SIMULATION OF SINUSOIDAL COMMUTATION OF BRUSHLESS MOTOR FOR STARTING OF LINEAR ENGINE-GENERATOR

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By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved:

Saiful Azrin b Mohd Zulkifli
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2010

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.

Norazwan b Bidin

DEDICATION

All undertakings are solely to seek the pleasure of Allah, our creator. May He be pleased with this humble effort.

ACKNOWLEDGEMENT

All praises go to Allah, our sustainer, without whose grace and guidance, no effort could attain success. I would like to express my gratitude to my supervisor, Mr. Saiful Azrin b Mohd Zulkifli for his invaluable assistance and technical guidance which has motivated me to contribute my fullest to this project.

In addition, gratitude is dedicated to close friends who have been all the way tolerating and helping me in providing moral and technical support during the course of this project. Their constant support has greatly contributed immensely to the success of this research.

To my parents, no words can ever express my gratitude for the love, support, encouragement and patience. Without those love and advice, I could not have been to complete this project today.

Finally, I would like to thank Universiti Teknologi PETRONAS (UTP) for providing me with the excellent environment and access to facilities to complete this project.

I thank all of them from the very bottom of my heart.

ABSTRACT

To start a free-piston linear engine-generator (LG), it requires favorable amplitude and speed for combustion to occur. The LG is able to do reciprocating motion for starting. Indeed, to do the reciprocating motion, there are some mechanical factors to be taken into consideration such as compression pressure of the engine cylinders and their air spring character. For this project, it only focuses on the electrical subsystem required to provide for the motoring force for starting.

This work discusses the electrical aspects of starting the LG and builds the respective models to simulate the starting process. Series of simulation and experimentation runs are performed to validate and analyze the results. Before proceeding to sinusoidal commutation strategy, rectangular commutation characteristics have been studied. Performances of 6-step and square wave commutation were observed. This activity is vital to lead to the understanding on sinusoidal commutation. There are two concepts that need to be applied in producing sinusoidal commutation: direct injection of AC current source to the model and applying PWM switching method to produce the AC current injection. Effectiveness of the starting strategy using sinusoidal commutation is investigated by comparing the results of these two methods applying ideal AC voltage source and the PWM switching to produce AC voltage from a fixed DC source. The former will be a clean 3-phase AC voltage while the latter shall be an application of DC-AC inverter – both to generate AC sinusoidal commutation for motoring of the LG for starting process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

K_V	Electromagnetic Profile
K_F	Motoring Force Profile
LG	Linear Generator
EMF	Electromagnetic Force
PWM	Pulse Width Modulation
BLDCM	Brushless DC Motor
MATLAB	Mathematics Laboratory Software

CHAPTER 1
INTRODUCTION

1.1 Background Study

A brushless DC motor (BLDCM) is a synchronous electric motor powered by direct current electricity (DC) and has an electronically controlled commutation system. The BLDCM differs from the conventional (brushed) DC motor as it does not have brushes. In a brushed motor, brushes will make mechanical contact with a set of electrical contacts on the rotor (commutator) hence forming an electrical connection between the DC electrical source and the armature coil-windings. As the armature rotates on the axis, the stationary brushes come into contact with different sections of the rotating commutator. The commutator and brush system form a set of electrical switches, each firing in sequence, such that electrical power always flows through the armature coil closest to the stationary stator [1][7].

In a brushless motor, the permanent magnets rotate and the armature remains static. This raises the problem on how to transfer current to different coils of the static armature. In order to achieve this, an electronic controller is needed to replace the brushed system that is used in brushed DC motor. To be precise, a BLDCM uses a solid-state circuit – a set of transistors to perform the switching of current to the different coils.

A BLDCM offers several advantages over the brushed DC motor such as [7] [8]:

a) More efficient in converting electricity into mechanical power
b) Maintenance-free (no wear and tear of brushes)
c) Higher power density
d) Long operating life

1.2 Problem Statement

A BLDCM achieves electronic commutation by using an Inverter Bridge – an arrangement of transistors. Improper commutation will lead to poor motor performance. In a previous research, rectangular commutation is able to reciprocate the LG to reach the amplitude for starting – 69mm, but it occurs at a much higher speed – 26Hz. In this project, effectiveness and efficiency of sinusoidal commutation will be studied. MATLAB/Simulink will be employed as a tool to study sinusoidal commutation to provide for the motoring force required to start the Linear Generator (LG).

1.3 Objectives

The objectives of this project are:

a) To understand and study brushless motor and electronic commutation.
b) To familiarize with existing MATLAB/Simulink program for rectangular commutation of the LG.
c) To implement sinusoidal commutation of 3-phase linear motor through MATLAB/Simulink.
d) To analyze effectiveness and efficiency of sinusoidal commutation by comparing two methods – applying ideal AC voltage source and PWM switching to produce AC voltage from a fixed DC bus.

1.4 Scope of Study

This project will cover the following:

a) Understanding theory of brushless commutation linear motor and its variant of rectangular and sinusoidal switching
b) Simulation on MATLAB/Simulink
c) Analyze data pattern and relate to the effectiveness and efficiency of sinusoidal commutation comparing the two methods.

CHAPTER 2
LITERATURE REVIEW

2.1 BLDCM Structure

BLDCM is a type of synchronous motor. This means the magnetic field generated by the stator and the rotor rotate at the same frequency. A BLDCM does not experience the 'slip' and comes in single-phase, 2-phase and 3-phase configuration. For this project, it will be using 3-phase linear motor, built as a linear generator (LG), whose prime mover is an a free-piston, linear internal combustion engine.

2.1.1 Stator

The stator of a BLDCM consists of stacked steel laminations with windings placed in the slots which are distributed in a different manner. Most of the BLDCM have three stator windings connected in star fashion and constructed with numerous coils interconnected to form a winding [7].

There are two types of stator winding variants: trapezoidal and sinusoidal motor. This project uses the latter. Different stator windings will give different types of back electromagnetic force (EMF). The torque output of a sinusoidal motor is smoother than a trapezoidal motor but it gives an extra cost due to extra winding interconnections [1].

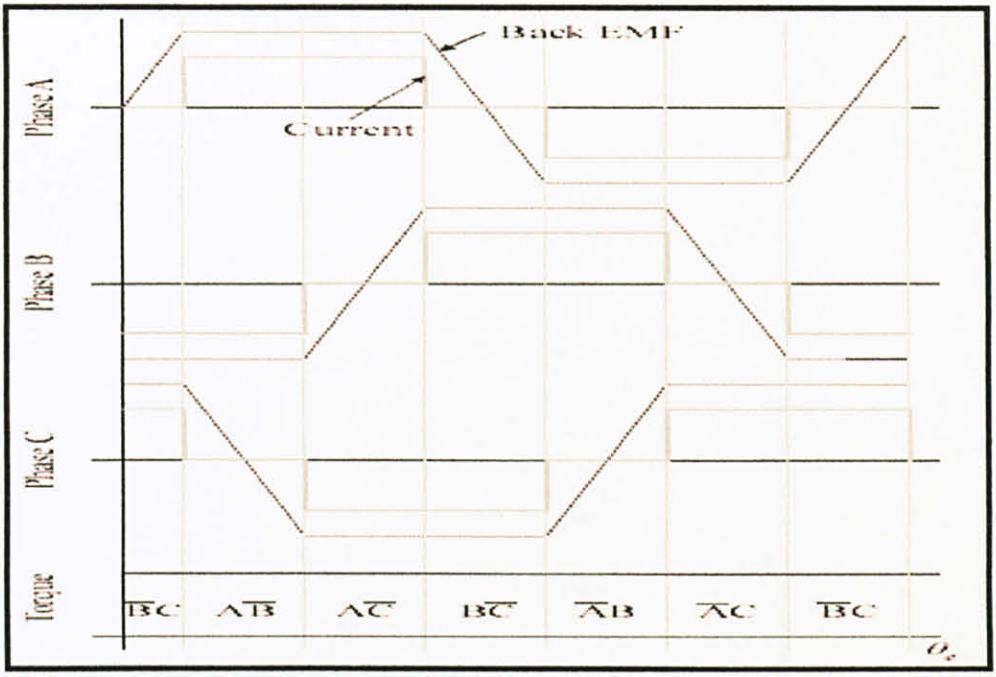


Figure 1   Sinusoidal back EMF [7]

2.1.2 Rotor

Rotor is made of permanent magnets and it can be varied from two-to eight-pole pairs with alternating North (N) and South (S) poles. Ferrite magnets are traditionally used to make permanent magnets. But nowadays, rare earth alloy magnets are more popular because it has higher magnetic density per volume and enables the rotor to compress further for the same torque. In addition, alloy magnets can improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets [7]. Figure 2 shows different possible arrangement of magnet in a rotor.

