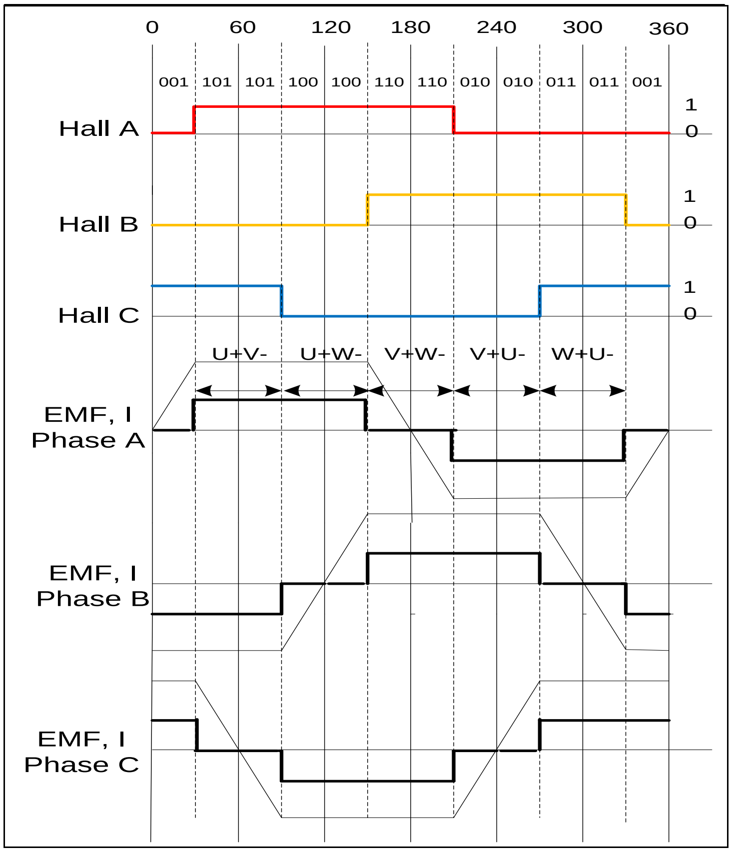


Figure 2.9 Relationship between Hall sensor, back-EMF and reference current (Yedamale, 2003) (Krishnan, 2003) (Sathyan, 2009)

2.3.2 Six-step Trapezoidal Control of BLDC Motor

BLDC motor is operating based on electronic commutation performed by a controller. It is regarded as a strong candidate for low-cost motor drive applications along with its advantages over other electric machine such as high efficiency, low maintenance and simple control (Lee, 2003). It has the stator construction that resembles synchronous machine with permanent magnet as part of its rotor construction. In order to rotate the BLDC motor, it needs interaction between rotor magnetic field of permanent magnet and stator magnetic field generated at stator current. The magnetic field at stator side is rotating as the result of electronic commutation driven by DC to AC power inverter.

In term of BLDC motor controlling technique, it is essential to have the simple and reliable method as the controller involves electronically commutation. Further more, simplicity in controlling can balance back its high cost set-up that becomes major concern in industries. Therefore, 120 six-step controlling method has become very common due to their control simplicity (Han, 2008). Each phase is allowed to be open circuited for a fraction of motor revolution following the signal generated by Hall sensor. The stator current conduction pattern happen such that only two phases of star connected winding are connected in series with DC bus and the third winding is open (Sathyan, 2009). For variable speed control application, it is suitable to use an open-loop voltage mode pulse-width modulation with full-bridge inverter (Chen, 2009).

In order to get constant output torque, the stator current is driven through a motor winding during the flat portion of the back-EMF waveform (refer Figure 2.9). At inverter side, only two switches are turned ON, one in high side and one in low side. The inverter switches are operated such that each phase carries current only during the 120-degree period when the back-EMF is constant (Sathyan, 2009). Therefore, there is a commutation event between phases for every 60-electrical degree as seen in Figure 2.10. By referring to Figure 2.9, notice that during each 60-degree interval, it will only require one phase to have a current +I (indicated by +), the other to have –I (indicated by -), and the third to have a zero current (open). These currents satisfy Kirchoff's Current Law in wye –connected phase windings (Mohan, 2002).

