STUDY OF PHASE ADVANCE ANGLE CONTROL METHOD FOR BRUSHLESS DC (BLDC) MOTOR

By

MUHAMMAD NAJMUDDIN BIN ABU BAKAR

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
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for the Degree
Bachelor of Engineering (Hons)
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CERTIFICATION OF APPROVAL

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Approved:

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September, 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD NAJMUDDIN BIN ABU BAKAR

ABSTRACT

The brushless DC (BLDC) motor is recognized by the linear speed to voltage and torque to current. It has high fast dynamic response and high power density with high proportion of torque in sprite of small size drive. However, it is difficult to conventional BLDC motor to drive at high speed operating mode (limited top speed). It is because of the torque and speed response characteristic of the motor at high speed operating mode are deteriorated by the motor inductance components in stator winding. Phase advance angle method is one method used to control the phase current and improve torque and speed response at high speed operating mode of BLDC motor. This project concentrates on the operation of BLDC motor under high-speed motoring mode. Extended simulation results prove the validity of phase advance angle control method, considering lossless motor operation and the same parameters of an actual BLDC motor. In this project also, the results of laboratory testing are demonstrated to prove the compatibility of the purposed phase advance motor drive on actual BLDC motor. Both simulation and experimentation results confirm that phase advance angle control method is capable to extend the speed beyond the designed motor speed.

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In the name of Allah, the Most Gracious, the Most Merciful. Praise to Him the Almighty that His blessing and guidance in giving me strength, courage, patience, and perseverance to endure this Final Year Project. Hereby, I am glad to express all my appreciation to everyone who helped me through this Final Year Project.

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MUHAMMAD NAJMUDDIN BIN ABU BAKAR

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LIST OF ABBREVIATIONS

DC	= Direct Current
BLDC	= Brushless Direct Current Motor
FYP	= Final Year Project
EMF	= Electromagnetic Force
CPA	= Conventional Phase Advance
PWM	= Pulse Width Modulation
VFI	= Voltage Fed-Inverter

NOMENCLATURE

V_{dc} = dc supply voltage

T_r = rated torque

P_r = rated power

P = number of poles

N_b = base speed in rpm

N = rotor speed in rpm

n = relative speed = N/N_b

E_b = peak phase to neutral back emf at base speed

E_n = peak phase to neutral back emf at relative speed n

= n E_b

R = motor resistance

L =motor inductance

M = mutual inductance

$L_o + L_s$ = leakage plus self inductance

Ω_b = base speed in electrical rad/sec

CHAPTER 1

INTRODUCTION

1.0 Project Background

The permanent magnet brushless DC (BLDC) motor is one type of motors which quickly has gained attention and widely used in industries such as automotive, aerospace, household appliances, industrial automation equipments and instrumentation. As in conventional DC motors where they use mechanical commutator and brushes, they are subject to wear and require maintenance. BLDC motors are electronically commutated which make them virtually maintenance-free motor [1, 2]. Although in terms of present-day technology, BLDC motor and conventional DC motors are said to have similar in their static characteristics, actually they have differences in some aspects. The most significant difference is their mechanical structure. A conventional DC motor is a type of motors which designed to be run from a direct power source and it is internally commutated. In a typical DC motor, the permanent magnets (stator) are at stationary position and the spinning armature contains electromagnetic called the rotor [3, 4]. Even though the construction of conventional DC motor is simple and cheap to manufacture compared to BLDC motor, but it has a lot problems. Some of disadvantages of conventional DC motor are:

i) The brushes restrict the maximum speed of the motor
ii) The brushes action (making/breaking connections) produces sparks and electrical noise
iii) The brushes limit the number of poles that armature can have
iv) The motor is harder to cool since it have electromagnetic in the center of motor.

Unlike brushless DC motor, it is referred as a Direct Current (DC) type motor because of DC power is applied to various stator coils in predetermined sequential pattern in order to drive the coils. BLDC motor is effectively an AC motor which electronically commutated via an integrated inverter, which produces an AC electric signal from DC electric source to drive the motor, additional sensor and electronics control the inverter output. This type of motor has permanent magnets on the rotor and contains electromagnetic on the stator. Table 1 shows other comparison of conventional DC motor and BLDC motor.

Table 1: Comparison between Conventional DC Motor and Brushless DC (BLDC) Motor [1, 2].

	Brushless DC (BLDC) motors	Conventional motors
Winding connections	The simplest grade: • 2-phase connection Normal grade: • Y-connected 3-phase winding with grounded neutral points Highest grade: • Δ- connected or Y-connected 3-phase connection	Ring connection The Simplest: • Δ-connected
Commutation method	Electronics switching using transistors	Mechanical commutation (need contact between commutator and brushes)
Distinctive features	Free maintenance Lost-lasting	Quick response and excellent controllability Commutator and brushes subject to wear and need regular maintenance
Reversing method	Rearrange logic sequence	Applying reverse terminal voltage
Detecting method of rotor's position	Hall element, optical encoder, etc	Automatically detected by brushes

Referring to Table 1, the comparison is made based on type of winding connections, commutation method, distinctive features, detecting method of rotor's position and method for reverse motoring. From the table, it shows BLDC motor have many advantages over conventional DC motor. Thus, it is preferred by many industries especially for many applications.

1.0.1 BLDC motor types

BLDC motor can be categorized based on its phase number, flux direction, construction and Back EMF production. BLDC motor can be in single phase, two phase or three phase. Out of these, three phase motors are the most popular and widely used in industrial applications. Physically, there are two types of BLDC motors: in-runner and out-runner [5, 6]. Out-runner motors have permanent magnets arranged around the inside of a can that is then attached to the shaft. The electrical cols are located in the center of the motor with the can and its magnets running on the outside. The other BLDC motor type based on construction is in-runner motor type. Unlike out-runner motors, in-runner motors have their magnets attached directly to the motor shaft and the motor coils surrounding the shaft and magnet. For in-runner motors, the efficiency is directly proportional with motor rpm. The faster a motor spins, the more efficient it will be. Table 2 shows the differences between in-runner and out-runner types of BLDC motor.

Table 2: Differences between Out-runner and In-runner Types of BLDC motor [5, 6}.

 **Out-runner Type**	 **In-runner Type**
• Less efficient compared to in-runner • Low rpm, high torque • Silent • No gearbox required	• More efficient compared to out-runner • High rpm, low torque • More noise production • Required gearbox

BLDC motor can also be classified in terms of flux direction into two types: axial and radial flux [7, 8]. Figure 1 shows the axial flux BLDC motor topology. Usually axial flux BLDC motor is in disc shape. This type of motor differs from the other types of motors. The difference is not the magnet construction shape but the flux direction and the shape of the motor. The flux goes through the radially from the rotor axe.

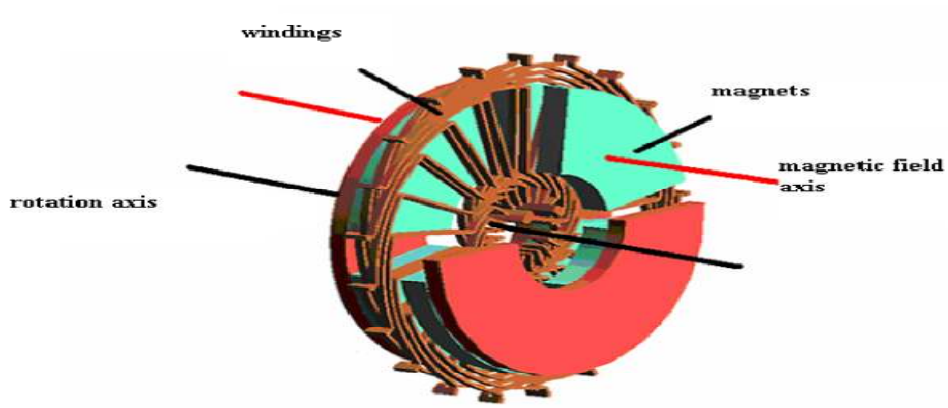


Figure 1: Axial Flux BLDC Motor Topology [7, 8]

In axial flux machines, flux goes through the axe direction and the shape of the motor is also disc type. Another type of flux direction is radial flux BLDC motor. Figure 2 shows the radial flux BLDC motor topology. This type of motor is commonly used in servo applications. The motor axial length is usually longer and the inertia of the motor is kept small in order to have small response time to any changes in load.

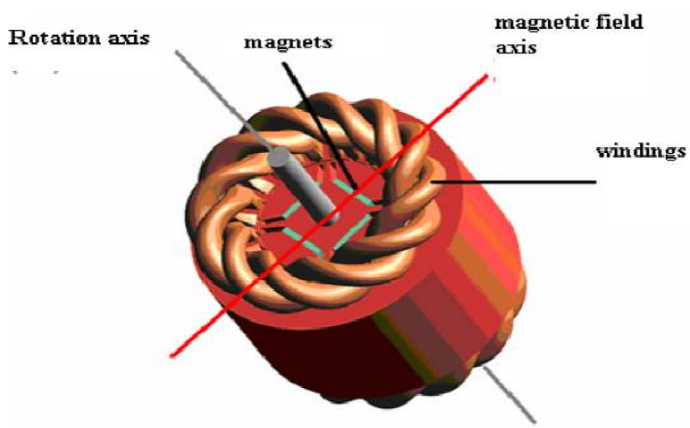


Figure 2: Radial Flux BLDC Motor topology [7, 8]

Other criteria to extinguish BLDC motor is based on back EMF generation [9, 10]. According to Lenz's Law, back Electromotive Force (EMF) is a voltage generated at each winding due to BLDC motor rotation and this voltage opposes the main voltage supplied to the winding. Equation (1) is the back EMF equation according to Lenz's Law.

$$Back\ EMF = (E) \propto NlrB\omega \qquad (1)$$

where: *E* is the supplied voltage

N is the number of winding turns per phase

L is the length of the rotor

r is the internal radius of the motor

B is the rotor magnetic field density

ώ is the motor's angular velocity

Based on Eq (1) , the polarity of back EMF is in apposite direction of the energized voltage and the magnitude depends mainly on three factors:

i) The number of turns in stator winding
ii) Angular velocity of the rotor
iii) Magnitude field generated by the rotor magnets.

Commonly there are two types of brushless DC (BLDC) motors: sinusoidal-type and the well known trapezoidal-type. Figure 3 shows the trapezoidal back EMF produced by trapezoidal-type motor and sinusoidal back EMF produced by sinusoidal-type motor. In addition to the motor characteristic, the phase current is also trapezoidal and sinusoidal depending on types of motors.

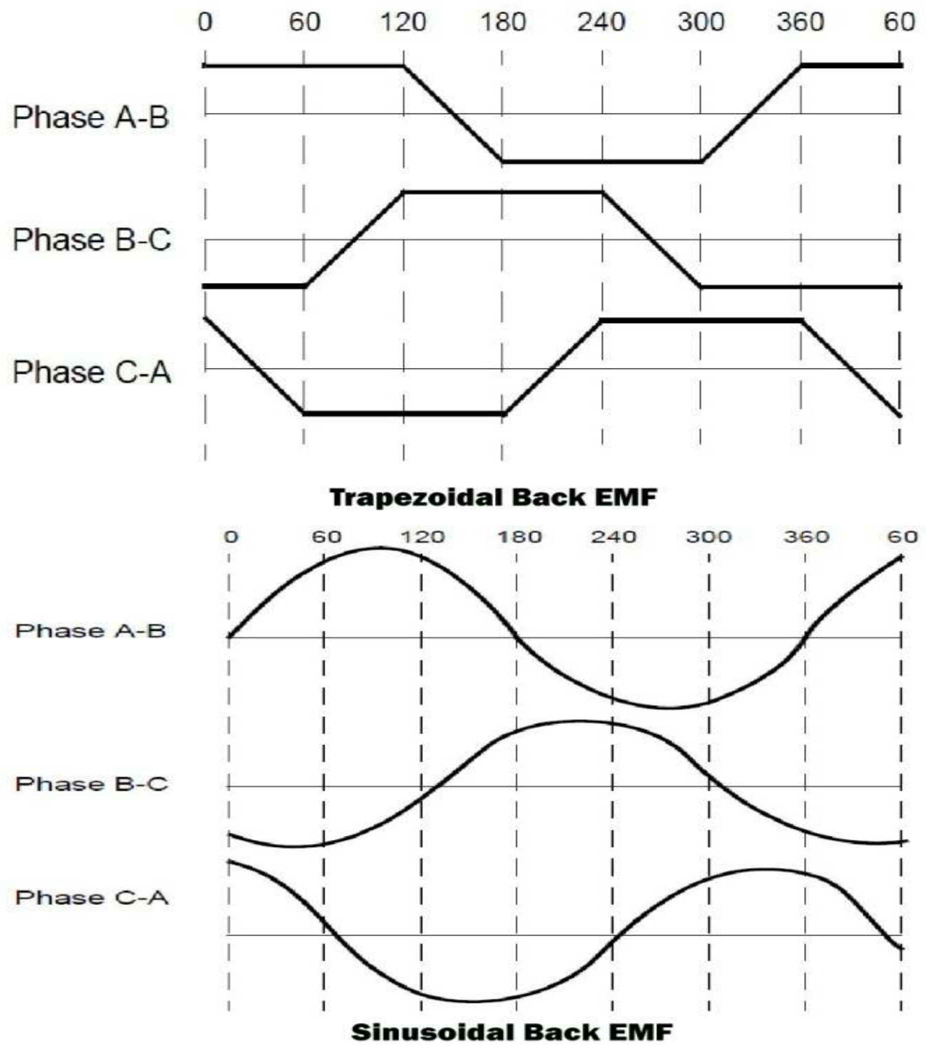


Figure 3: Back EMF waveforms produced by trapezoidal-type and sinusoidal-type respectively. [9, 10]

These types of back EMF generations are based on motor physical construction. Some physical conditions that lead to trapezoidal back EMF are:

i) No stator or magnet skew
ii) Discrete magnet poles with uniform magnetization
iii) Concentrated windings.

These conditions produce sharp transitions in the flux linkage which give the trapezoidal back EMF waveform. For sinusoidal back EMF, some of physical condition which lead to the production are:

i) Sinusoidal magnetization
ii) Stator and/or magnet skew
iii) Overlapped or sinusoidally-distributed winding
iv) A coreless stator (no steel lamination)

BLDC motors have many advantages over conventional DC and induction motors [11, 12]. Some of the advantages are long operating life, noiseless operation, high dynamic response, higher speed ranges, better speed versus torque characteristic and highest power capability for a given size and weight. Such advantages are very useful for many applications where efficiency, space and weight are critical factors for example in land vehicle drive systems. This project mainly focuses on the application of BLDC motor for electric vehicle.

1.2 Problems Statement

Although continuously growing researches by many countries and companies on the improvement of electric vehicles, much of these activities are focused on the battery technologies. This is because many electric vehicles have limited power sources. Nevertheless, it is substantial to improve the other areas of electric vehicles systems in order to achieve greatest performance from the present battery technology. One of the methods is by maximizing the utility of the BLDC motor with a particular battery as well as minimization of the electronics necessary to drive it. This project is to develop a method to improve the drive system for electric vehicles application.

1.2.1 Problem Identification

As mentioned earlier, there are two different flux direction types for BLDC motor: sinusoidal and trapezoidal. The trapezoidal-type is famous due to lower price and the ability to produce more output power per frame size than other kinds of motors. This project will focus on trapezoidal flux BLDC motor. Although this type of BLDC motor is commonly used, there are two main disadvantages. The first disadvantage is that it is difficult to conventional BLDC motor to drive at high speed operating mode (limited top speed) and the second disadvantage is the generation of more torque ripples compared to sinusoidal-type [27]. In most application, particularly for electric vehicles, a wide range speed control of motor drives is necessary. This project will focus on overcoming the first disadvantage using a method called "Phase Advance Angle Control Method" and the method to extend constant power speed range of BLDC motor will be demonstrated.