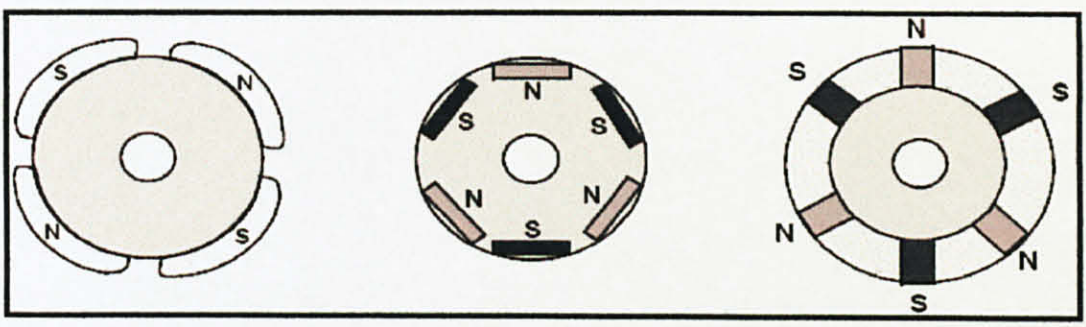


Figure 2   Rotor Magnet Cross Section [7]

2.2 BLDCM Back EMF

When a BLDCM rotates, each winding generates a voltage known as back Electromotive Force or back EMF. Lenz's Law states that this back EMF will oppose the main voltage supplied to the windings. The polarity of this back EMF is in opposite direction of the energized voltage. Back EMF depends mainly on three factors [7]:

a) Angular velocity of the rotor
b) Magnetic field generated by rotor magnets
c) Number of turns in the stator windings

The back EMF will increase if the speed of the rotor increases. The potential difference across a winding can be calculated by subtracting the back EMF value from the supply voltage. If the motor is driven beyond the rated speed, back EMF will increase substantially hence will decrease the potential difference across the winding and reducing the current drawn which results in torque decreasing. The current and torque are equal to zero when the supply voltage is equal to the sum of the back EMF and losses in the motor.

2.3 BLDCM Basic Operation

Although the above diagram is on rotating brushless motor, the theory and concepts apply equally well to a brushless linear motor. To provide the force to reciprocate the piston, the LG is operated as a brushless and permanent for magnet linear motor [3]. Current is injected into the stator coils creating a magnetic field of the permanent magnets on the translator shaft. A motor force is created which will push on the translator shaft with a certain magnitude. The direction of the translator's motion will depend on the relative position of the permanent magnets with respect to the fixed stator coils.

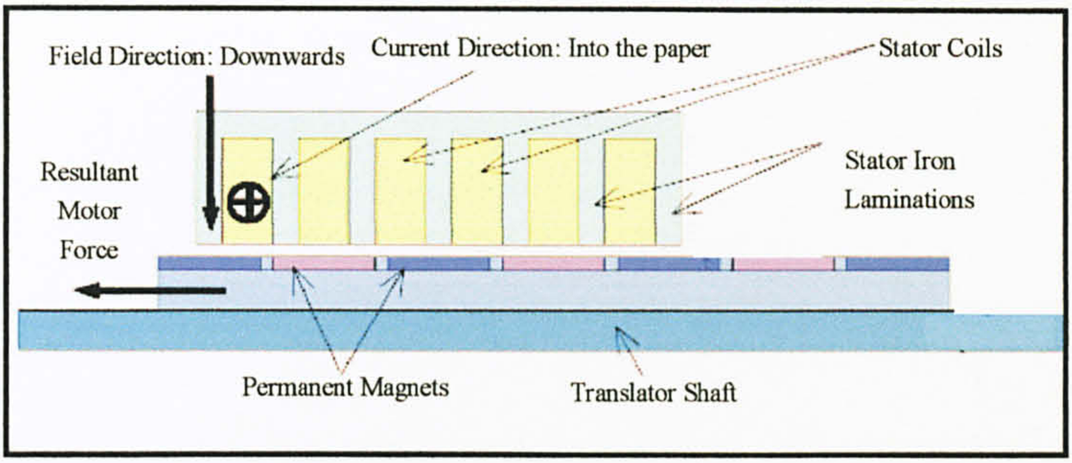


Figure 3 Interaction of Magnetic Fields in Linear Generator [3]

2.4 BLDCM Drive System

Brushless motor requires a drive to supply commutated current to the motor windings synchronized to the rotor position. To perform, this feedback position sensor is needed to commutate the brushless motor. Some drives might be commutating and may include bus current control with or without current-loop [5].

For the implementation of this project, IGBTs will be used instead of currently practiced is MOSFETs. However, this project only performs simulation using MATLAB Simulink. In simulation, IGBTs or MOSFETs appear as a force-commutated transistor switches.

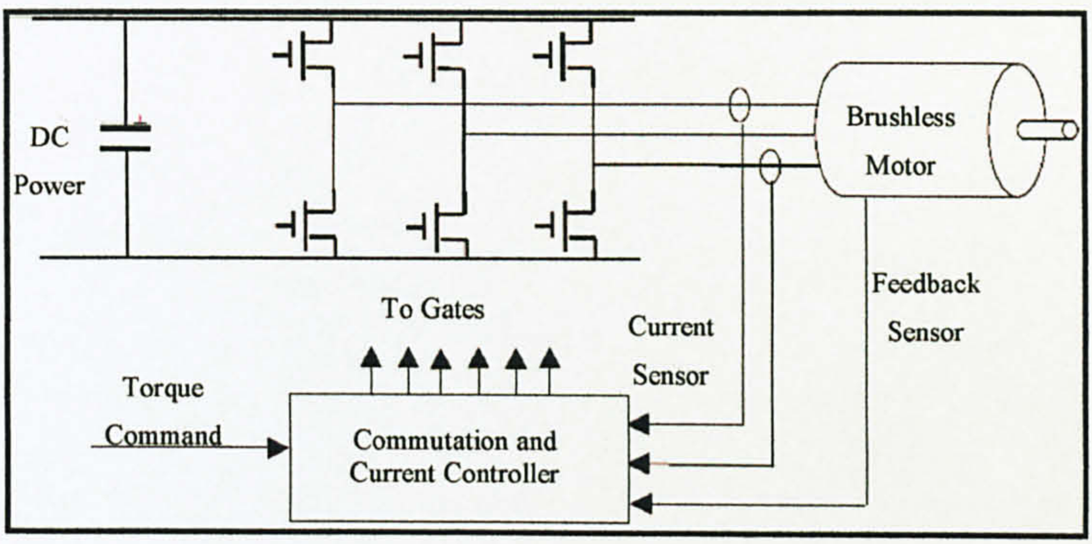


Figure 4 Typical BLDCM Drive System [5]

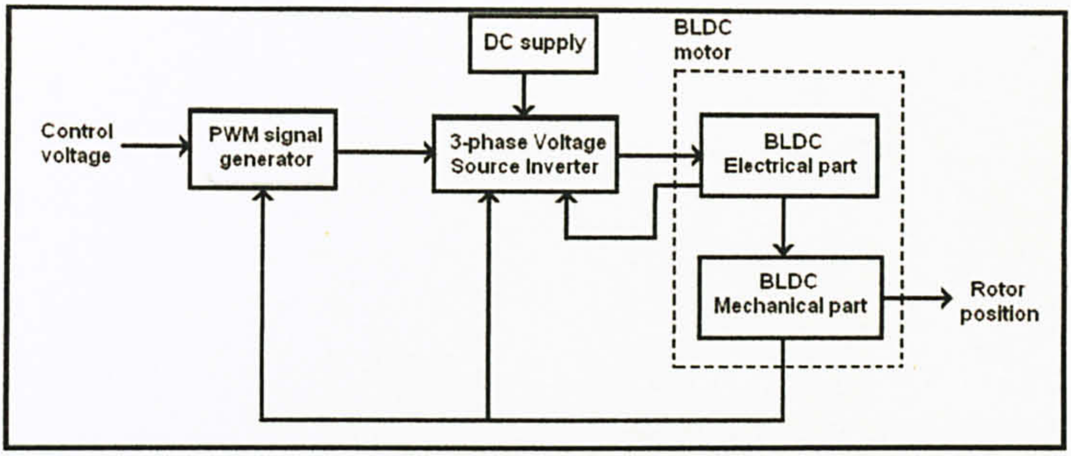


Figure 5 Block Diagram of BLDCM Drive System [4]