For six-step controlling technique, there are six distinct switching steps. Considering three phases stator winding consist of "U" phase winding, "V" phase winding and "W" phase winding, the switching configurations are U+V-, U+W-, V+W-,V+U-, W+U- and W+V- (indicated in Figure 2.9). This sequence is visualized in the Table 2.1. The highlighted phase sequence in this table is the phase winding that being energized at particular step. The BLDC motor will rotates 360 electrical degrees if the six switching configurations are changed sequentially at 60-degree intervals in synchronization with the rotor position. This controlling technique is called 120-degree method because each switch of the power inverter is turned ON for 120 electrical degrees. To rotate the motor with 6-step method, the current is commutated with six-steps in one cycle. In each step only two phase windings carry current.

Table 2.1 Electronic commutation sequence

Switching Step	Phase Sequence		
	U	V	W
Step 1	U+	V+	W+
	U-	V-	W-
Step 2	U+	V+	W+
	U-	V-	W-
Step 3	U+	V+	W+
	U-	V-	W-
Step 4	U+	V+	W+
	U-	V-	W-
Step 5	U+	V+	W+
	U-	V-	W-
Step 6	U+	V+	W+
	U-	V-	W-

As BLDC motor is an AC machine, it needs three-phase AC supply to operate and produces three-phase back-EMF. Therefore, three-phase bridge inverter that converts DC to AC signal is needed to drive the motor. Inverter for motor controlling applications is usually controlled by MCU. The MCU is responsible in providing signal to turn ON inverter power switches (commonly MOSFET or IGBT) in sequence based on the code written inside the MCU. In BLDC motor drive, the electronic commutation is controlled by dedicated MCU that will switch ON two power switches out of six switches of the three-phase bridge inverter at one time. Its primary job is to produce two signals at one time (dependant on Hall sensor signals) that are sent to the power switches. The PWM signal determines how long each cycle the power switch in the H bridge inverter are ON sending energy to the load (Jacob, 2002). The bridge inverter for this project consists of six power MOSFET as illustrated in Figure 2.10. There are three pairs of switches that used to provide path for the current to flow in the three-phase stator winding of the BLDC motor. In Figure 2.10, for example to flow current in phase U+ (also known as phase A) and phase V- (also known as phase B) windings, switch Q1 and Q6 must be turned ON. One important thing need to be avoided is any pair of the inverter switches cannot be turned ON at the same time. For instant, if Q1 and Q4 are turn ON at the same time, over-shoot current will occur as the result of short circuit of DC positive and negative terminal and most likely will damage the power switches. This is one of the reasons why MOSFET driver is needed. The chosen MOSFET driver must have the capability to prevent two pair of power switches on the same phase from conducting at the same time.

2.3.3 Power Inverter

Inverter is a DC-to-AC converter. It changes a DC input voltage to a symmetric AC output voltage of desired magnitude and frequency (Rasyid, 2004). Inverters can be generally classified into single-phase inverters and three-phase inverter. Both inverter types use switching devices such as BJT, MOSFET, IGBT, MCT and GTO. For three-phase inverter, two types of control signal can be applied to the switching devices: 180-degree conduction or 120-degree conduction. This thesis focuses on 120-degree conduction. In 120-degree type of conduction, each transistor is turned ON for 120-degree as shown in Figure 2.10.

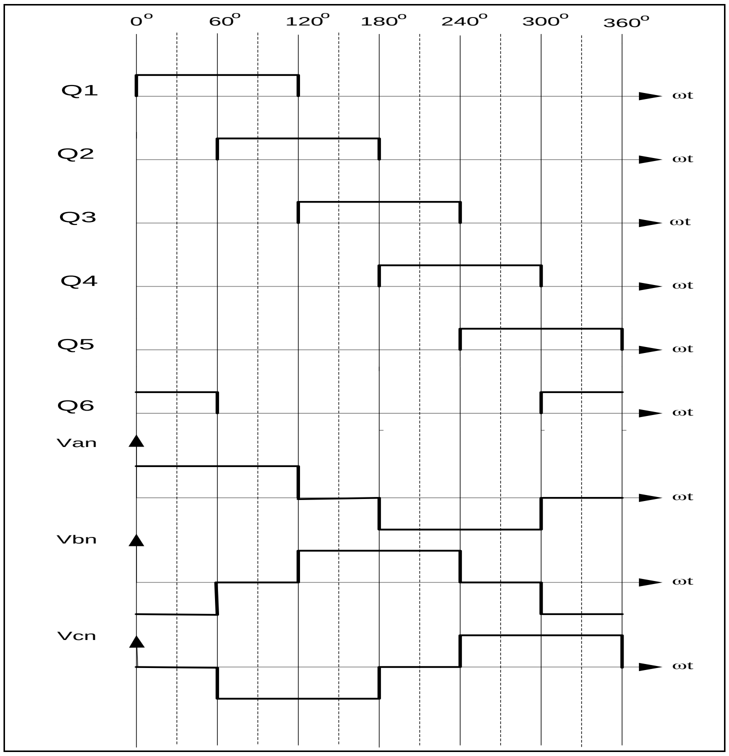


Figure 2.10 Gating signal for 120-degree conduction (Rasyid, 2004)