1.2.2 Significant of Project

This project is important and can be used as reference to improve performance of a BLDC motors especially in transient operations such as vehicles propulsion power and torque requirements. Although this method has been introduced in early 90's, they are not given detailed attention by automotive industries since at that time internal combustion engine was commonly used. Nowadays, since economical and environmental factors are the main priorities. A lot of researches have been conducted to improve the electric and hybrid vehicle.

1.3 Objectives

The main objective of this project is **to study the effect of Phase Advance Angle Control Method on the 3-phase permanent magnet brushless DC (BLDC) motor**. Within this main objective, there are 3 sub-objectives. They are:

1. To develop and simulate the 3 phase brushless permanent magnet DC (BLDC) motor model and motor drive using MATLAB Simulink.
2. To test and validate a phase advance control algorithm on 3 phase brushless permanent magnet DC (BLDC) motor model and motor drive using MATLAB Simulink.
3. To test and validate the proposed Phase Advance Angle Control Method in series of experiments.

1.4 Scope of Research

There are two types of operating modes for BLDC motor: normal speed mode (below base speed) and high speed mode (above base speed). This project will focus on high speed operating mode. Figure 4 shows the conventional drive system for BLDC motor block diagram. The conventional motor drive consists of controller, gate drive, inverter and three-phase BLDC motor. The highlighted components in Figure 4 are discussed in this project. Motor drives algorithm for Phase Advance Angle Control Method will be developed. The model then will be verified and tested using real BLDC motor. The fabrication of motor drive which consists of gate driver and inverter will be inserted in the project's methodology.

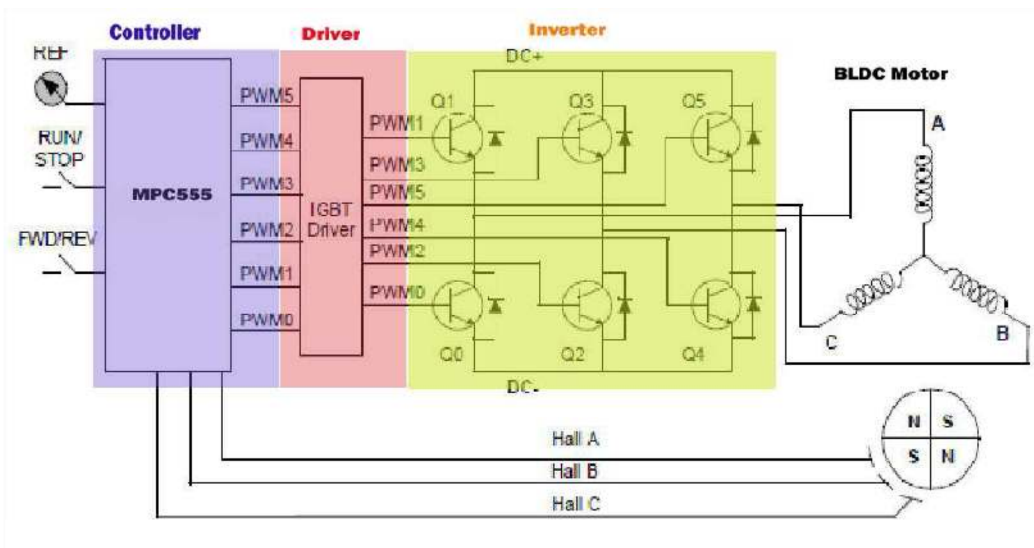


Figure 4: Phase Advance Drive System for BLDC Motor. [1, 2]

1.5 Relevancy and Feasibility of Study

Generally, to conduct a research mentions to the practical way in which the research was conducted according to the systematic attempts to generate evidence to answer the research question. Thus, relevancy and feasibility of any conducted project or research is crucial in order to determine the volubility of the project.

1.5.1 Relevancy of Study

Brushless DC (BLDC) motor is characterized by linear torque to current and speed to voltage. It has low acoustic noise and fast dynamic response. Furthermore, it has high power density with high proportion of torque to inertia in spite of small size drive. The BLDC motors are used widely in industry especially in automotive. However, at high speed operation, torque and speed response characteristic are deteriorated by motor inductance components in stator winding. Eventually, it is difficult for BLDC motor requires a wide range of operating speeds. By studying Phase Advance Angle Control Method, the weakness of BLDC motor can be rectified.

1.5.2 Feasibility of Study within the Scope and Time Frame

Throughout the first semester for final year project (FYP I), literature review on Phase Advance Angle Control Method has been conducted as many as possible. It covers fundamentals, methodologies, equations used, BLDC motor drive model and all related applications. The model for phase advance and BLDC motor has completely developed. Since the model only requires knowledge of motor parameters, it has been done within early of second semester.

After the full model of motor drive and BLDC motor have been developed, the experimentation is carried out. Based on Gantt chart, this project is feasible to be completed within 2 semesters.

CHAPTER 2
LITERATURE REVIEW

2.0 Reviews on Effect of Phase Advance Angle Method for BLDC Motor

Brushless DC (BLDC) motor has many advantages such as high power density, high efficiency, high dynamic response, good controllability and long operating life. In most application where high power BLDC is needed, particularly for electric vehicles, tools machines, etc, it is necessary to have wide range speed control of motor drives [1, 2, 13]. Figure 5 shows torque-speed envelope for BLDC motor.

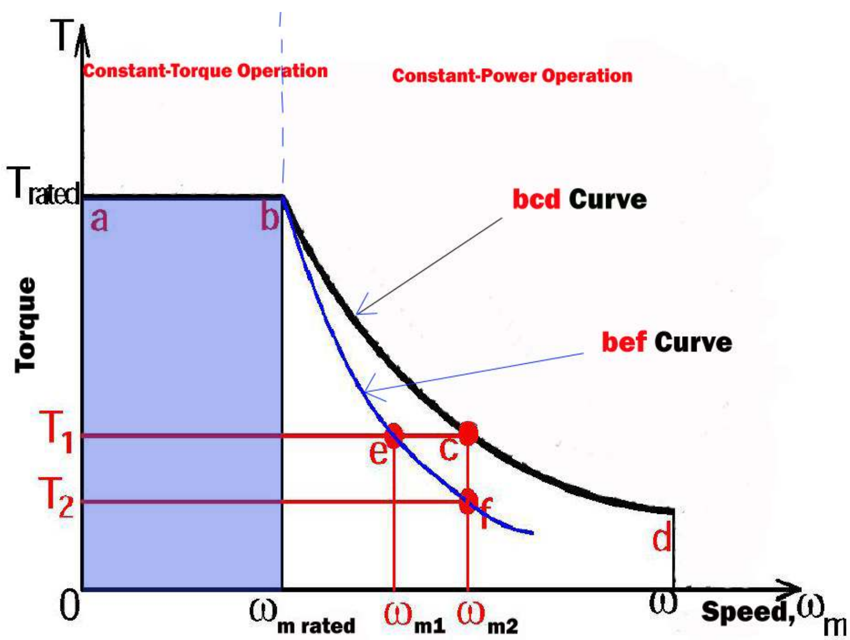


Figure 5: Torque versus Speed Envelope for BLDC motor. [26]

Referring to Figure 5, when the motor operates at lower speed less than base speed (**$\acute{\omega}_{mrated}$**), the motor drive will be required to provide a constant output torque known as “Constant-Torque Operation”. When the motor operates above the base speed, the load torque will decrease with the speed. In this study, base speed can be defined as the highest speed at which rated torque can be developed in the low speed current regulation mode. In electric vehicle application, instead of producing constant output torque, constant-power operation is preferred because it can substantially reduce the size and cost of motor drive. However, a conventional drive system cannot operate along the ***bcd curve*** which known as the power limit curve, where it is maximum speed for a given load torque, due to voltage saturation. The conventional motor drive system can only operate along the ***bef curve***. It needs additional special control technique to extend the constant power speed range of the motor. Previously, there are several methods introduced to extend limit such as field weakening control method, overlapping method and PWM chopping method [14-17], this project it will focus on one method called Phase Advance Angle Control Method.

Typically, a conventional three-phase inverter with 120 electrical-degrees and two-phase conduction scheme is used to drive a three-phase BLDC motor. Electrical degree is a unit of time measurement as applied to alternating current, 1 complete cycle is equal to 360 electrical-degrees [18]. The basic idea of the scheme is to control the line current as a rectangular waveform as well as to keep it in phase with the corresponding phase back EMF in order to generate the optimal constant output power as shown in Figure 6.

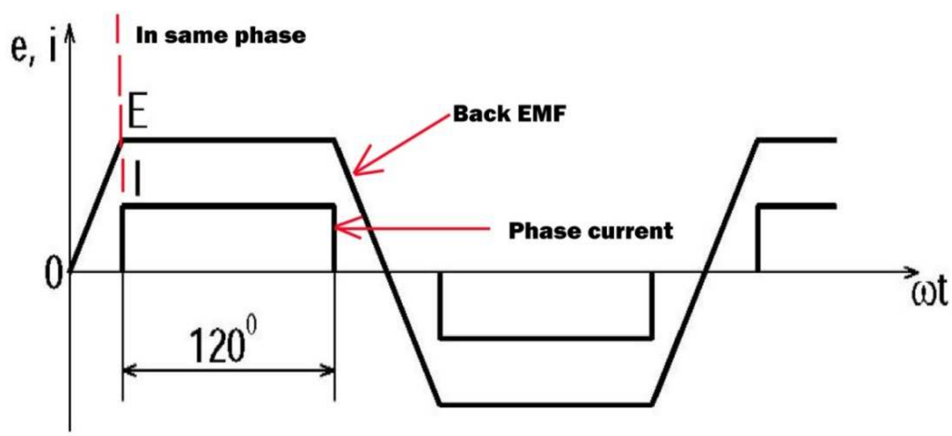


Figure 6: Typical phase current and back EMF waveforms of BLDC motor. [27]

Figure 6 shows the phase current is in the same phase with back EMF. In addition for the control scheme, the components of line current and back EMF are also in phase with each other.

Figure 7 shows a conventional controller for BLDC motor drive. The motor drive consist of a common six transistor voltage-fed inverter (VFI) bridge, namely S1, S2,S3,S4,S5,and S6. Each transistor having a parallel bypass diode and also three phase BLDC motor [19]. The inverter power switches are generally controlled using pulse width modulation (PMW) patterns. In the brushless DC motor (BLDC) motor model, L_s and R_s are the equivalent phase winding resistance and phase winding inductance respectively. e_{an}, e_{bn} and e_{cn} representing the back EMF for each phase.

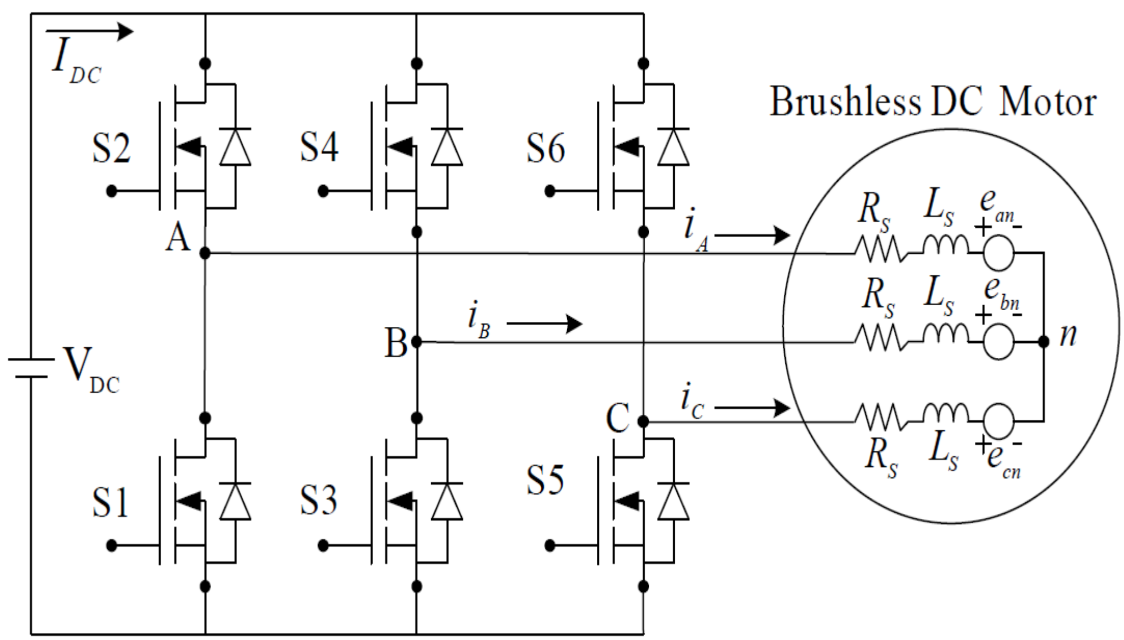


Figure 7: Conventional Controller [19]

The same type conventional controller will be used to control a trapezoidal type of back EMF BLDC motor in this study. Generally for trapezoidal type of back EMF BLDC motor, the stator currents i_A, i_B, and i_C are controlled to have rectangular waveforms and be in phase with the corresponding back EMFs e_{an}, e_{bn} and e_{cn} respectively. If a fast inner control loop is applied to the motor drive such that the direct control loop or the current controls loop, the pulse width modulation (PWM) duty cycle is controlled in one switching cycle to achieve desired goals.

Figure 8 shows the approximate resultant waveforms of stator currents and back EMFs for conventional controller commutation in Figure 6.

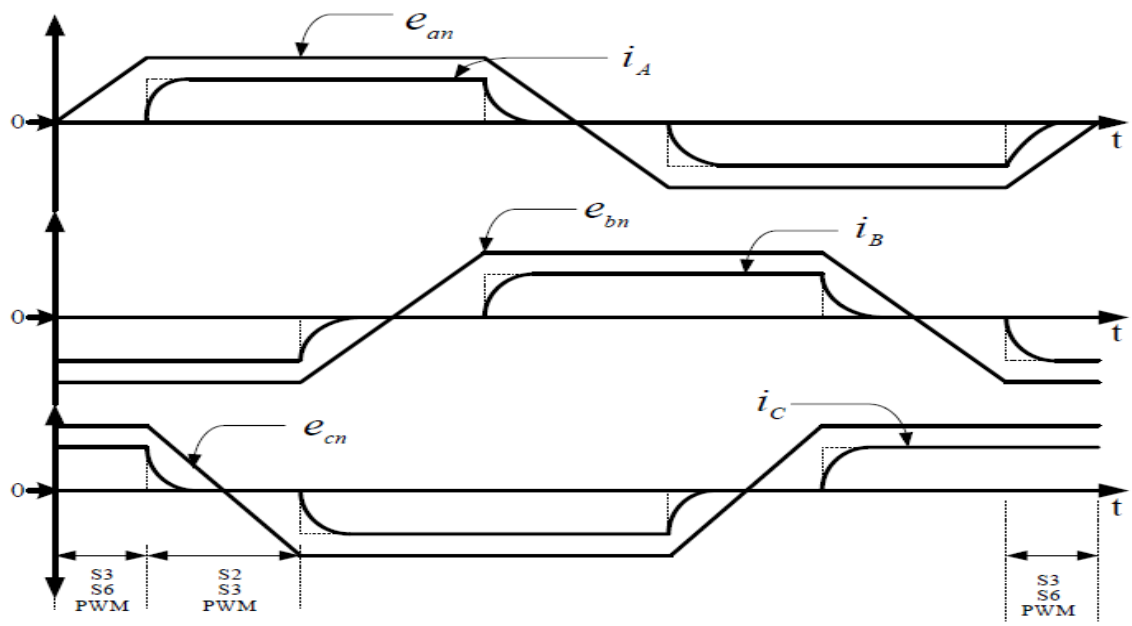


Figure 8: Approximate resultant waveforms of stator currents and back EMF for conventional controller commutation in Figure 7 [19].