Figure 5 shows the block diagram of BLDCM drive system. It consists of four main components:

a) PWM signal generator
b) Voltage source inverter
c) Electrical part
d) Mechanical part

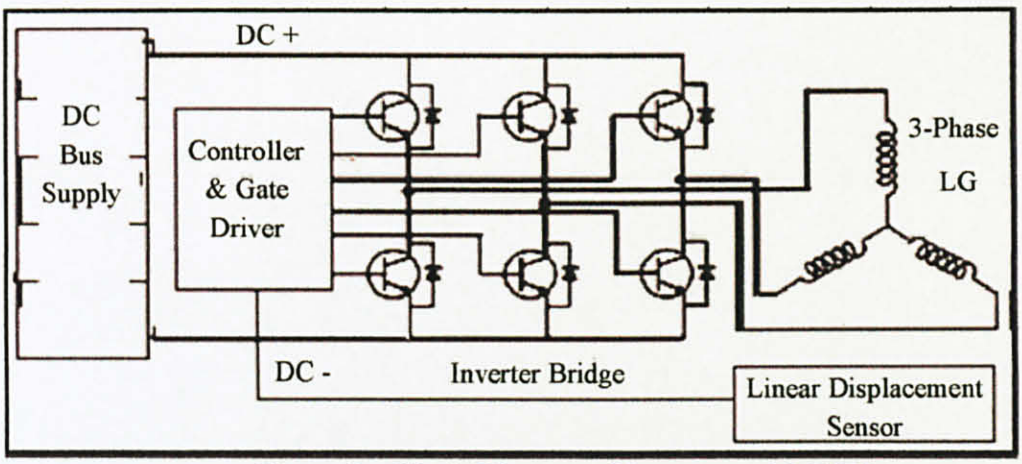


Figure 6 Block Diagram of Inverter and LG [3]

Figure 6 showing the inverter and 3-phase LG. The hardware responsible for current injection consists of a common type of motor drive used in rotating brushless motor applications.

2.5 BLDCM Commutation Technique

Current injection is vital for commutation process which will affect the effectiveness of the starting process of the linear engine – generator (LG). Current must be properly injected into the coil at the right time by switching on and off certain drive transistors based on translator position and electromagnetic K_V profiles of the 3-phases of the LG.

2.5.1 Rectangular commutation

Rectangular or block commutation consists of discrete on/off switching of the transistors at fixed, finite and pre-determined positions of the translator. Rectangular commutation can be achieved in the 2 variants of 6-step and square-wave.

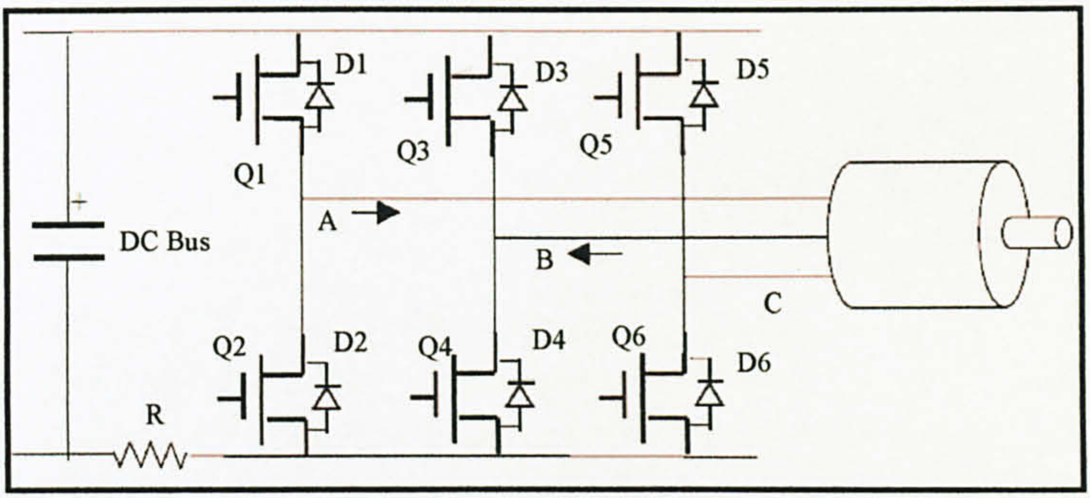


Figure 7 Switching Configuration [5]

Referring to Figure 7, the phase voltage can be divided into positive and negative. For the positive, the top switch will be on and the bottom switch is off while for the negative, the top switch will be off and the bottom switch will be on. When both switches are off, no voltage is injected and the terminal voltage is governed by the back EMF voltage of the motor.

2.5.1.1 6-Step

6-step commutation is widely used for BLDCM commutation because it's very simple compared to the other commutation. At any one time, two out of the three phases are energized so that current is positive in one phase and negative in another, while the remaining third phase is floating (not energized).

2.5.1.2 Square-wave

Square-wave commutation allows slightly higher current levels with the same DC bus voltage since all three phases are energized. Two phases having one current direction while the remaining phase has the opposite current flow. Therefore, with all phases energized (two positives and one negative or one positive and two negatives), more current can be injected into coils.

In both rectangular techniques, discrete switching of the transistors do not allow for the possibility of varying the effective level of injected current; it depends on the connected bus voltage and the circuit's effective resistance and inductance. To have a variable current level, the DC bus voltage needs to be made variable via a separate circuitry [2].

2.5.2 Sinusoidal commutation

Sinusoidal commutation is similar to rectangular commutation in the fact that it involves energization of certain pairs of transistors. However, instead of discrete switching, sinusoidal commutation performs the switching at a very high rate using the PWM technique.

To design a sinusoidal profile, we need to follow the electromagnetic Kv characteristics of the 3-phase motor. Sinusoidal commutation and closed-loop current control can make the effective current follow a certain pre-set current profile while the sinusoidal flux distribution can produce synchronized sinusoidal waveforms of the 3-phase currents. The resultant effective motoring force after summing up the individual force contributions from each phase is a constant-magnitude motoring force, neglecting non-idealities of harmonics and corresponding force ripples [1] [3].

2.6 Pulse Width Modulation (PWM)

The basic principle of PWM is that it uses high frequency of switching in order to allow regulation of the injected current by varying the duty cycle of the energized transistors.

The increasing of duty cycle will produce higher voltage hence will increase the speed of the motor. Since the brushless motor is highly inductive, the motor current produced from this switched voltage would be almost identical to that from the fixed voltage whose magnitude is the average of the switched voltage waveform. PWM is responsible to control the quantity of the injected current and this make it possible to control both motion and velocity of moving translator [6].

In this project, PWM technique is used in the second method to produce 3-phase AC sinusoidal voltage for a fixed DC source current control (DC-AC inverter) is implemented in this project.

2.6.1 Principle of 3-Phase PWM Inverter

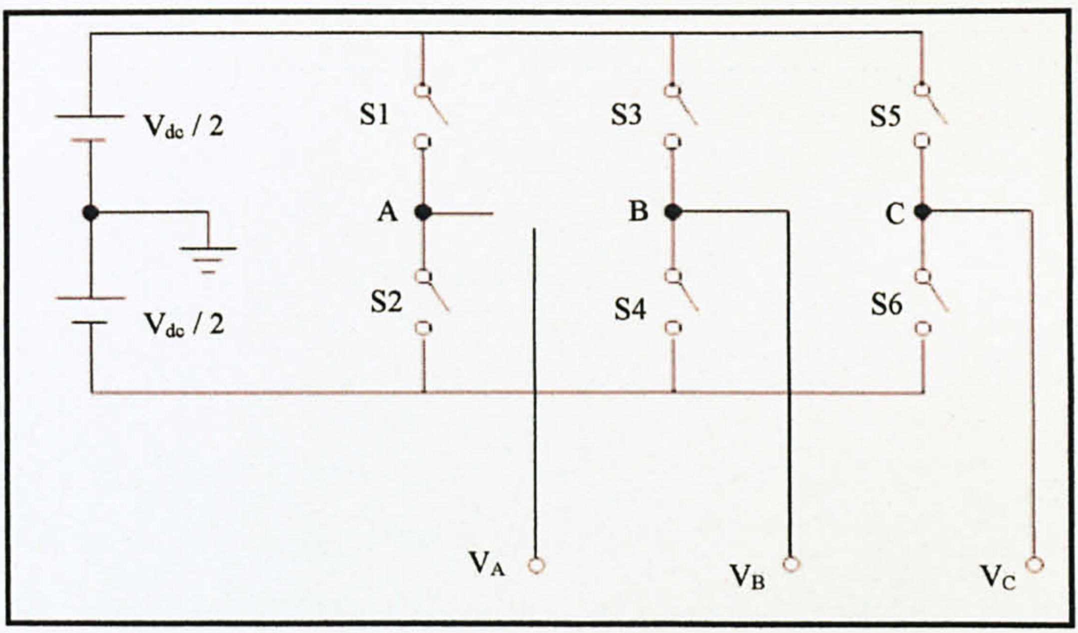


Figure 8 Three-Phase PWM Inverter [6]

Figure 8 shows the architecture of a three-phase PWM inverter. To produce the 3-phase AC sinusoidal voltage from a fixed DC source, a triangular of a same frequency as the PWM signal is compared to the 3-phase of sinusoidal signal. Whose phase is 120° apart from each other. The triangular waveform is calls the carrier wave signal (V_{tri}) and the sinusoidal signal becomes the control signal ($V_{control}$).