This switching sequence follows the commutation shown in Table 2.1. At any instant time, two power switches is ON. For example during the first 60-degree, Q1 and Q6 is turned ON. Therefore, at any time, two load terminals (Y-connected) are connected to the DC supply and the third one is left open. The potential of this open terminal depends on the load characteristics and would be unpredictable (Rasyid, 2004). When the next 60-degree occur, Q1 and Q2 will ON while Q6 is OFF. Q1 remain ON for 120-degree and will turn OFF when the third commutation step occur. In this 120-degree conduction type, each power transistor will be turned ON for 120-degree and this will result in quasi-square voltage (Van, Vbn and Vcn) as shown in Figure 2.10.

In switch-mode converters for motor-drive applications, there are two devices which are primarily used: MOSFETs at low power levels and IGBTs in power ranges extended to mega watts level (Mohan, 2002). In this project, power

MOSFET is used as power switching devices of the bridge inverter. MOSFET is suitable as switching devices because of their low ON-state losses in low voltage ratings, fast switching speed and ease of control (Mohan, 2002). This project uses six IRF540N n-channel MOSFETs to structure three-phase bridge inverter. To turn ON the MOSFET completely, a positive gate-to-source voltage of 10 volts must be applied. Maximum drain current is 33A with drain-to-source resistance is 0.040 Ω. Maximum switching frequency allowed by this MOSFET is 1MHz. However this project uses PWM of 10kHz to switch ON the MOSFET (refer detail specifications in appendix). The gate-to-source voltage should continuously be applied in order to keep the MOSFET in its ON state. This MOSFET The inverter has three switches at high side and low side. The high side will be fed with PWM signal while the low side will be triggered with High or Low signal during commutation.

2.3.4 BLDC Motor Simulation

Simulation motor driver is a common and essential stage of developing motor drive system especially when it involves the use of microcontroller. Modern motor drive includes a lot of control algorithm to come out with better motor performance suitable for intended applications. In this case, BLDC motor drive which has a lot of controlling technique and basically is driven on electronic basis needs simulation model before being converted to hardware implementation. As this motor involves a lot of controlling mechanism, a lot of analysis need to be conducted in order to ensure the motor is running without significant errors that affect its performance.

Commercial software that can be used by researchers is MATLAB software from MathWorks Inc. It is a multinational corporation that specializes in mathematical computing software founded by Jack Little, Cleve Moler and Steve Bangert in 1984. MATLAB with its additional package Simulink, offers an analysis of various field of enginnering. Simulink is a component of Matlab used for modelling, simulating and analyzing multi-domain dynamic system. It works by modelling design system using basic graphical block diagramming tool and a customized set of block in its library. This software provides good analysis results and hence suitable for many engineering modelling.

Matlab Simulink can be used easily in modeling motor drive system. It even provides simulation model of motor drives using simpower block-set. To model the drive "manually", all the related mathematical equations can easily be modelled using basic block-set. As BLDC motor drive involves electronical commutation, the power electronic part and BLDC motor part can be presented in a set of block-set. The BLDC motor model can be modelled depending on the controlling technique and type of BLDC motor itself. From the complete model with correct mathematical equations and operation flow, the output such as speed, torque and phase current can be monitored.

To produce a complete design that can be commercialised, it starts with research and development. For simulation stage, very powerful, trusted and well-recognized software is needed. Besides Matlab Simulink, there is a few other software available to simulate the designed circuit on hardware basis. One of them is Proteus VSM (Virtual System Modelling) from Labcenter Electronics in UK. It is currently the only package available with a comprehensive range of microcontroller model (Bates, 2006). Therefore for application such as BLDC motor drive that includes MCU as its primary controller, this software suits very well. Proteus VSM covers almost all popular microcontrollers from PIC, ATMEL, Motorolla, NEC, etc. In addition, Proteus VSM is the most complete package available at the moment for designing and testing embedded applications, providing an extensive range of passive and active components, mixed mode simulation and interactive peripheral hardware (Bates, 2006). With this software, for the first time ever, it is possible to develop and test such designs before a physical prototype is constructed (Su, 2010).