Referring to Figure 8, taking the commutation period between "S3 S6 PWM" and "S2 S3 PWM", phase current i_A starts increasing toward the demanded current amplitude as well as phase current i_C starts decreasing to zero. The generated phase current waveforms are not perfectly rectangular in shape as shown in Figure 6. This is due to inductance components in stator windings [20]. These waveforms satisfied the theory of conventional controller [1, 2] which is in phase with back EMF. However in practical, phase current is not achieved to rated current level instantaneously due to the inductance components of stator windings. At low speed, the inductance effect is negligible, thus this will not cause any serious problem for controlling the BLDC motor. However, at speed which above the rated speed, the motor performance will be significantly deteriorated [21]. The inductance reactance of the stator windings results in a significant time delay which cause the time taken for the current to reach its rated value is a large portion of a phase conduction interval. The rated current level is only attained at the end of the interval.

Hence, an optimization of drive system is demanded to improve the performance of phase current. In order to overcome this issue, a method called Phase Advance Angle Control Method was introduced in 1995, by C. C. Chan *et al*.. They proposed that this method could be used to extend the constant power speed range of BLDC motor [22], thus overcame the weakness of BLDC motor. This proposed method can be used by shifting (advancing) the original applied voltage in Figure 6 to specific range of angle as shown in Figure 9. In other words, this technique is achieved by injecting the current earlier from the back EMF. Figure 9 shows waveform of constant-power operation (high speed operating mode control by phase advance).

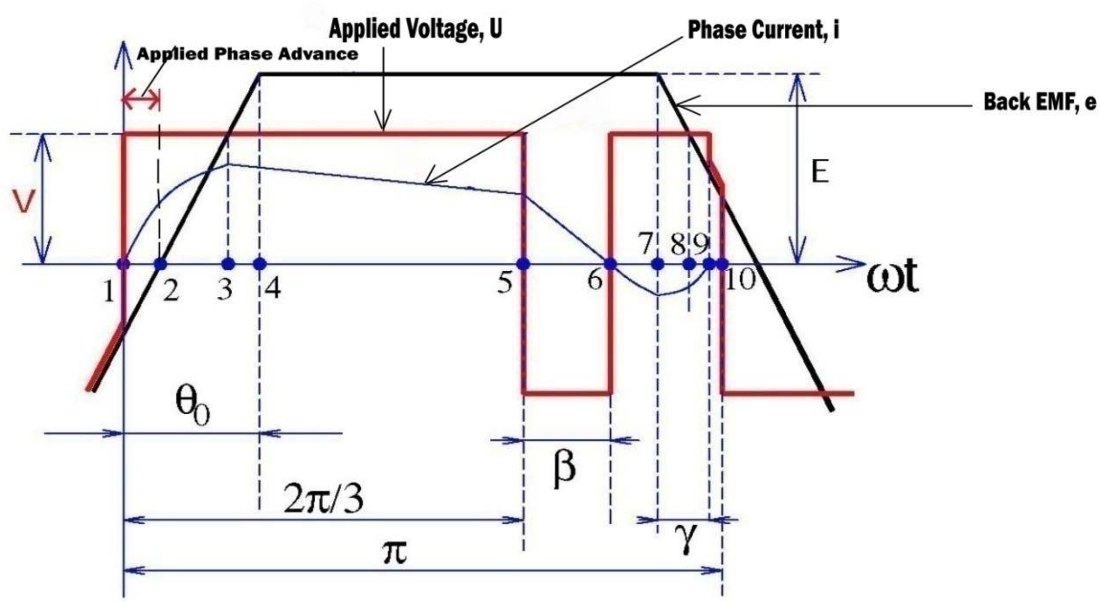


Figure 9: Sample of Waveform at Phase Advanced Angle [27]

Figure 9 shows that the phase current leads (advanced) the back EMF at certain value of angle in stage 1- 2 (blue node in Figure 9). The main idea of this approach is explained as follows. There are two types of electromotive forces in the phase winding of a BLDC motor. There are back EMF which is induced by the magnet field of a rotating of permanent magnet and transformer electromotive force which is induced by the transformer action of the time-varying stator current in the phase winding. The concern is when the BLDC motor operates above the base speed, the phase-current leads the phase EMF. There is a corresponding advance angle for every given reference speed. In C. Chan *et al,* they purpose a larger phase advanced angle to generate larger leading angle so that a better performance could be expected [22].

According to Chan *et al.* , in high speed operating mode, the winding phase resistance is negligible since the back EMF is higher than the applied voltage (e > U). So they represent the 3-phase permanent magnet BLDC motor as shown in box on Figure 10 [22].

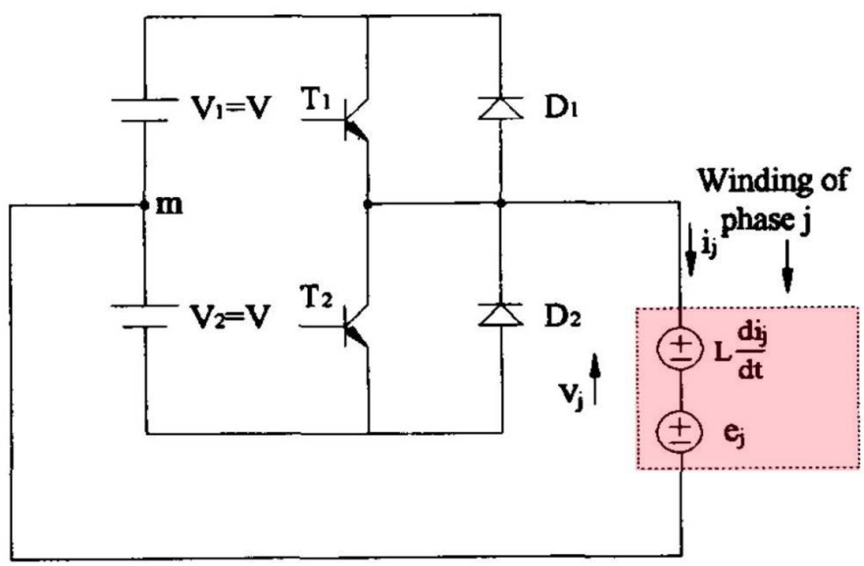


Figure 10: Equivalent per Phase Circuit Proposed in Chan et al paper. [17]

In 1997, C. S. Cambier *at al*. have invented the brushless DC motor using phase timing advancement (Conventional Phase Advance) [23] but the patent had same limitations with C. Chan [24]. This method requires equivalent motor inductance per phase which must be sufficiently large. Nowadays, the BLDC motor is usually constructed from rare-magnet materials such as samarium-cobalt or neodymium-iron-boron and these materials have low internal inductance. Depending on the value of inductance, the motor current magnitude may be of several times greater than rated when operating in high speed mode as mentioned by J. S. Lawler *et al.* [24, 25]. J. S.

Lawler *et al.* have proposed a better motor drive inverter circuit diagram known as Dual Mode Inverter Control (DMIC) and BLDC motor as shown in Figure 11 [25].

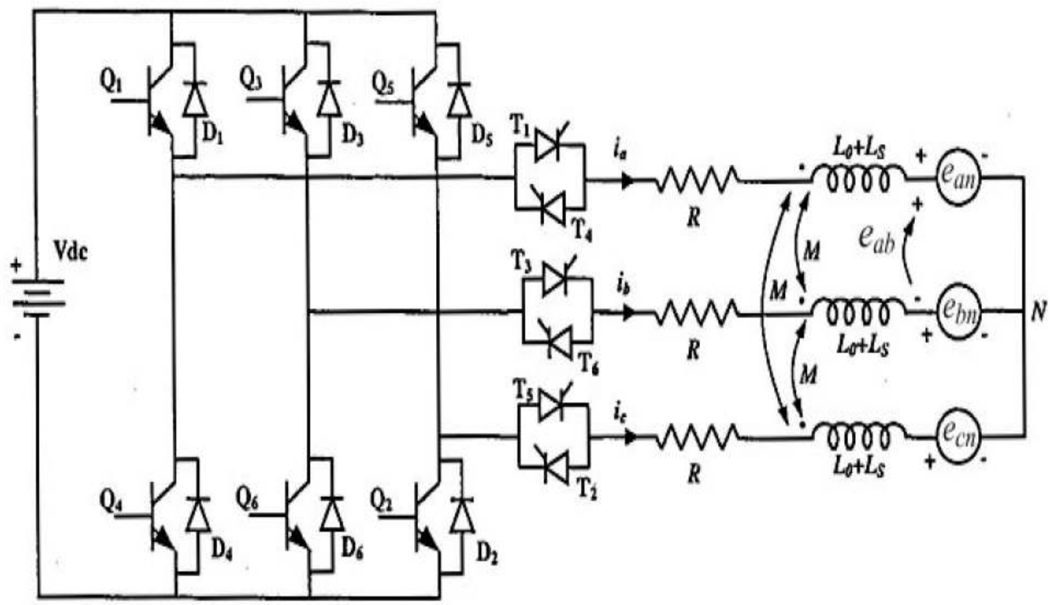


Figure 11: Dual Mode Inverter Control (DCIM) topology and BLDC Motor model. [24]

Referring to Figure 11, the Dual Mode Inverter Control (DCIM) consists of a common six transistor voltage-fed inverter (VFI) bridge. Each transistor has a parallel bypass diode, which is interfaced to the motor through an AC voltage controller. The AC voltage controller consists of three pairs of anti-parallel silicone controlled rectifiers (SCRs). The purpose of the thyristors is to block undesired conduction of the bypass diodes during high-speed operation. During this operating mode, the magnitude of motor back EMF is substantially larger than the value of DC supply voltage. Since the bypass diodes form a diode rectifier between high-voltage motor back EMF and the DC supply, there is a natural tendency towards flows through the series combination of thyristor and transistor although during commutation the current flow may be through a bypass diode and thyristor. DCIM is capable to control low inductance BLDC motor at high-speed motoring mode.

In this project, when all loss mechanism (such as skin effect on winding resistance, friction, eddy currents and hysteresis current) are neglected, the constant power speed range (CPSR) of BLDC motor is infinite when it is driven by Dual Mode Inverter Control (DCIM). The proposed advance angle is from 0° to 60° leading to infinite CPSR.

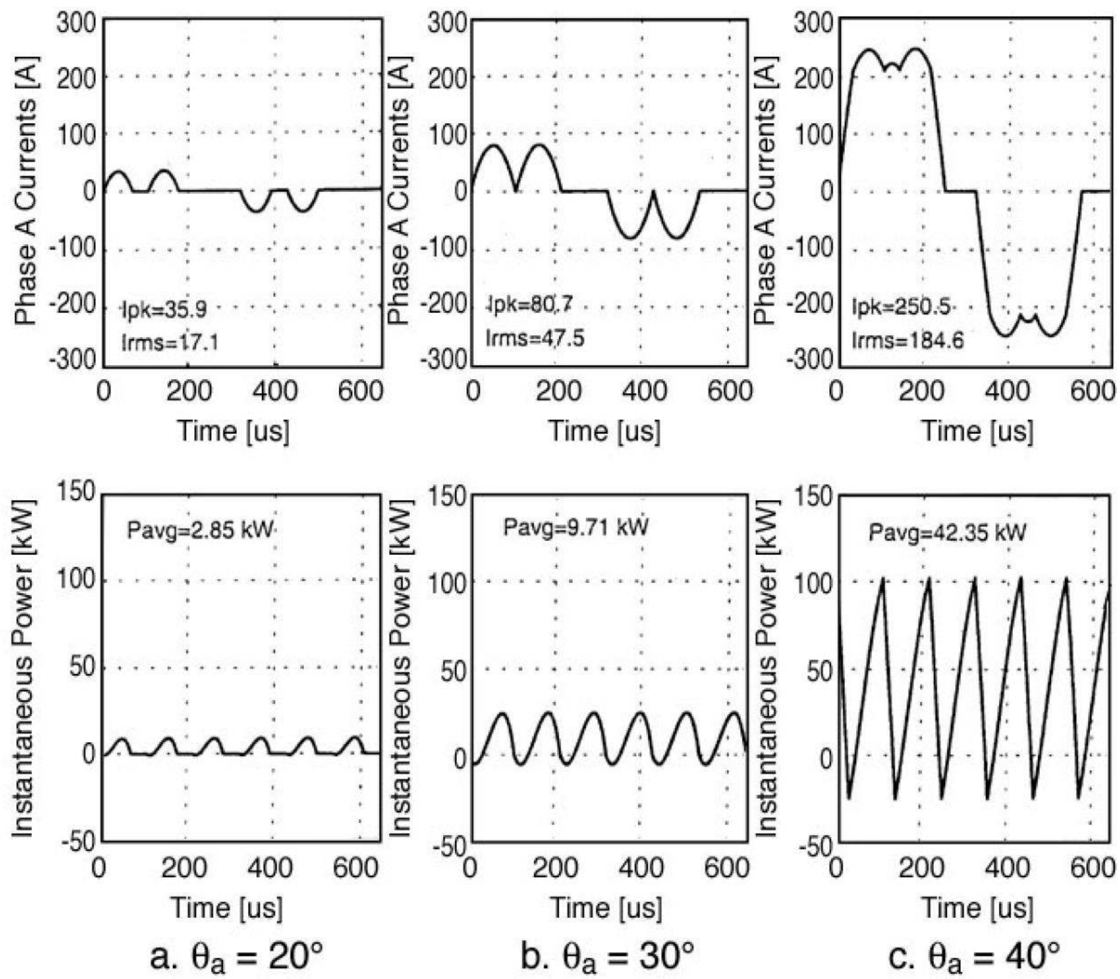


Figure 12: Instantaneous phase A motor current at 15600 rpm (6 times of base speed). [24]

Figure 12 shows simulation results for advance angle at 6 times of base speed. In these simulation results, they have proven that even though the speed has been increased 6 times, the current is still under the motor's current rated value [24-25]. In physical drive, losses will limit the CPSR.

In 2007, B. Nguyen & M. C. Ta completed "The phase advance approach" by overcoming the weakness of method proposed by C. Chan *et al.* According to C. Chan *et al.* [22, 27], they only examined the phase current when the amplitude of back EMF is higher than the amplitude of applied voltage as shown in Figure 13 by assuming the winding resistance is negligible. However in real situation, the amplitude of the back EMF can be lowered than the amplitude of applied voltage and the phase winding resistance is not always negligible. Figure 13 shows the waveforms of phase advance when back EMFs lower than amplitude of applied voltage.

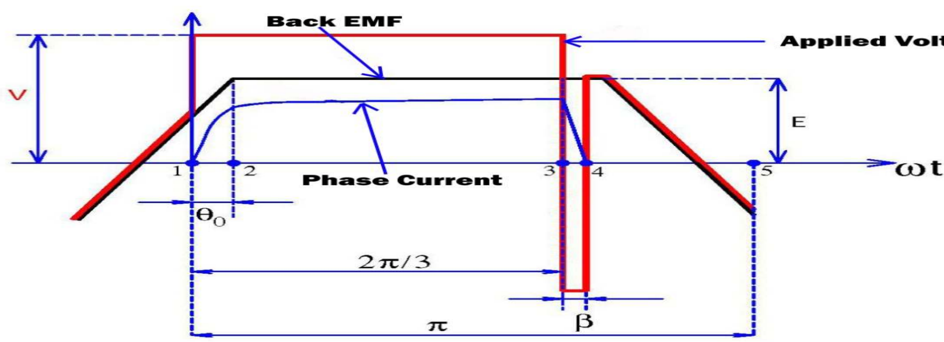


Figure 13: Waveforms of back EMF less than applied voltage, U. [27]

Referring to C. Chan *et al.,* they also proposed that the value of the phase advance was regulated by an approximate linear relationship with motor speed [22]. Also B. Nguyen & M. C. Ta proposed a more accurate curve since they had taken the stator resistance into consideration in their experiment [27]. A detail about these papers summarized in Table 3.

Recently, X. Tu & C. Gu had published a paper titled "Direct Torque Control of Novel Transverse Flux Permanent Magnet Motor Based on Phase Advance Commution" [28]. In this paper, they proposed transverse flux permanent magnet motor with BLDC Drive to be applied to direct drive electric vehicles. In their experiment, a direct torque control (DTC) with position sensors was employed instead of flux linkage observer. The purpose was to reduce torque ripple and obtain faster torque response where eventually was validated by MATLAB Simulink on the prototype. So fundamentally, an important improvement of BLDC motor control is phase advance method. Table 3 shows the summary of the literature review on this phase advance angle method.