When the magnitude of the V_{tri} is larger than $V_{control}$, the PWM signal is off. Otherwise, when the $V_{control}$ is larger than V_{tri}, the PWM signal is on.

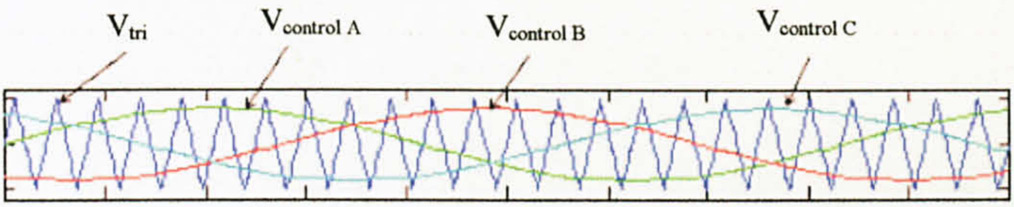


Figure 9 Waveform of three-phase sine PWM Inverter [6]

Figure 9 shows waveform of carrier wave signal (V_{tri}) and control signal ($V_{control}$).

CHAPTER 3
METHODOLOGY

The procedure and stages of the entire project is shown in the flowchart below.

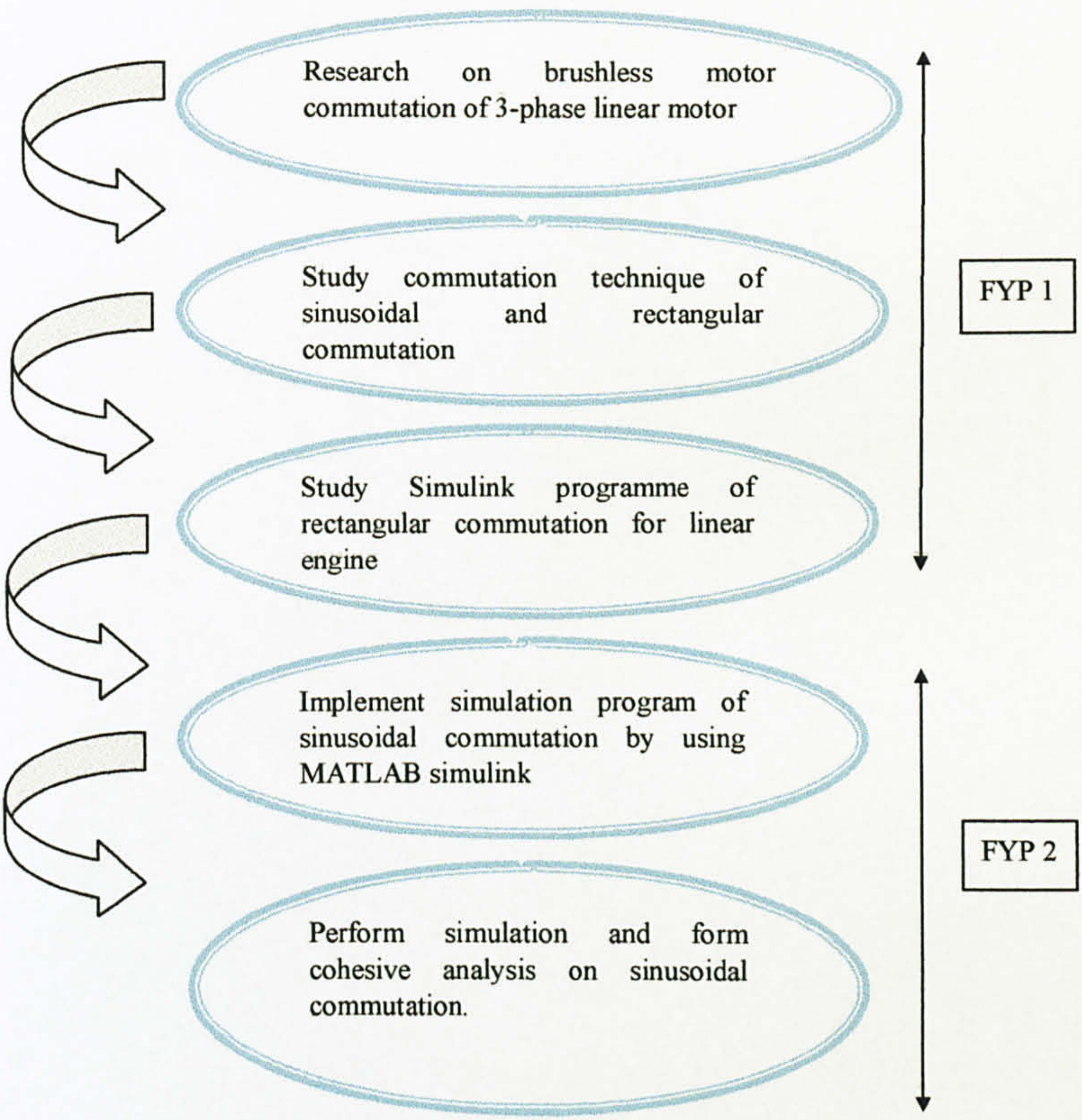


Figure 10 Flowchart of Methodology

CHAPTER 4
RESULTS AND DISCUSSION

This chapter will present the results of rectangular commutation and sinusoidal commutation: ideal AC voltage source energization and PWM switching method.

4.1 Rectangular Commutation

Rectangular or block commutation consists of discrete on/off switching of the transistors at fixed, finite and pre-determined positions of the translator.

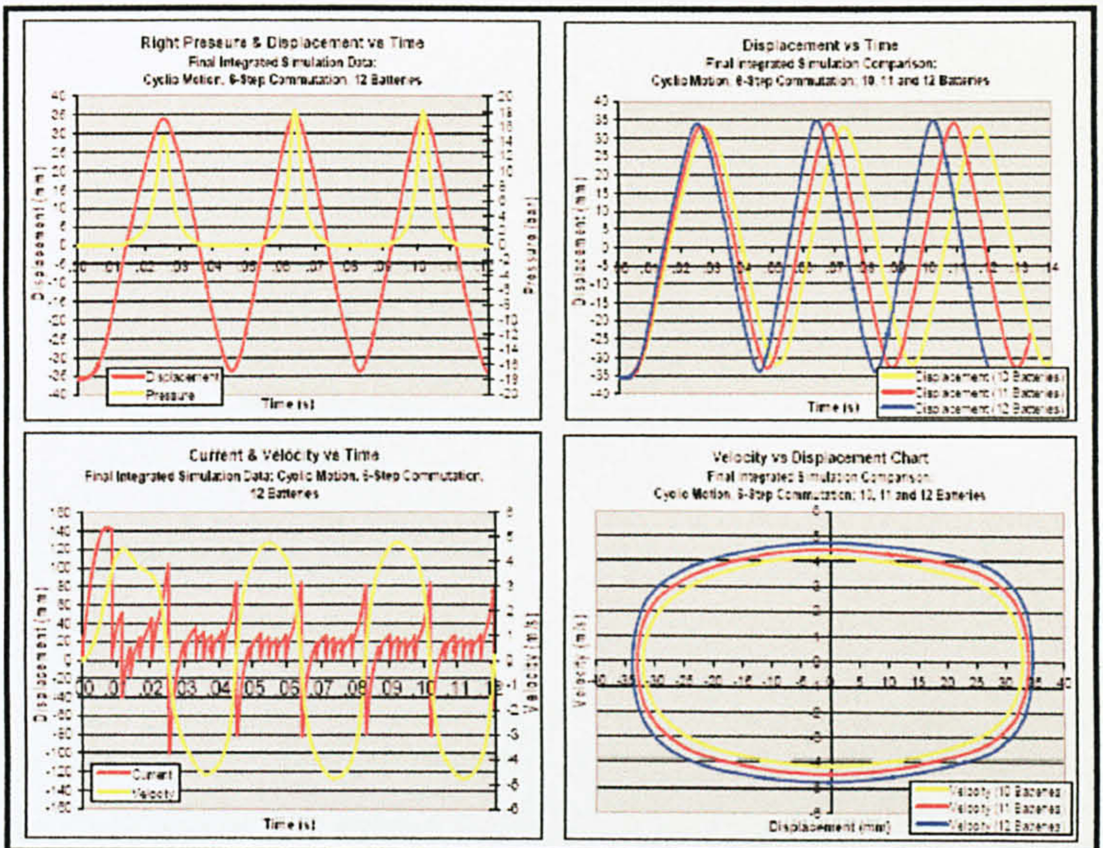


Figure 11 Results of final simulation tests with up to 144-Volt DC bus voltage [4]

For the results, it is shown that to achieve the required starting amplitude of 69mm, DC bus of 144V (12 batteries) is needed. Furthermore, the resultant frequency is about 26Hz is higher than required starting speed for the LG.

4.1.1 LG Block Diagram

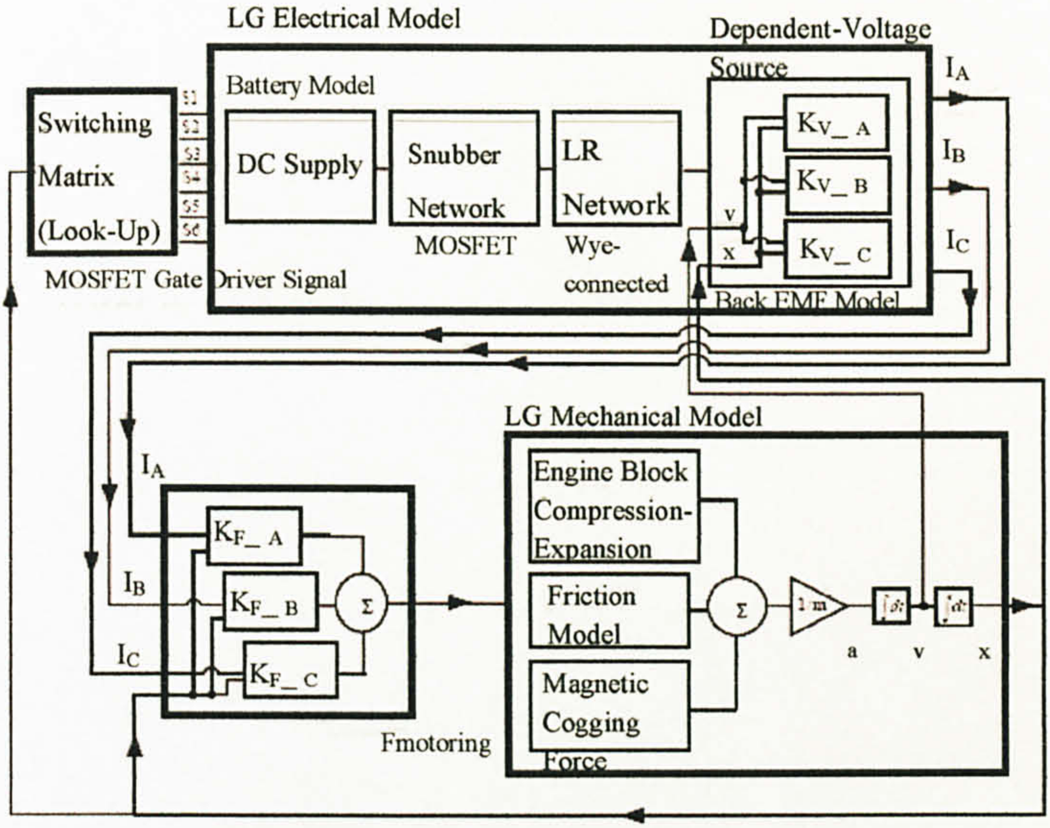


Figure 12 LG Block Diagram of Integrated Electrical and Mechanical Model [2]

4.1.2 Electrical Subsystem Model

A model for the electrical subsystems consists of a DC supply source, inductive-resistive network model, electromagnetic models of flux, K_v (emf) and K_f (motor force). The function of look-up table is to provide displacement points throughout the stroke of linear generator by rectangular commutation. The K_v (back emf) is a function of velocity. Output of the LG of electrical model is the 3-phase currents, I_A, I_B and I_C and it will become the input of LG Motor Force Model. Each phase is multiplied by K_f profile to produce the final motoring force, $F_{motoring}$. The resultant of

$F_{motoring}$ is an input to the mechanical subsystems model of LG. Motoring force is the output of the electrical subsystems and input of the mechanical subsystems, velocity and displacement are outputs of the mechanical subsystems and inputs of the electrical subsystems [2][3][9].

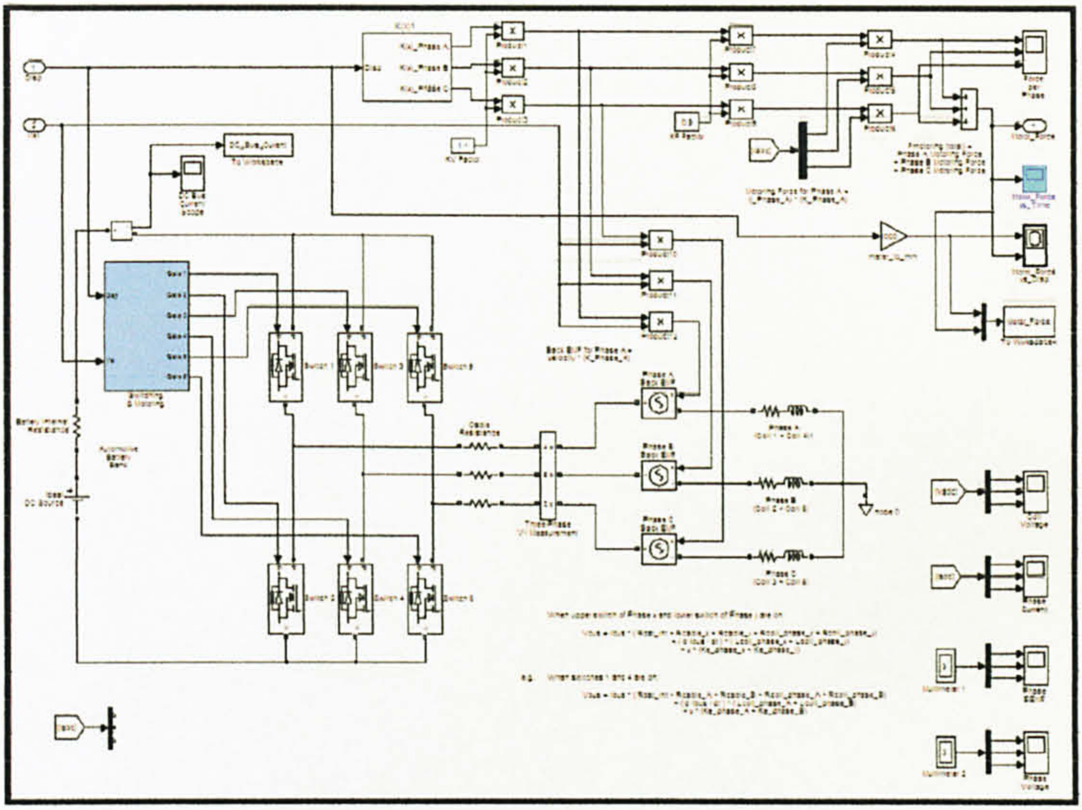


Figure 13 LG Electrical Model on MATLAB/simulink [2]

4.2 Sinusoidal Commutation

For this technique, it uses two methods:

a) Ideal AC voltage source energization
b) PWM switching method

4.3 Ideal AC Source Energization

The objective of this energization is to observe experimentally the effect of supplying a 3-phase AC voltage source; to achieve the sinusoidal commutation. By supplying AC voltage, regardless of the position of the translator, the following results are obtained.