Table 3: Review on Phase Advance Angle Method

Publication Year	Author(s)	Paper Title	Design Approach	Description
1995	C. C. Chan *et al.*	Novel Wide Range Speed Control of Permanent Magnet Brushless Motor Drives	• Present a novel approach for wide range speed control by phase advancement of phase current.	• The value of back EMF is higher than applied voltage during phase advancement and winding resistance is negligible. • Proposed to shift angle up to 30°
1997	Cambier *et al.*	Brushless DC Motor Using Phase Timing Advancement	• Patent Conventional Phase Advance (CPA) Method	• To overcome deficiencies of BLDC motors. • Switching amplifier for selective supplying current to respective phase winding in based on control signals output from detector (detect rotor postion)
2001	J. S. Lawler *et al.*	Limitation of the Conventional Phase Advance Method for Constant Power Speed Operation BLDC Motor	• Explaining the limitation of Conventional Phase Advance	• Identify key limitations of Conventional Phase Advance (CPA) • One of the limitations is CPA cannot been applied to BLDC motors which have low internal inductance.

2001	J.S Lawler *et al.*	Extending The Constant Power Speed Range of Brushless DC Motor through Dual Mode Inverter Control. (Part 1 and 2)	• Proposed a new inverter control topology and explaining the limitation of Conventional Phase Advance.	• Use new inverter control called Dual Mode Inverter Control. • Considering the low inductance of motor. • Simulation and physical testing on motor.
2007	B. M. Nguyen *et al.*	Phase Advance Approach to Expend the Speed Range of Brushless DC Motor.	• Completing the weakness of method proposed by C. C. Chan *et al.*	• Considering the case when back EMF lower than applied voltage during high speed operating mode. • Derive Mathematical Derivation of Phase Advance Approach\ • Proposed better phase advance curve.
2009	S. M. Sue *at al.*	A Phase Advanced Commutation Scheme for IPM-BLDC Motor Drives	• A phase advanced commutation by advancing the gating time of inverter.	• The approximate advanced phase angle is calculated according to information of rotor speed, duty cycle of inverter switch and stator winding time constant. • Modified basic control scheme.
2009	C. L. Chiu *et al.*	An Accurate Automatic Phase Advance Adjustment of Brushless DC Motor.	• Phase Advance approach by analyzing the induced voltage of the Hall sensor.	• Considering other harmonics components which influence the real phase advance angle. • Propose an improved circuit

				when harmonic components are considered.
2010	H. Kong *at al*	Study on Field-weakening Theory of Brushless DC Motor Based on Phase Advance Method.	• Restrain the increase of back EMF using transformer EMF action.	• An analysis is made on the field-weakening effect caused by the phase advance method of BLDC motor. • Deduces the mathematic expression of phase advance angle by utilizing the concepts of rms current.
2011	X. Tu & C. Gu	Direct Torque Control of Novel Transverse Flux Permanent Magnet Motor Based on Phase Advance Commutation	• Used novel transverse flux permanent magnet motor (TFPMM) with brushless DC drive to direct-drive electric vehicle	• Employed direct torque control (DTC) with sensors instead of flux linkage observer.

From Table 3, all designs are focused on improving the performance of BLDC motor. Phase advance can be achieved by many methods. Some examples of the methods are:

1. Adjusting the Hall sensors position at a leading position.
2. Advancing the inverter gating time such that the phase angle of the stator current can lead corresponding back EMF.

Among all methods, advancing the inverter gating time is more popular. This method is highly gaining attention by many researches since there is a wide area to be developed. Some of design approaches based on this method are new inverter scheme and different advance algorithm to drive the motor drive. In this study, Phase Advance Angle Control Method will be developed based on advancing inverter gating time and the algorithm to control the firing angle of inverter gates.

CHAPTER 3
METHODOLOGY

3.0 Project Workflow

To ensure a smooth flow progress in completing this project, there are 2 main steps involved. Figure 14 shows the project workflow. The workflow is based on Gantt chart for FYP I and FYP II.

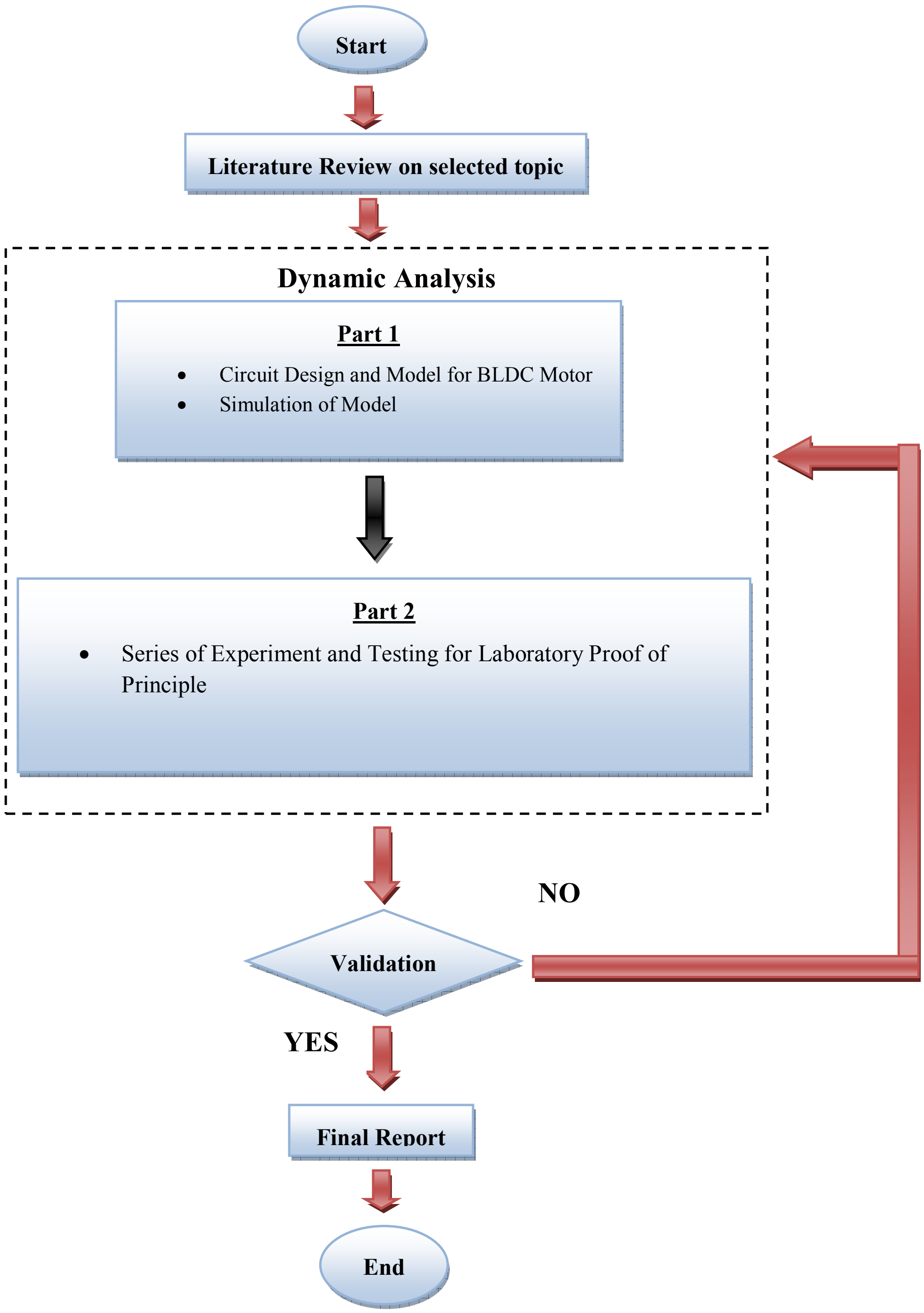


Figure 14: Project's Flowchart

Gantt chart

The project was started with literature review on Phase Advance Angle Control Method during the first week in the first semester of final year project. This step is continued until thirteen week in the second semester of final year project. The part 1 of this project started at the fourth week of FYP 1 as shown in Table 4. The progress for project completion is based on FYP 1 and 2 Gantt chart as shown in Table 4 and Table 5.

Table 4: Gantt chart Final Year Project I

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic: "Study of Phase Advance effect on BLDC motor"	■	■												
2	Literature Review on Topic Selection		■	■	■	■	■	■	■	■	■	■	■	■	■
3	Project Work (PART 1) - Circuit Design and Modeling				■	■	■	■	■	■	■	■	■	■	■
4	Submission of Extended Proposal						□								
5	Proposal Defense (Presentation)									□					
4	Project Work (PART 1) - Simulation							■	■	■	■	■	■	■	■
8	Project Work (PART 2) - Motor Drive Fabrication												■	■	■
9	Draft Report													□	
10	Interim Report														□

□ Important Date

■ Project Progress

Table 5: Final Year Project II

Gantt chart FYP II

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Literature Review on Topic Selection	■	■	■	■	■	■	■	■	■	■	■	■	■		
2	Project Work (PART I) - Circuit Design and Modeling	■	■	■	■	■	■	■	■							
3	Submission of Progress Report								□							
4	Project Work (PART I) - Simulation	■	■	■	■	■	■	■	■							
5	Pre - EDX											□				
6	Project Work (PART II) - Result Validation								■	■	■	■				
7	Draft Report													□		
8	Final Report														□	
9	VIVA															□

□ Important Date

■ Project Progress

3.1 PART 1- Simulation of Phase Advance Angle Control Method on BLDC Motor Model

In this dynamic analysis step, it is divided into 2 parts. In the first part, the model of the BLDC motor as well as the motor drive has been determined. Based on the parameters values which are obtained from the actual BLDC motor used in Part 2, the BLDC motor is simulated in the simulation software using MATLAB Simulink. Figure 15 shows the MATLAB Simulink brushless DC (BLDC) block diagram. It consists of a three-phase motor rated 1 kW which is fed by six-step voltage inverter. The inverter is a MOSFET bridge of SimPowerSystems™ library. The three-phase outputs of the inverter are applied to the PMSM block's stator winding. The load torque will also be applied to the machine's shaft and the inverter gates signals are produced by decoding the Hall Effect signals of the motor. The results such as speed in rpm and phase current are the main concern in this project since they will be compared with Phase Advance Angle Control Method. The first part of methodology was carried out during 5th week and as the first step, the model of common brushless DC motor fed by the conventional six-step inverter controller as shown in Figure 15 has been fully studied and simulated. In this model, there is a PI controller for speed regulation and the results for this model are shown in Figure 16 and 17.

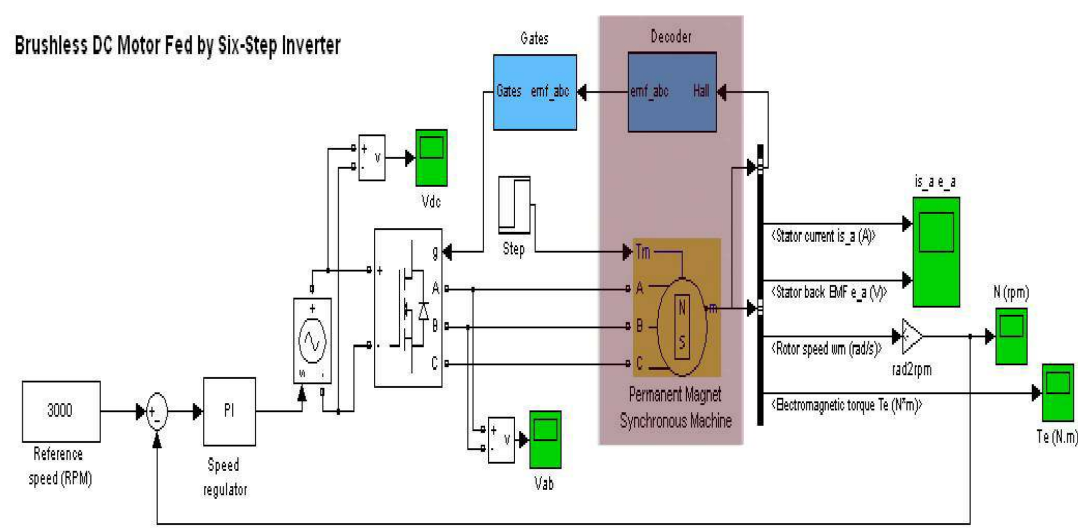


Figure 15: Brushless DC Motor Fed by Six-Step Inverter

Since the main purpose of this project is to increase the speed of BLDC motor without damaging the motor (current is below rated value), the graph for speed and current will be set as the reference for project progress. In figure 15, a value of 3000 rpm was set as reference speed and a torque 10 N.m was introduced at time 0.1 sec. The purpose of having speed regulator is to take a signal representing the demanded speed and drive the BLDC motor at the speed. It is done by measuring the feedback speed and comparing to current speed, then the controller will compensate with the changes. The responses of BLDC motor are observed and analyzed.

The response of the system is shown in Figure 16. Figure 16 shows the graph of speed rotor against time. Based on the response, the controller was compensated with the introduced load torque at 0.1s. The controller takes approximately 0.03 seconds to compensate with the load changes.

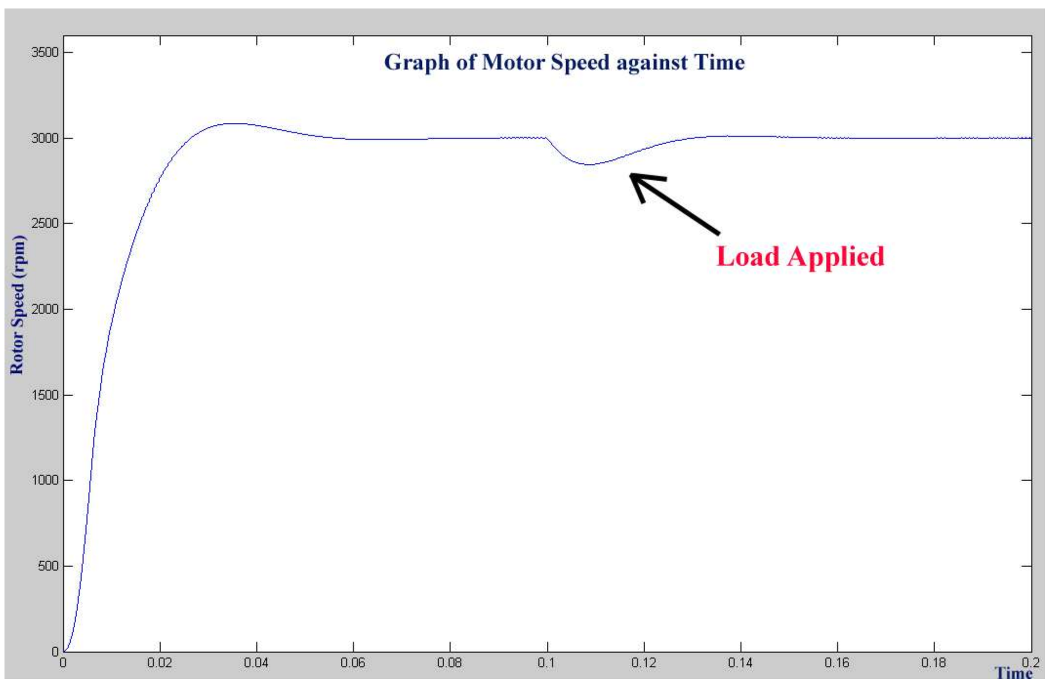


Figure 16: Motor Speed, rpm

Figure 17 shows the phase stator current for phase A. Phase B and C also have the same behavior of response but having phase delay. The phase current increase as the load torque increase.