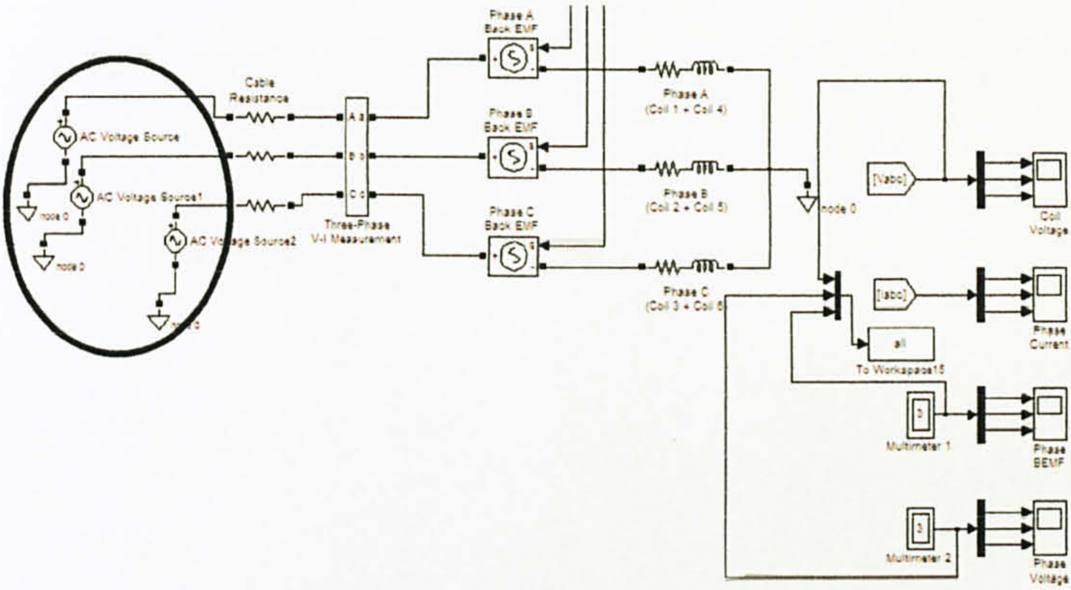


Figure 14 3-Phase AC Voltage Source Used to Replace Voltage-Source Inverter (MOSFETs)

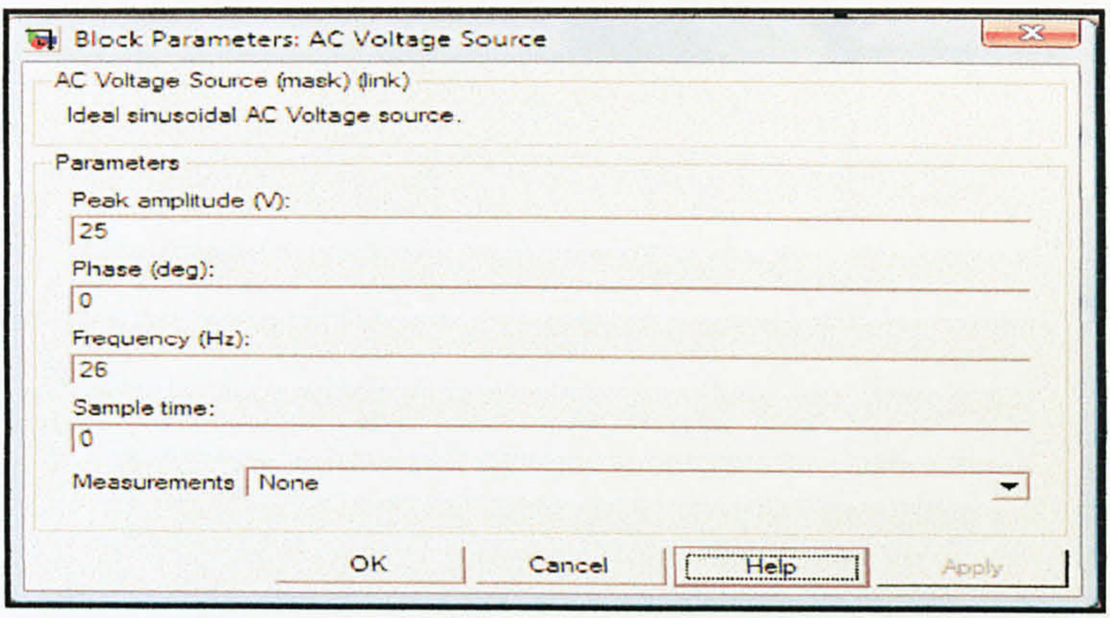


Figure 15 Block Paramters of AC Voltage Source [9]

4.3.1 Variation of AC Voltage Source

In this case, the applied voltage is varied from 25V-150V whilst the frequency is fixed at 26Hz. The frequency value is chosen at 26Hz because it was found as operating frequency in rectangular commutation. Different voltage amplitudes are tested: 25V, 50V, 60V, 70V and 150V. Motor force image and graphs of displacement versus time are captured from the simulation and shown below (Figure 16 to 27)

4.3.1.1 Results of 25V AC Amplitude

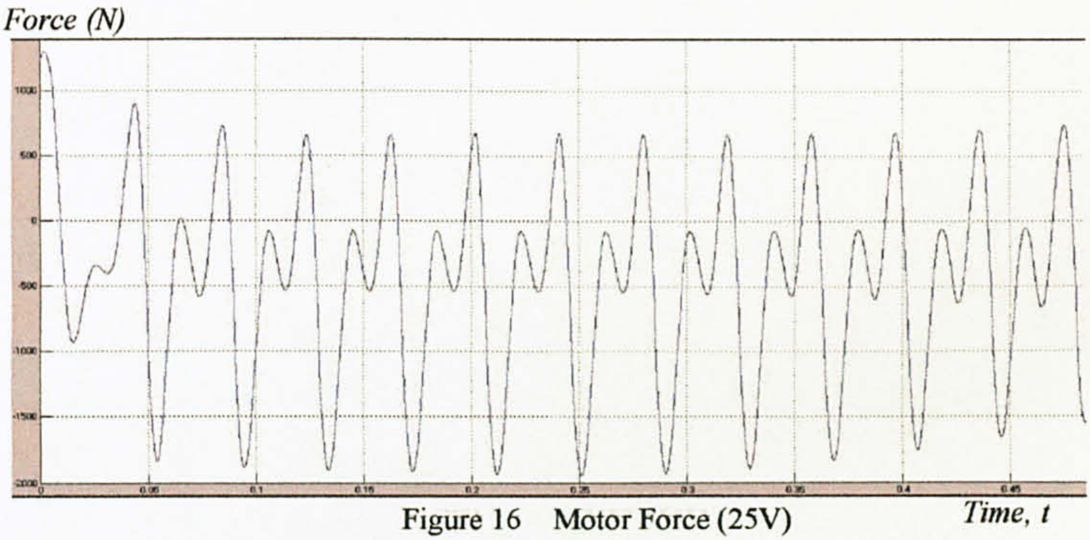


Figure 16 Motor Force (25V)

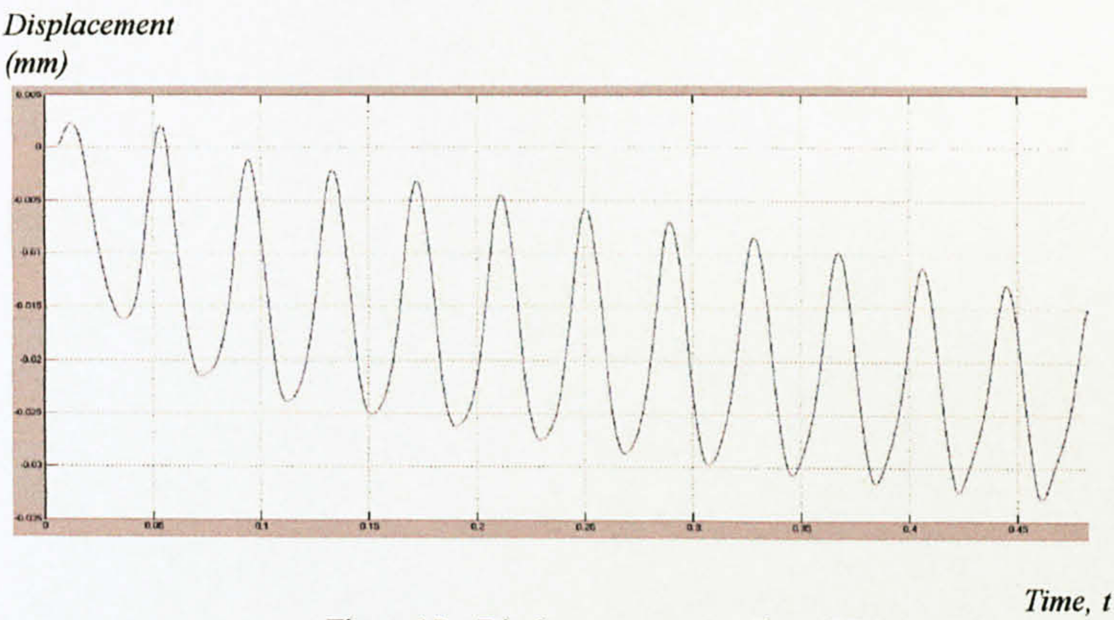


Figure 17 Displacement versus Time (25V)

4.3.1.2 Results of 50V AC Amplitude

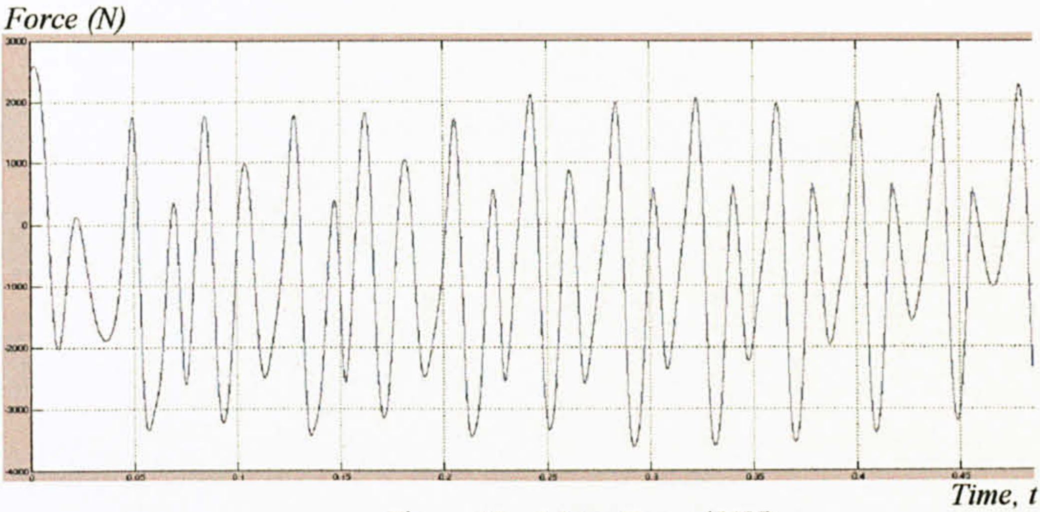


Figure 18 Motor Force (50V)

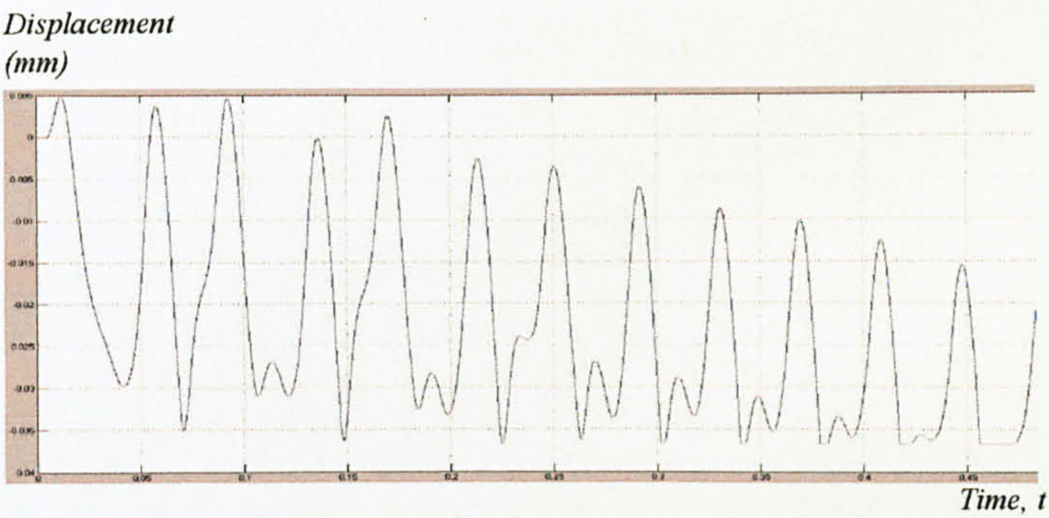


Figure 19 Displacement versus Time (50V)

4.3.1.3 Results of 60V AC Amplitude

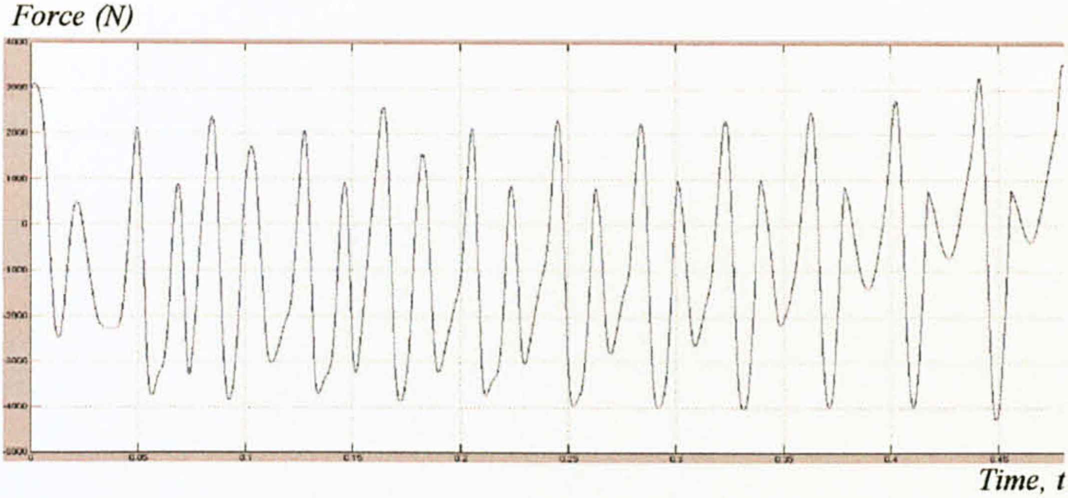


Figure 20 Motor Force (60V)

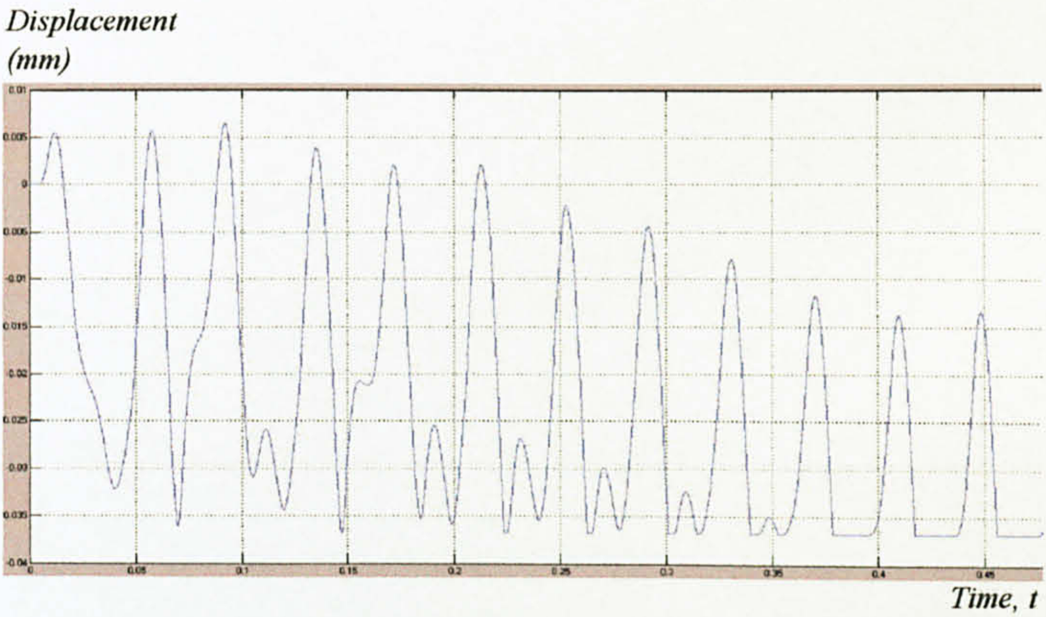


Figure 21 Displacement versus Time (60V)