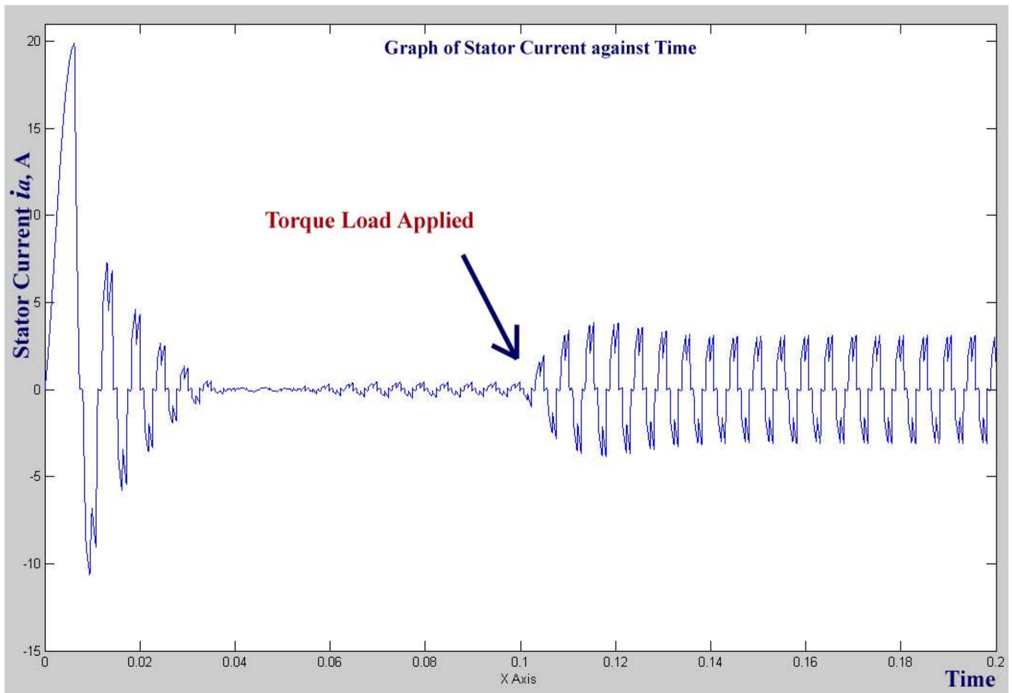


Figure 17: Stator Current and Electromagnetic Force

In order to reduce the complexity of the model, the controller is taken out and the reference speed has become applied voltage. This represents the limited supplied of electric vehicles. The controller is no longer required since the purpose of this project is not to maintain a process speed when disturbance is introduced but only to see the effect of phase advance on the speed of BLDC motor. Figure 18 shows the simulation model without controller. For this example, a voltage value of 96 VDC is applied to the model.

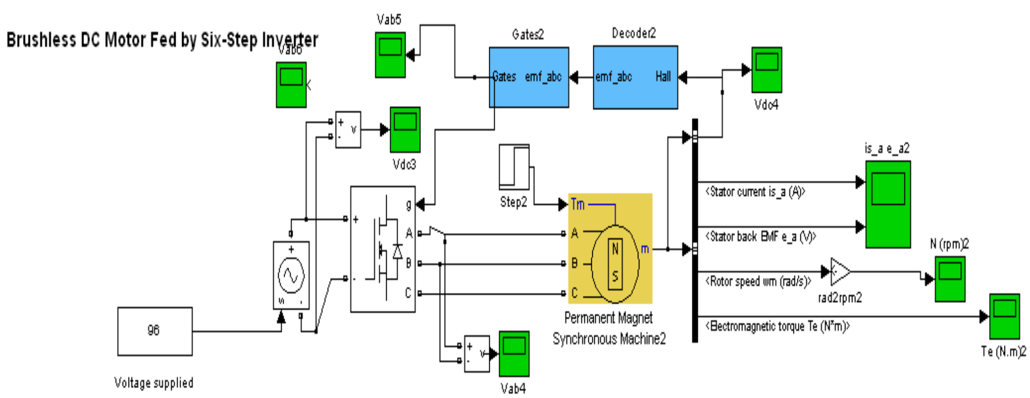


Figure 18: BLDC motor model without PI controller.

Then, phase advance angle is introduced to the model. Figure 19 shows the model with phase advance effect. Although this is not a proper technique, the purpose of this step is only to show the effect of phase advancement. The correct technique of Phase Advance Angle Control method will be discussed later.

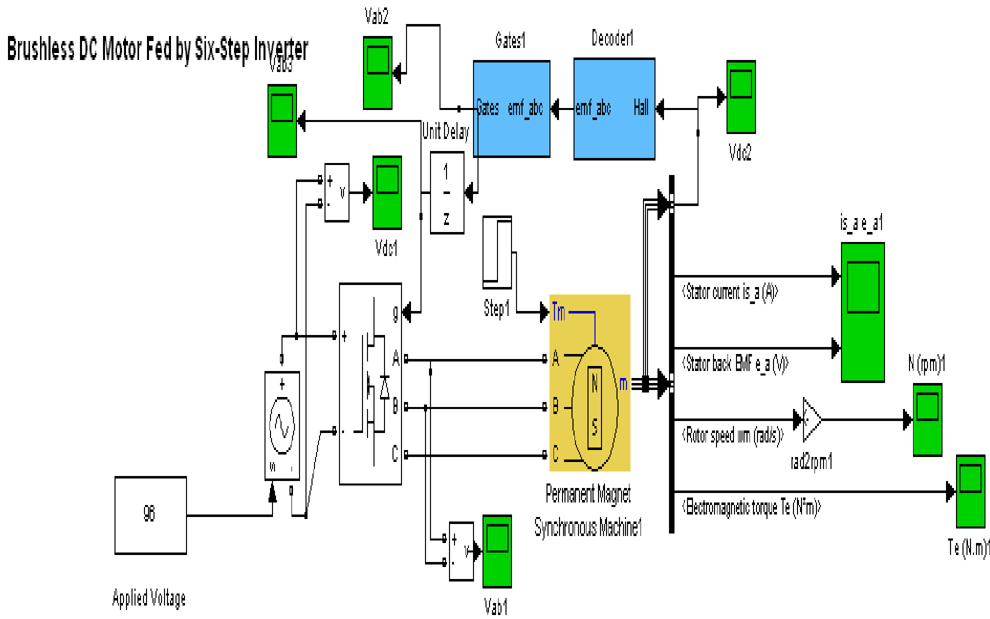


Figure 19: BLDC motor with Phase Advance

Referring to Figure 19, by observing the timing for firing angle of inverter, a unit delay component is located between the gate inverter and the inverter and timing is calculated. The purpose is to delay the signals at the correct timing so that it looks like advance to the original signal.

Figure 20 shows the graph of rotor speed against time for BLDC motor conventional controller and phase advance effect. With 96 VDC supplied, the rotor speed is at 545 rpm. The result then was compared with the controller with phase advance effect in Figure 21.

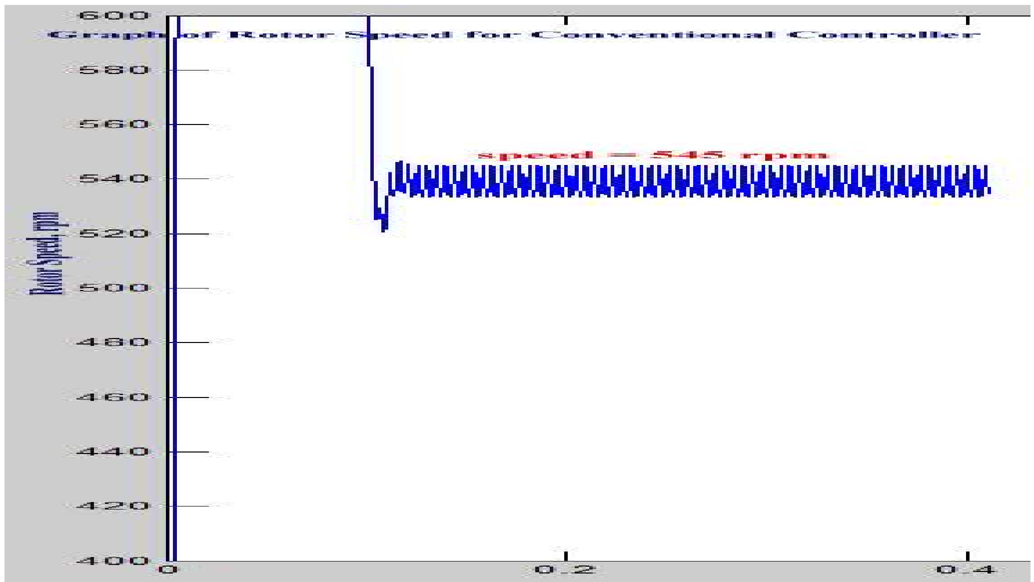


Figure 20: Rotor Speed for Conventional Controller Commutation

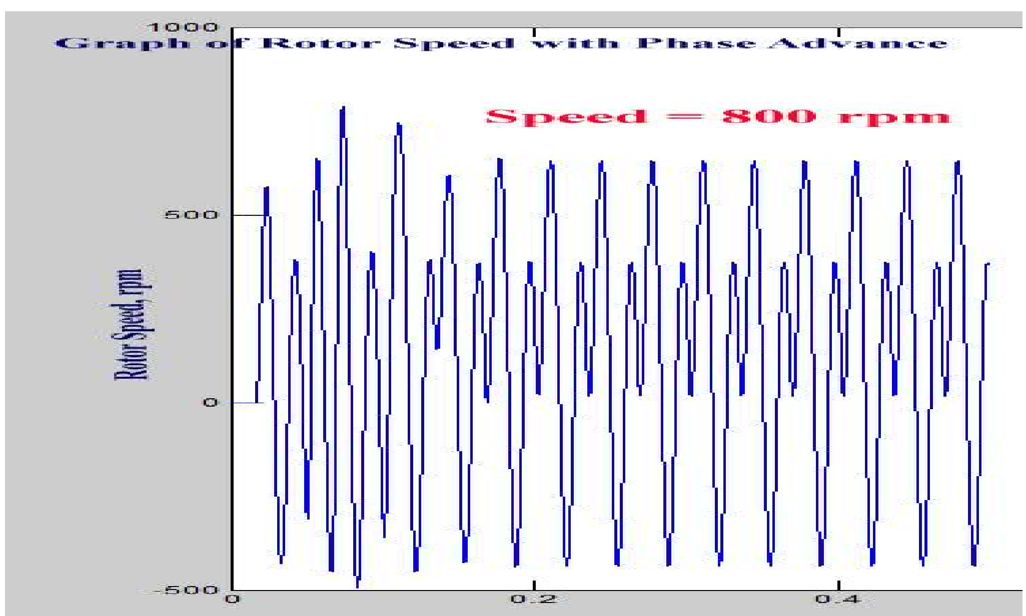


Figure 21: Rotor Speed with Phase Advance Effect

Reffering to Figure 21, the rotor speed is increasing from 545 rpm to 800 rpm at same applied voltage. The phase advance angle is approximately 50 °. From this phenomena, it is proven by advancing the current phase angle, it increases the speed of the motor. Safety precaution should be taken such as by varying phase angle value not resulting in an excess of rated phase motor current in order to avoid the motor from damage. By analyzing the waveform details in Figure 20, the result is not yet valid since the waveform goes to negative speed. This is because this Phase Advance Angle Control Method technique is not correct. The purpose of this step is to shows the simple effect of advancing the phase angle of BLDC motor phase current only. The actual model and technique are developed for the subsequent step.

The highlighted blocks in Figure 15 show the focused area in this project. In this Part 1 as referred to Figure 14 of Project's Flowchart, the proposed motor drive for phase advance and 3 phase permanent magnet brushless DC (BLDC) motor model are developed. Figure 22 shows the reference model of motor drive and BLDC motor used. The actual BLDC motor model is developed based on this reference model and the parameters obtained from actual BLDC motor.

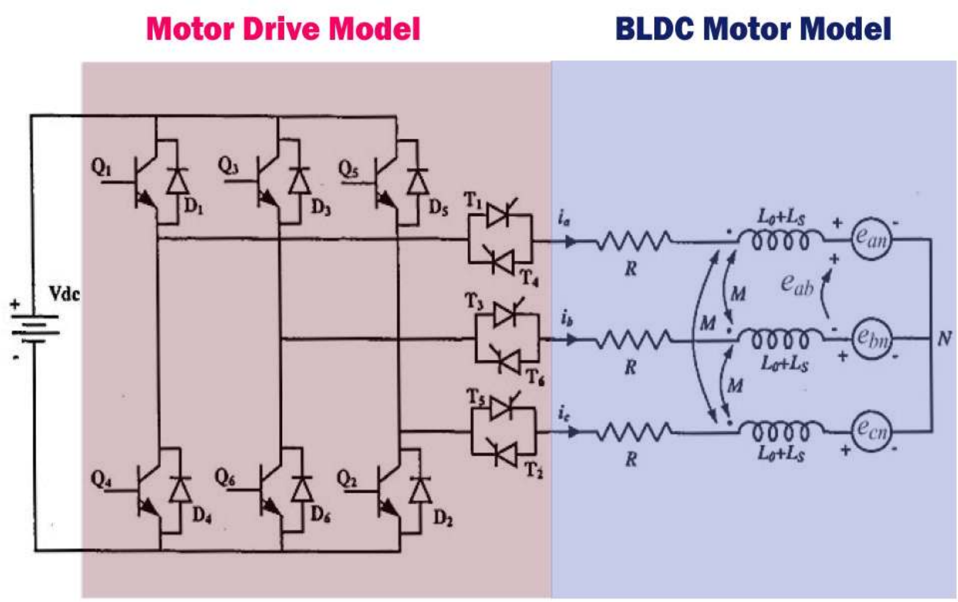
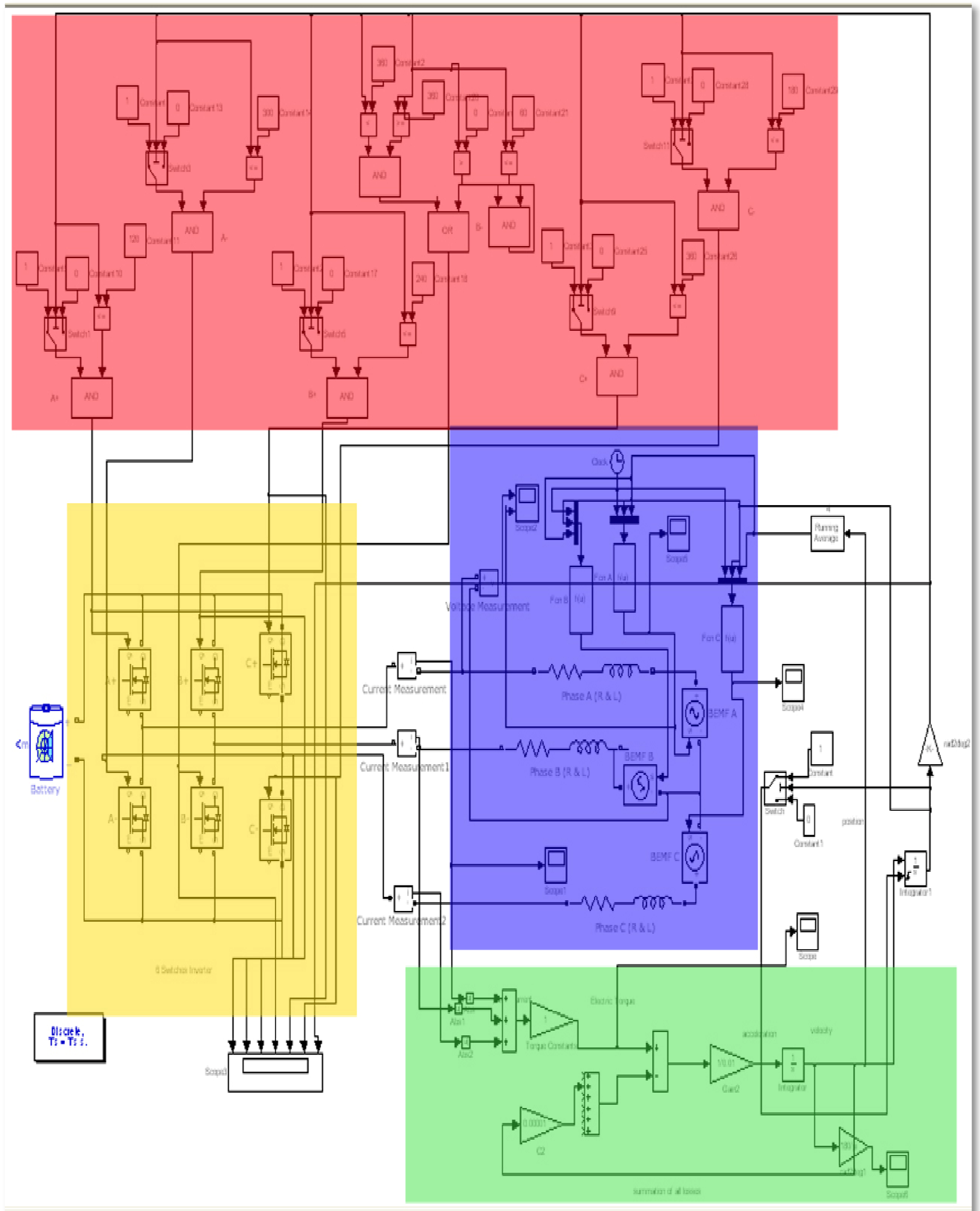


Figure 22: Model of Inverter and BLDC Motor for MATLAB Simulink. [9]

The BLDC motor drive model consists of back EMF, phase winding resistance and inductance. The gates drives and inverter will be similar to the conventional motor drives. The difference is how the signal from hall sensor will be applied in order to apply Phase Advance Angle Control Method. Then, a complete model of motor drives that enables to drive the BLDC motor at high speed operating mode is demonstrated. The torque and current characteristic will be observed from the simulation result.

In order to implement phase advance angle control method effectively, an optimized model is important. Figure 23 shows model developed. This model is first developed by assuming a lossless motor; more simulation tests on the model are required. The full model consists of 3-phase BLDC motor model (shows in blue box), six transistors voltage-fed inverter (VFI) bridge which each transistor has a parallel bypass diode (orange box), inverter gate commutation (red box), and electrical to mechanical block mechanism. The theory is tested and proven using simulation for lossless BLDC motor model and use the parameters of an actual BLDC motor. The speed regulator is for close loop close is needed in this model to compensate the change in torque when load is applied in order to maintain the desired speed.



Legend:

	3-phase BLDC motor model
	six transistor voltage-fed inverter (VFI) bridge
	inverter gate commutator
	Mechanical

Figure 23:BLDC Motor Drive for Phase Advance Angle Control Method Model.

Referring to Figure 23, the BLDC motor drive model is developed based on several assumptions:

i) All power semiconductor components in inverter are ideal.

ii) All losses including stator and rotor iron losses are negligible.

iii) The motor is not saturated.

iv) Mutual inductances are constant and stator resistance at every phase is equal.

Thus, BLDC motor operation under these conditions can be represented in state space equation as:

$$\begin{bmatrix} va \\ vb \\ vc \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} ea \\ eb \\ ec \end{bmatrix} \ldots\ldots\ldots\ldots \quad (2)$$

where *va*,*vb*, and *vc* are the voltage supply for each phase, *ia*, *ib*, and *ic* are the rectangular shaped phase currents, *ea*, *eb*, and *ec* are the trapezoidal back EMFs, *R* is resistance for each phase and *L* is the phase inductance (self indunctance, *Ls* – mutual inductance , *M*)

For simplicity, following equations will be presented for phase A only by considering the others two phases (phase B and C) having the same magnitude but vary only on the phase. The Kirchhoff's Voltage Law (KVL) equation for each phase equation is:

$$v = Ri + L\frac{di}{dt} + e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

From equation (3), the electromagnetic torque can be obtained using equation (4).

$$Te = Kt * Iphase \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The important of having previous equation (3) and (4) is to represent the system by an equivalent rotational system. Figure 24 shows the rotational system of BLDC motor and Figure 25 shows the translation equivalent rotational system block diagram from Figure 24.

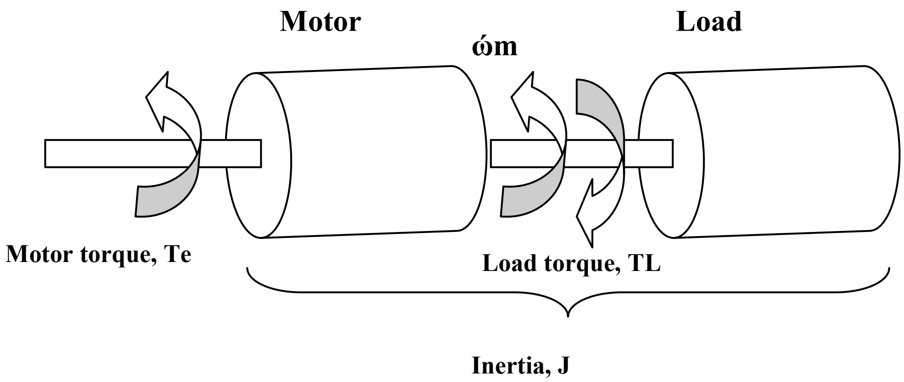


Figure 24: Rotational System of BLDC motor

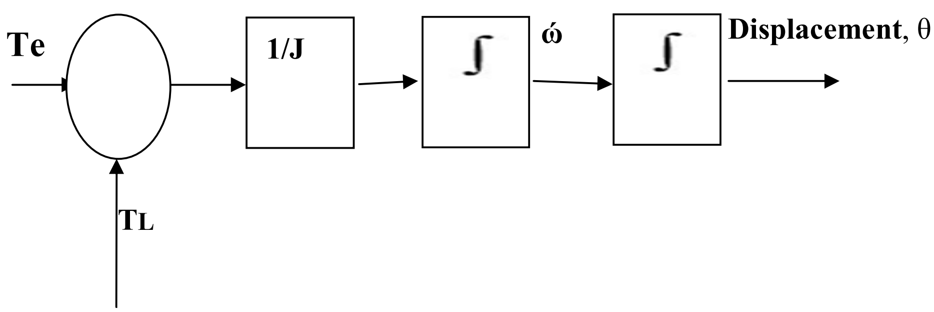


Figure 25: Equivalent Rotational System of BLDC Motor Block Diagram

Thus, the system can be system can be described by a first order mechanical system:

$$Te = T_L + \frac{d(J\omega m)}{dt} \quad \ldots\ldots (5)$$

For the system with constant inertia, dJ/dt = 0, equation (5) can be rewritten as:

$$Te = T_L + J\frac{d\omega m}{dt} \quad \ldots\ldots (6)$$

where Te is electromagnetic torque, T_L is load torque and J is inertia.

In order to get better explanation on Figure 23, it has been divided into 3 subtopics: 1) 3 Phase BLDC motor. 2) Voltage Fed-Inverter (VFI) Bridge 3) Commutation. 4) Mechanical Block.

3.1.1 3 Phase BLDC Motor model (Blue Box)

Figure 26 shows components of blue box in Figure 23. The blue box is a model for three-phase BLDC motor. The model consists of phase resistance, phase inductance and back EMF generator.

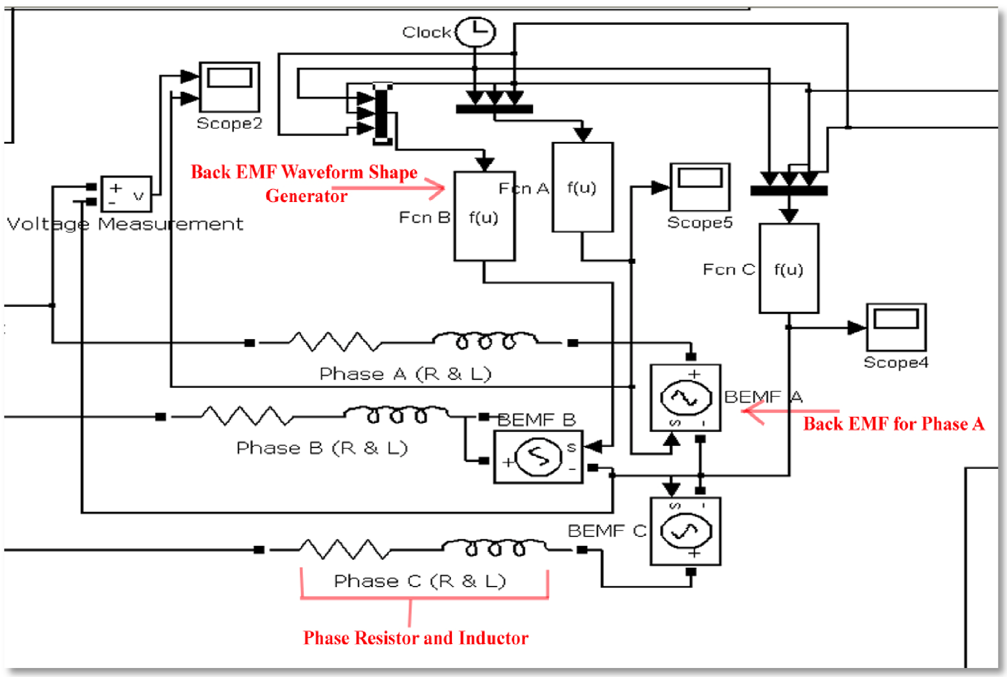


Figure 26: 3-phase BLDC Motor Model

When the rotor is stationary, the only resistance to current flow is impedance of the electromagnetic coils. The impedance consists of the parasitic inductance of the windings and parasitic resistance of the copper themselves. Usually, the resistance and inductance value are very small. Therefore, the start-up current would be very large if it is not limited. In Figure 26, the parasitic resistance and inductance are represented as phase resistor and inductor.

When the BLDC motor is spinning, the permanent magnet motor rotor will move past the stator coils. This action induces an electrical potential in the called Back Electromotive Force (back EMF). For an ideal motor, it will spin at a rate such that the back EMF exactly equals the applied voltage. Back EMF is directly proportional to the motor speed, ώ and it also can be determined from the motor

voltage constant *Kv*. Eq (7) shows the formula to calculate Back EMF.

$$Back\ EMF = \frac{\omega}{Kv} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

For actual BLDC motor, the shape of back EMF waveform is trapezoidal. In order to reduce the complexity of the first motor model, sine wave is chosen to be back EMF waveform. Eq (8) – (10) show the back EMF generation equation for Phase A, B, and C respectively,

$$Back\ EMF\ a = (Ke.\omega).\ \sin(\omega t + 0)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

$$Back\ EMF\ a = (Ke.\omega).\ \sin(\omega t + \frac{120}{180}.\pi)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

$$Back\ EMF\ a = (Ke.\omega).\ \sin(\omega t + \frac{240}{180}.\pi)\ \ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

where *Ke* is the electromagnetic constant, *ώ* is motor speed. The waveforms for phase B and C are delayed at 120° and 240° respectively.

3.1.2 Voltage-Fed Inverter (VFI) Bridge (Orange Box)

Figure 27 shows components of orange box in Figure 23. It shows a motor drive consists of a common six MOSFET act as voltage-fed inverter bridge (Q1, Q2, Q3, Q4, Q5, and Q6) and each MOSFET has a parallel body diode.

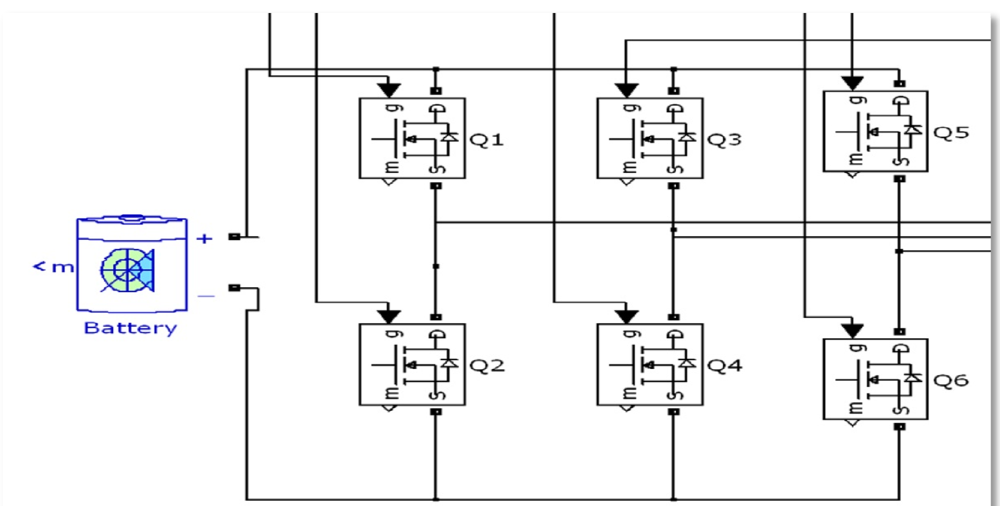


Figure 27: Voltage-fed inverter (VFI) bridge model

The purpose of having parallel body diode is to carry reverse current during regeneration (reverse motoring mode). These MOSFETs control will convert DC voltage supply (battery) to AC voltage using two-phase conduction scheme with 120 electrical degrees. The meaning of two-conduction scheme is that two phases will be sourced and sinked by current at the same time. Figure 28 shows the two phase conduction scheme for phase A BLDC motor.

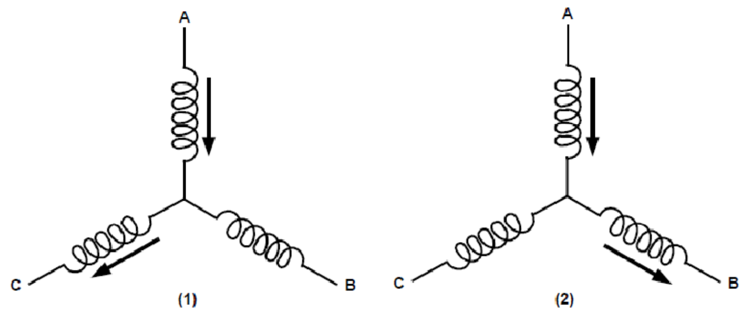


Figure 28: Winding Energizing based on Two-phase Conduction Scheme

For every 60 electrical degrees of rotation, one of Hall sensors changes the state. Therefore, it takes six steps to complete an electrical cycle and every 60 electrical degrees, the current switching will be updated. Table 6 shows the sequence for rotating the motor in forward motoring mode. The details of phase current waveform will be discussed in commutation block (red block).

Table 6: Sequence for Rotating the BLDC motor in forward motoring mode.

Sequence (steps)	**Active MOSFETs**		**Phase Current**		
			A	**B**	**C**
1	**Q1**	**Q6**	DC+	OFF	DC-
2	**Q1**	**Q4**	DC+	DC-	OFF
3	**Q3**	**Q2**	DC-	DC+	OFF
4	**Q3**	**Q6**	OFF	DC+	DC-
5	**Q5**	**Q4**	OFF	DC-	DC+
6	**Q5**	**Q2**	DC-	OFF	DC+

3.1.3 Commutation (Red Box)

Figure 29 shows components of red box in Figure 23. The red box shows a commutation for voltage-fed inverter bridge Phase A control. This model works synchronously with Table 6. This technique is a direct technique for commutation and it works by continuously keep the respective MOSFET to ON state so that the average applied voltage across the motor stator winding can be changed by modulating the switch duty cycle within the conduction interval.

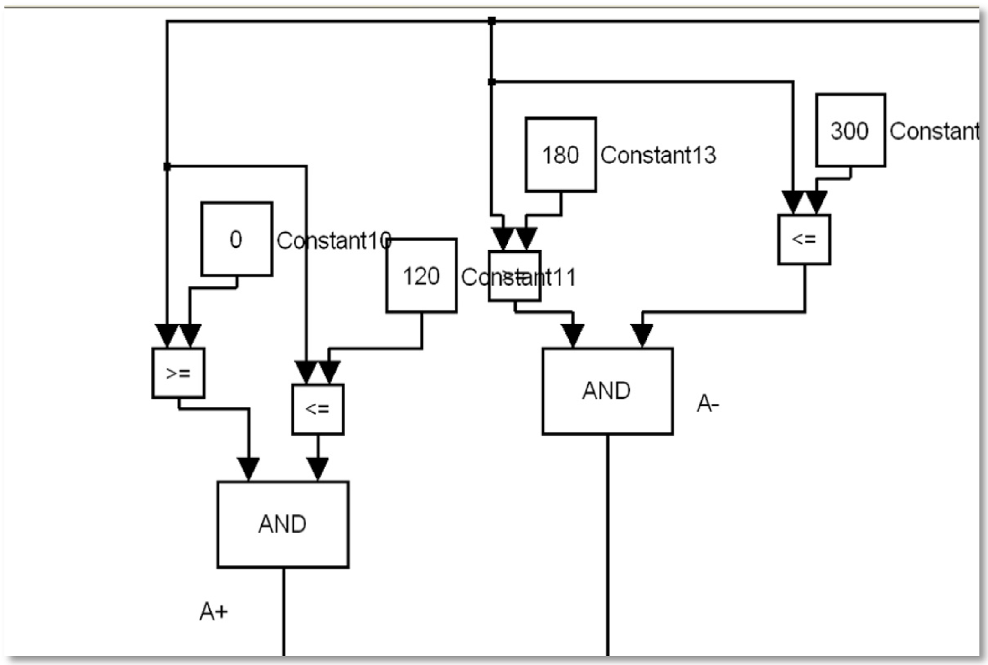


Figure 29: Phase A Using Direct Commutation Technique

The commutation works by comparing the signal received from mechanical block. The signal contains information of motor rotation angle in degrees (0°-360° range). The purpose of this commutation is to create a waveform of phase current by triggering the correct MOSFET according to phase back EMF.

Figure 30 shows the conventional waveform of phase current according to back EMF. The phase Advanced Angle Control Method can be applied by changing the condition of commutation block.

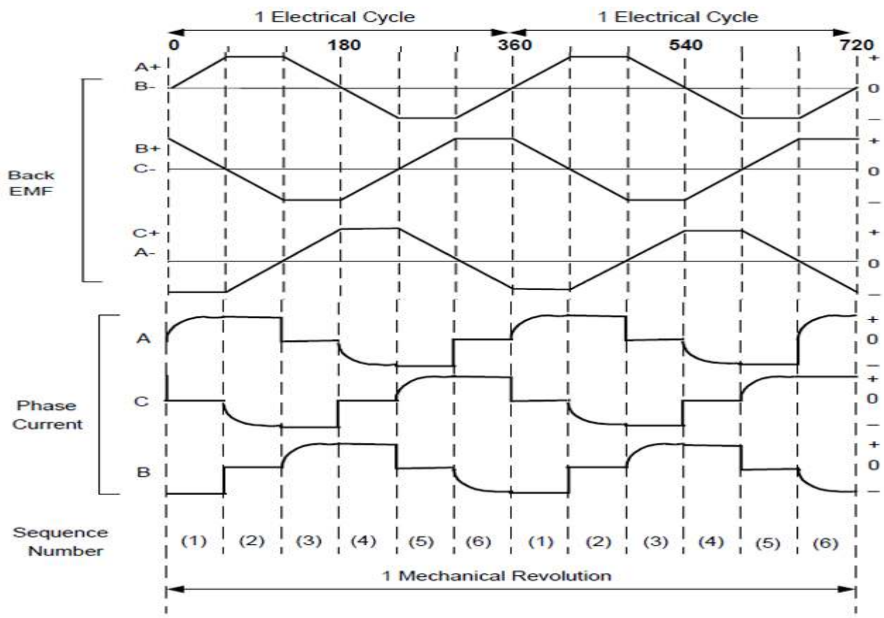


Figure 30: Conventional waveform of phase current according to back EMF

For conventional motor drive, it requires to produce phase current which is in phase with back EMF. Table 7 shows the condition for conventional commutation block in Figure 28. Phase Advance Angle Control Method can be applied by changing the condition of commutation so that the phase current will lead the back EMF phase by certain degrees. The sequence of commutation for the motor phase is A, B then C and the range of rotational degrees is 0°-360°.

Table 7: The conventional commutation condition for each commutation blocks

Motor Phase	**Condition**	
	+ve Amplitude	**-ve Amplitude**
A	**0 <= A+ <= 120**	**180 <= A- <= 300**
B	**120 <= B+ <= 240**	**300 <= B- <= 60**
C	**240 <= C+ <= 360**	**60 <= C- <= 180**

3.1.4 Mechanical Box (Green Box)

Figure 31 shows the mechanical block from BLDC motor circuit drive model. The functions of mechanical block diagram (Figure 31) are to convert or translate from electrical function to mechanical function such as speed and distance travelled and also to produce degree of rotation for commutation block diagram.

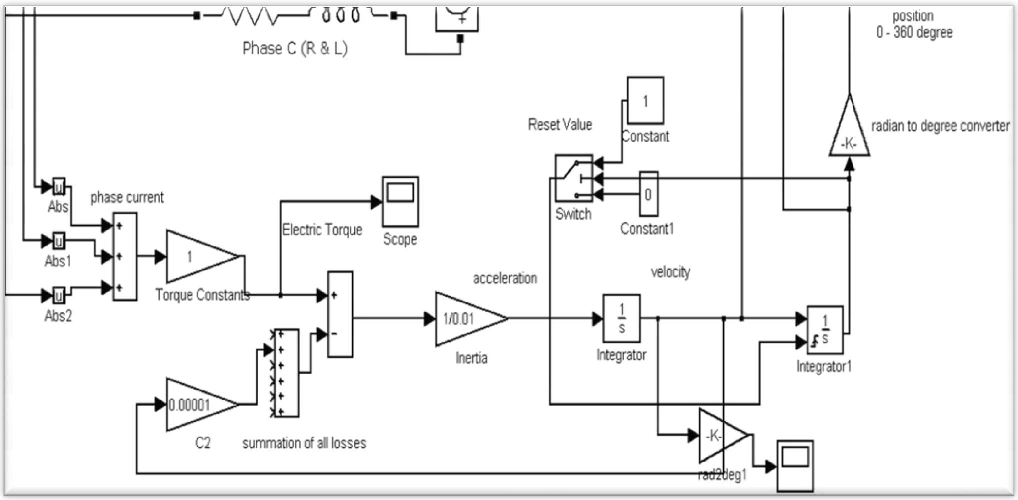


Figure 31: Mechanical Block Diagram

From previous Figure 26, phase current can be determined from the position the degrees of rotational can be obtained. Based on that information, Electromagnetic Torque, *Te* can be obtained using Eq (11).

$$Te = Kt \, . I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where, Kt = torque constant

I = phase current

Using Eq (12), the displacement (range travelled by motor) can be determined by integrating for two times.

$$a = \frac{F}{m} = \frac{Te}{J} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where, J = Inertia

m = mass

3.2 PART 2 – Laboratory Proof

The effect of phase advance control on brushless DC (BLDC) motor is tested and validated using the motor drive fabricated at the early of this part and the actual BLDC motor. A series of experiment have been carried out and the results are recorded. The purpose of in this part in methodology is to verify and validate the results obtained from simulation based on the theory with the physical test results. Figure 32 shows the flow chart for results comparison.

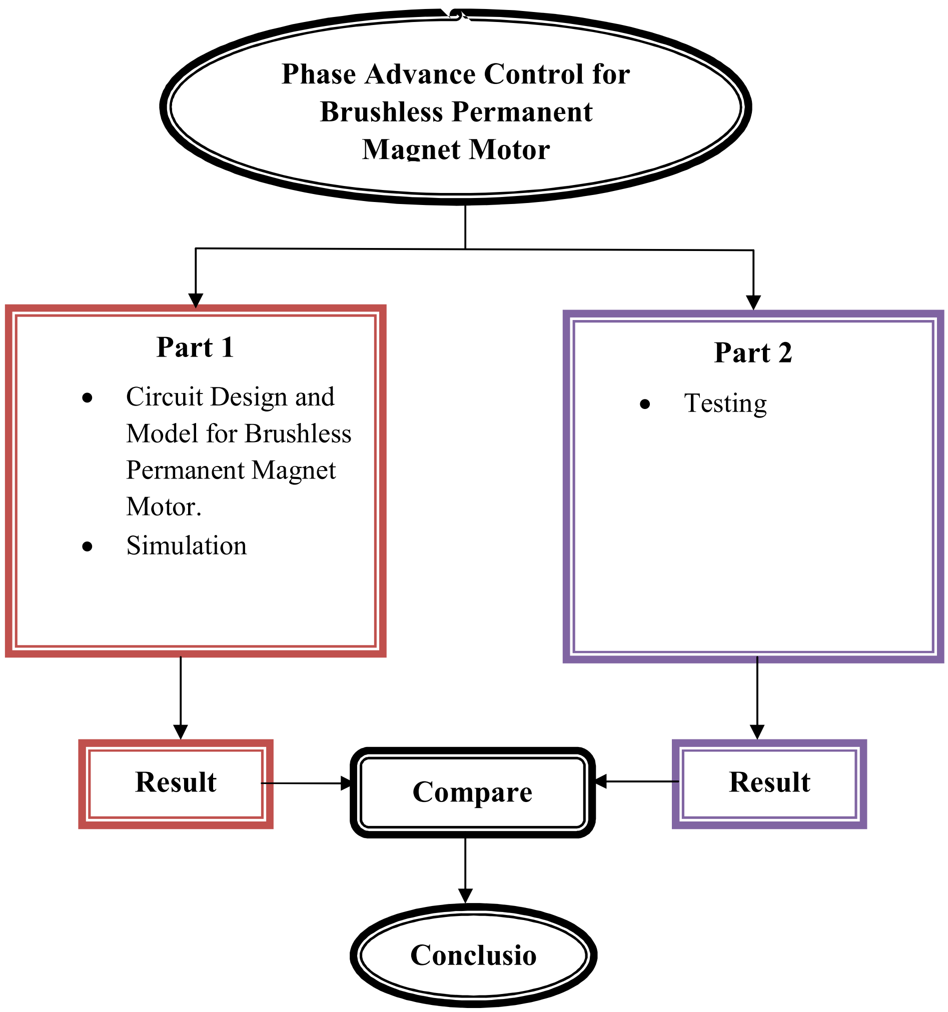


Figure 32: Results Comparison

3.2.1 Hall signal and Back EMFs waveforms

In order to successfully implement phase advance angle control method on a BLDC motor, the hall signals and back EMFs need to be studied. The purpose is to determine the set point (0° phase advance) from the hall signal and back EMF. Figure 33 shows the waveforms of Hall signals and back EMFs for the actual BLDC motor. Figure 33 shows the back EMFs is the same phase with hall signals which satisfies the previous commutation concept in simulation part. At this step, no voltage is applied to the BLDC motor. An assumption has been made based on the commutation sequence and back EMFs shape: the supply phase current will in the same phase with back EMFs based on the commutation signal.

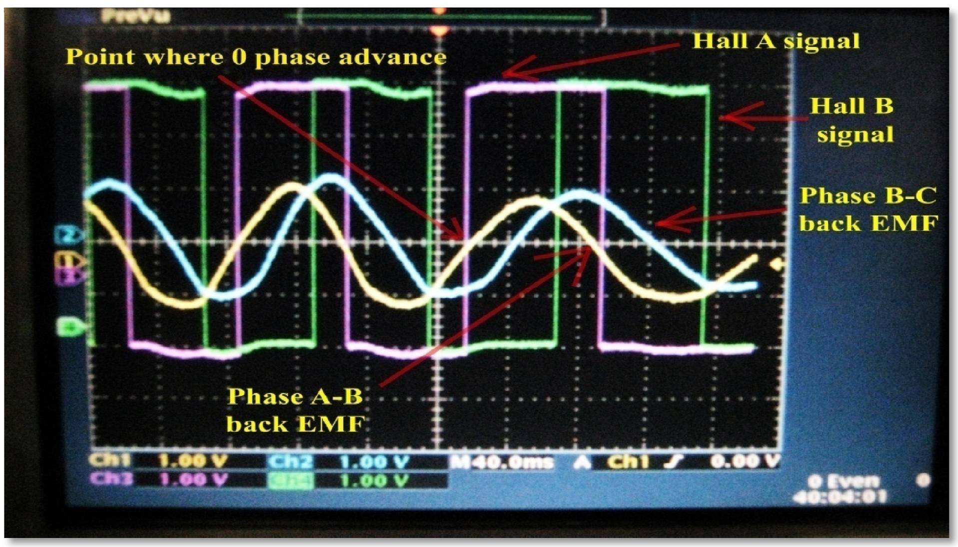


Figure 33: Hall Signals and Back EMFs waveforms

3.2.2 Hall signal and Phase Current

The waveform of phase current is observed in oscilloscope in order to validate early assumption as stated in section 3.2.1. Here, only phase A will be analyzed since others phases also will have the same waveforms. The only difference is that they have phase lag by certain value.

Figure 34 shows the phase A current waveform and hall A signal. The current is supplied to the each phase based on the commutation signal. Referring to Figure 34, the phase current is same with the commutation signal. In this experiment, the effect of phase advance angle will be studied by observing the speedometer meter value when we change the phase.

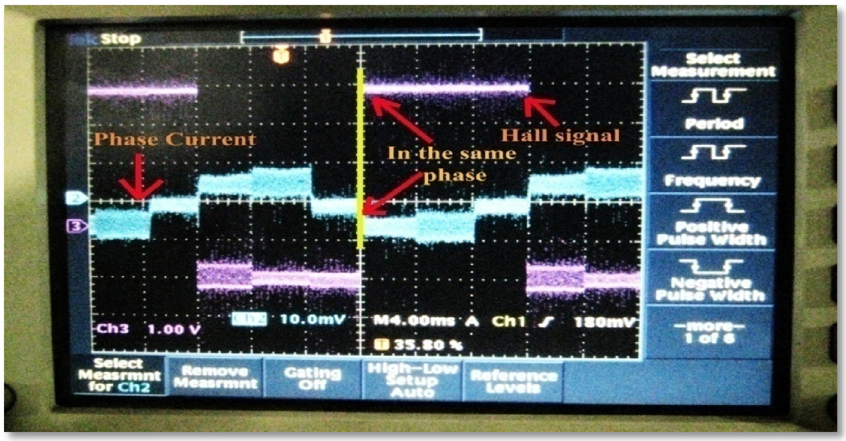


Figure 34: Phase A Current and Hall A signal waveforms

Then, the phase advance angle control method is implemented by changing the offset of the phase current so that it looks like the controller is injecting the current ahead from the commutation signal. Figure 35 shows the Phase A Current and Hall A signal Waveform with phase advance effect approximately at 40°. Since it is difficult to calculate the value of advanced angle, this experiment focused on effect of advancing the phase advance at one specific angle is which 40°.The results are recorded and discussed.

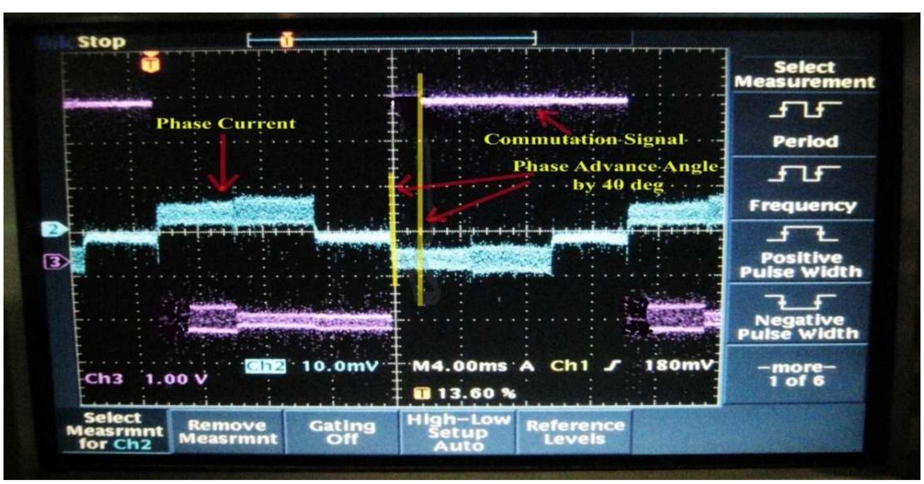


Figure 35: Phase A Current and Hall A signal waveforms with phase advance

CHAPTER 4
RESULTS AND DISCUSSION

From the theory, the phase advance method is predicted to be able to extend the constant power speed range of the BLDC motor. Based on *J. S. Lawler et al.* in [25,26], the phase advance angle value can be varied from 0° to 60° whereas the speed and power will increase proportionally with the increasing of angle. The experiment will be carried out to determine the effect phase advance angle value in order to produce the maximum speed without exceeding the rated current phase value of BLDC motor at different load torque.

4.1 PART I SIMULATION RESULTS AND DISCUSSION

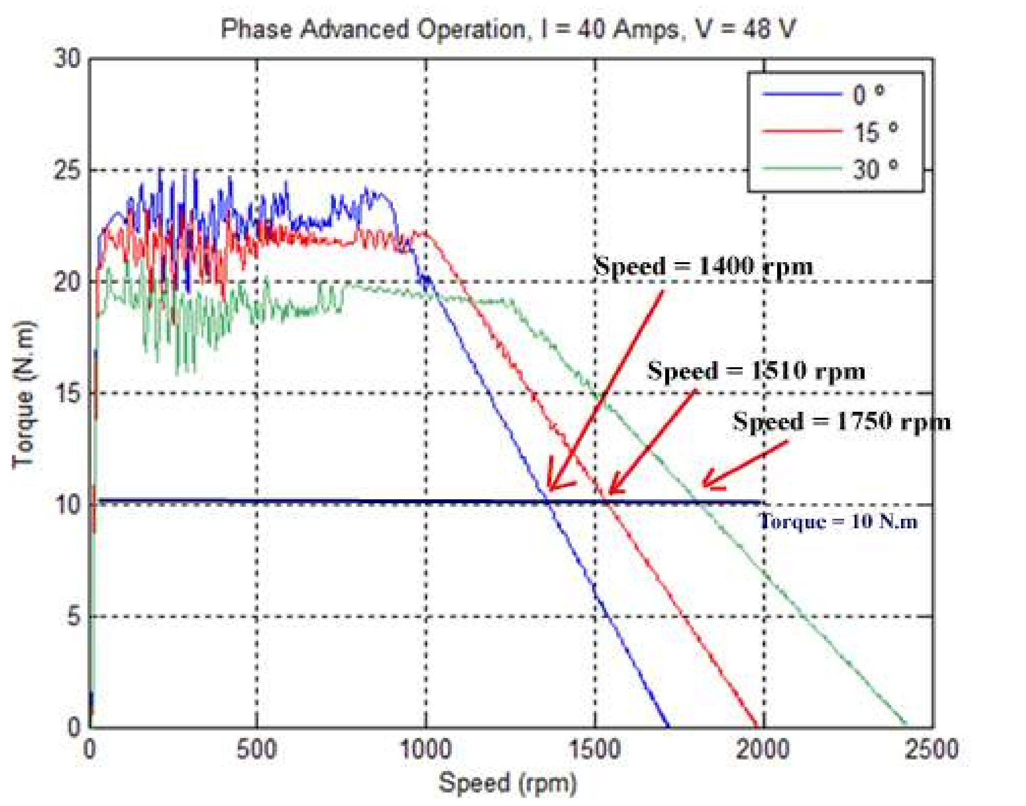


Figure 36: Torque versus Speed Characteristic for Phase Advance Angle Control Method

Figure 36 shows the simulation results for varying phase advance angle on brushless DC motor. The angle is varied from 0°, 15° and 30° respectively. The graph shows that torque will be reduced as the value of phase advance angle increases and so does the speed. In this result, only the characteristic of torque and speed are examined. The blue color line indicates the conventional motor drive (0° phase advance). The maximum speed when torque is equal to zero is 1750 rpm. The red line indicates the phase advance for 10°. It is noticed that the maximum torque is slightly reduced at constant torque operation and at torque is equal to zero, the maximum speed is 1990 rpm. The green line indicates phase advance angle for 30°. The maximum torque is reduced from 23 N.m to 30 N.m. The maximum speed at torque equal to zero is 2480 rpm. From this result, it is proven that the early hypothesis which as the phase advances angle increases, the maximum speed will also increase. For the operating speed improvement, it is measured at torque is equal to 10 N.m for every phase advance angle. The conventional BLDC motor speed without phase advance is 1400 rpm. At 10° phase advance, speed is 1510 rpm and the operating speed has increased as much as 7.86%. At 30° phase advance, speed is 17500 rpm and the operating speed has increased as much as 25%.

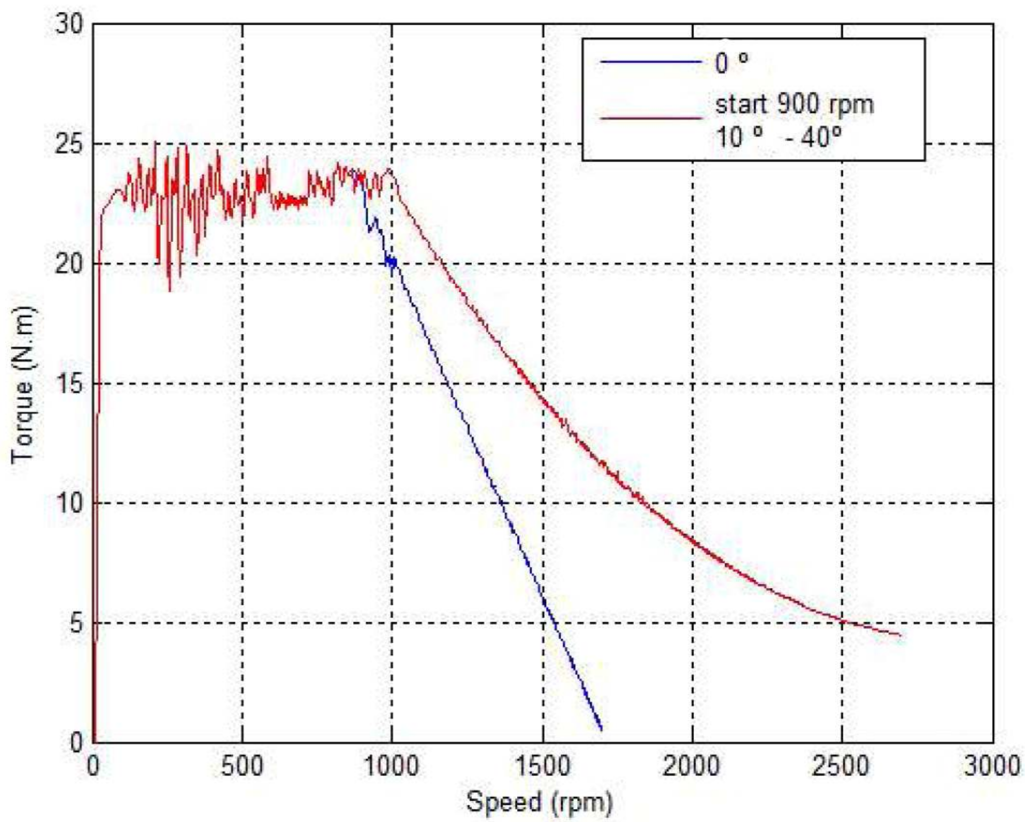


Figure 37: Torque versus Speed Characteristic

Figure 37 shows the characteristic of torque versus speed for brushless DC motor when the phase advance angle varies with speed. In this result, the maximum torque at constant torque operation is fixed. The effect of varying phase advance angle on BLDC speed is examined. The purpose to have this experiment is to determine the best torque versus speed characteristic for BLDC motor. This graph shows that effect of applying 10° of phase advance at speed equal to 900 rpm and continuously increases with the speed until phase advance angle is equal to 40°. Noted that, without changing the torque characteristic at constant torque operation (conventional motor drive), the phase advance angle control method is able to extend the BLDC motor operation into constant power operation (preferred).

4.2 PART 2 LABORATORY PROOF RESULTS AND DISCUSSION

The main objective is to validate the proposed phase advance angle control method on actual BLDC motor. To achieve this objective, the physical test was conducted at the same base speed (2700rpm) but with 2 different values of phase advance angle. The speed with 0 phase advance angle and approximately 40° phase advance.

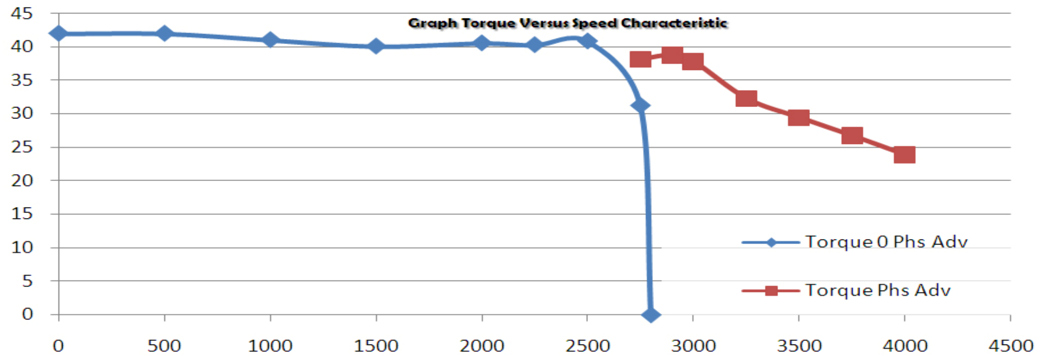


Figure 38: Torque versus Speed Charateristic

Figure 38 shows the torque versus speed characteristic of BLDC motor. The blue line indicates the conventional torque-speed curve. The red curve indicates the torque-speed characteristic when operating with phase advance effect. From the graph, it shows by applying phase advance angle control method, it is able to extend the speed beyond designed motor base speed. For motor operating speed, it is measured at torque is equal to 31 N.m for every phase advance angle. The conventional BLDC motor speed without phase advance is 2750 rpm. At 40° phase advance, speed is 3350 rpm and the operating speed has increased as much as 21.8%. Figure 39 shows the power versus speed characteristic for the same experiment. From the graph, it shows phase advance angle control method is able to extend the speed with the same amount of supply power.

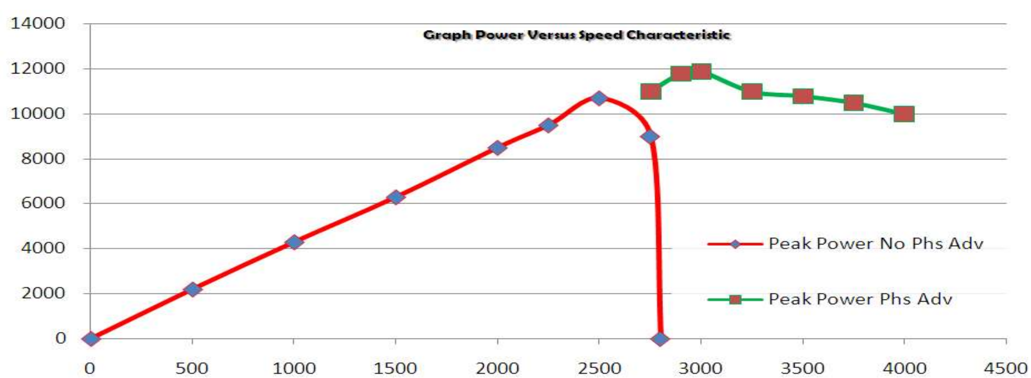


Figure 39: Power versus Speed Characteristic

CHAPTER 5
CONCLUSION & FUTURE WORKS

Conclusion

This project is completed within the proposed schedule. At the end of this project, the validity of hypothesis on effect of phase advance angle control method is proven. Even though, the phase advance method is already been applied and many improvement have done on this method, it is important to know the theory as well as the way to implement it on BLDC motor. There are two types of testing that have been conducted: simulation and experimentation. From simulation results, phase advance angle at 30° is able to improve operating speed range as much as 25%. From the experimentation result, phase advance angle at 40° is able to improve the BLDC motor operating speed range as much as 21.8%. Theoretically, the simulation result for 40° phase advance able to produce higher operating speed range than 25% but for experimentation result, it only able to improve 21.8%. The operating speed for experimentation result is decreasing due to losses from the motor and controller. From both results, the phase advance angle control method is proven to overcome the weakness of conventional controller and BLDC motor drive system.

Throughout this project tenure, there are several problems encountered. For example, the selection of BLDC motor drive model. Commonly there are two types of controlling BLDC motor techniques: six-step inverter and PWM. Each technique has different theory and implementation technique on the BLDC motor model. Thus, both methods have been tested and implemented on the BLDC motor model. The suitable technique (six-step inverter) has been chosen based on the compatibility on phase advance approach and has been discussed on this report. Therefore, results which are similar with expected results have been produced.

Although this method has been introduced in early 90's, it is not given detailed attention by automotive industries since at that time internal combustion engine was commonly used. Nowadays, since economical and environmental factors are the main priorities, a lot of researches have been conducted to improve the electric and hybrid vehicle. Thus, this study is valuable and important to improve performance of BLDC motor especially in transient operation applications such as electric vehicle. Phase advance angle control method is one of the methods to improve the efficiency of electric vehicles by focusing on the drive systems itself. It is also substantial to improve the other part of electric vehicles such as an aerodynamic design and also battery performance. Thus, further analysis should be conducted in order to achieve this objective.

Future Works

There are lots of development areas that can be done for continuation of this project and they will be very useful for the industrial application especially in automotive industry. The integration of normal operating mode control (below base speed) with the phase advance method will be made. So the drive systems are able to automatically select the correct control method for below and above base speed mode. Then, this controller will be integrated with transmission gear for electric vehicle to improve the characteristic of torque and speed as shown in Figure 40. The transmission gear can be used to extend constant power speed range for electric vehicle. For tranmissionless electric vehicles, phase advance is used. The weakness of extending the constant power speed range using transmission gear includes inefficiency working in high load torque. Therefore, by combining phase advance, it will improve the efficiency and performance of BLDC motor.

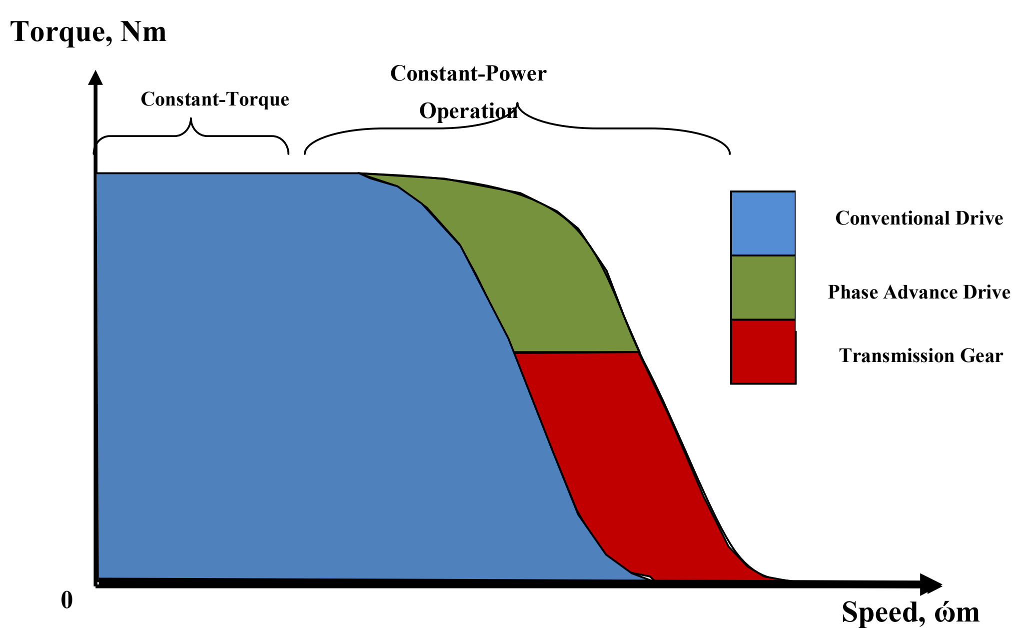


Figure 40: Future Works

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