4.3.1.4 Results of 70V AC Amplitude

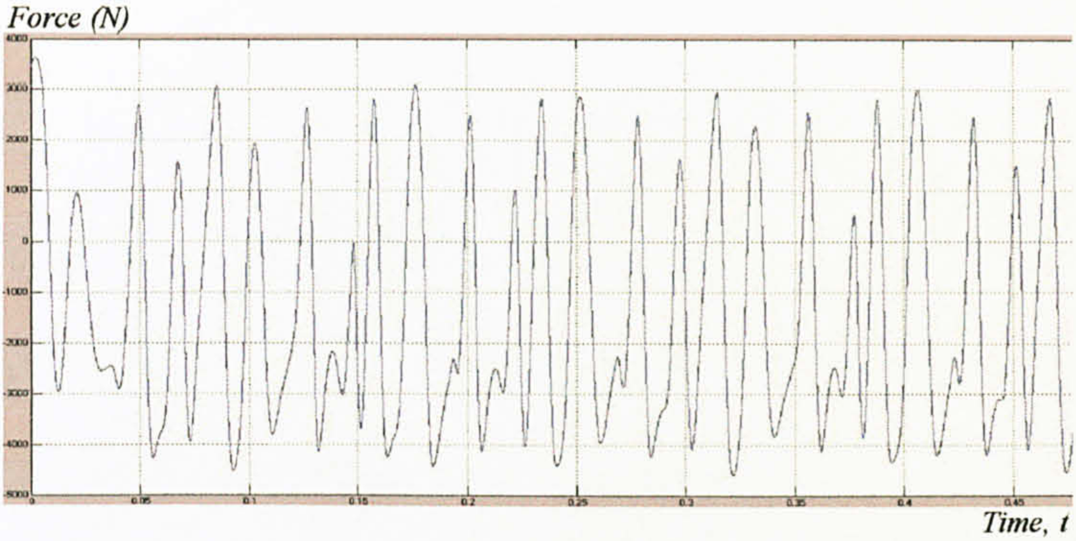


Figure 22 Motor Force (70V)

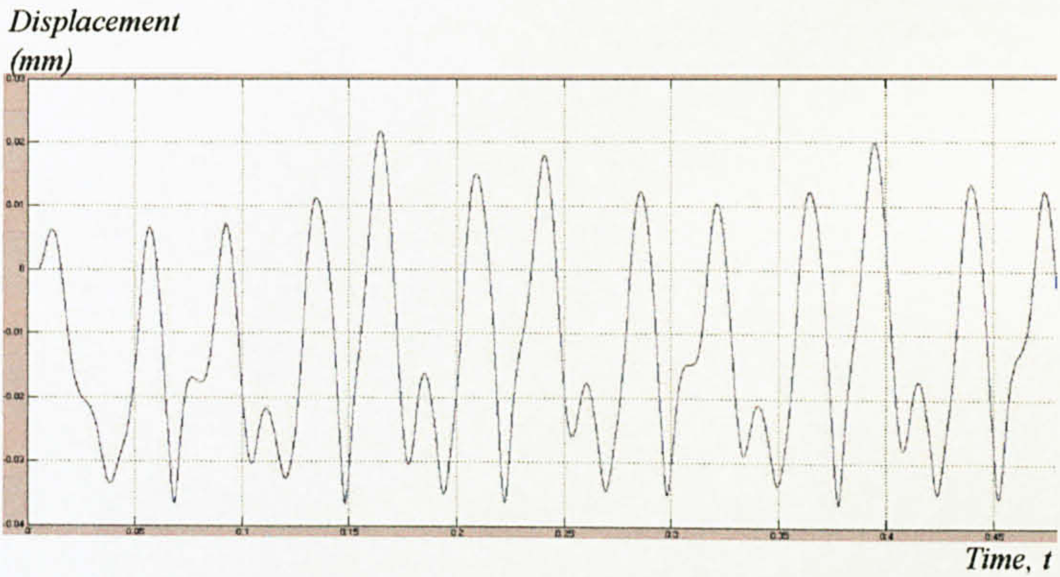


Figure 23 Displacement versus Time (70V)

4.3.1.5 Results of 90V AC Amplitude

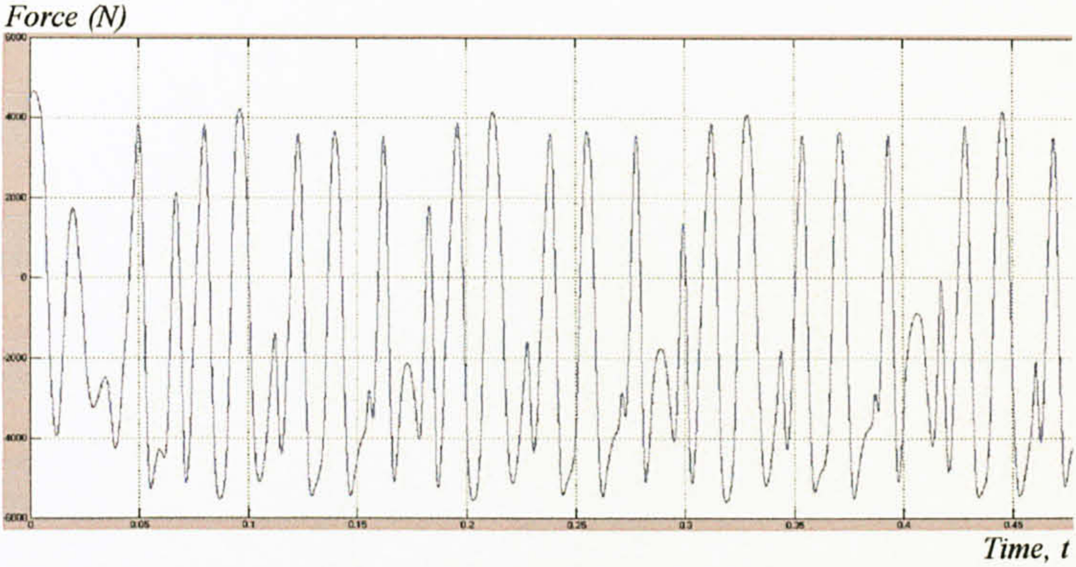


Figure 24 Motor Force (90V)

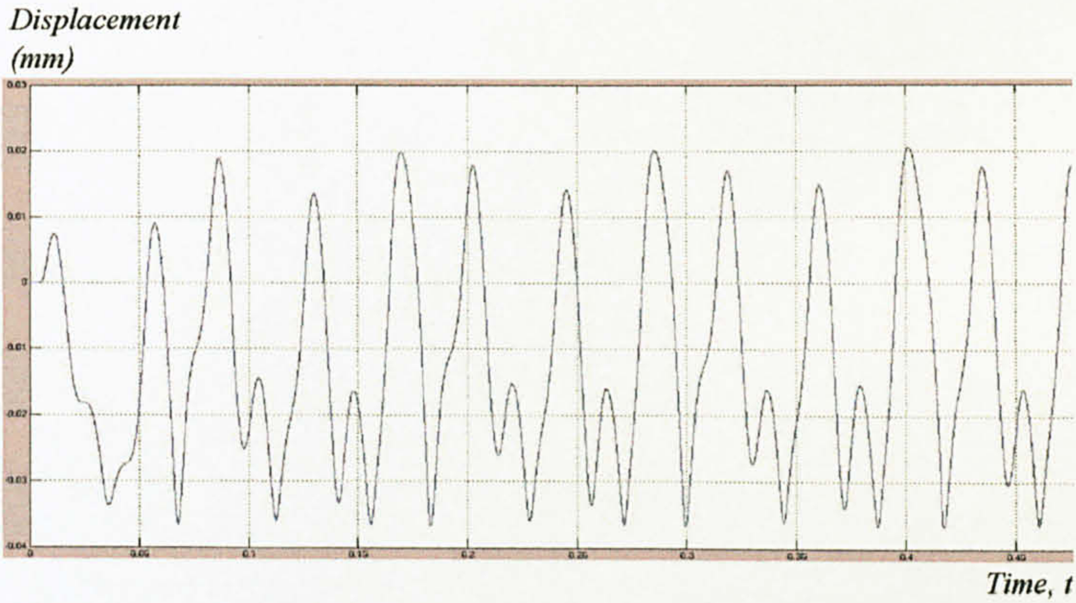
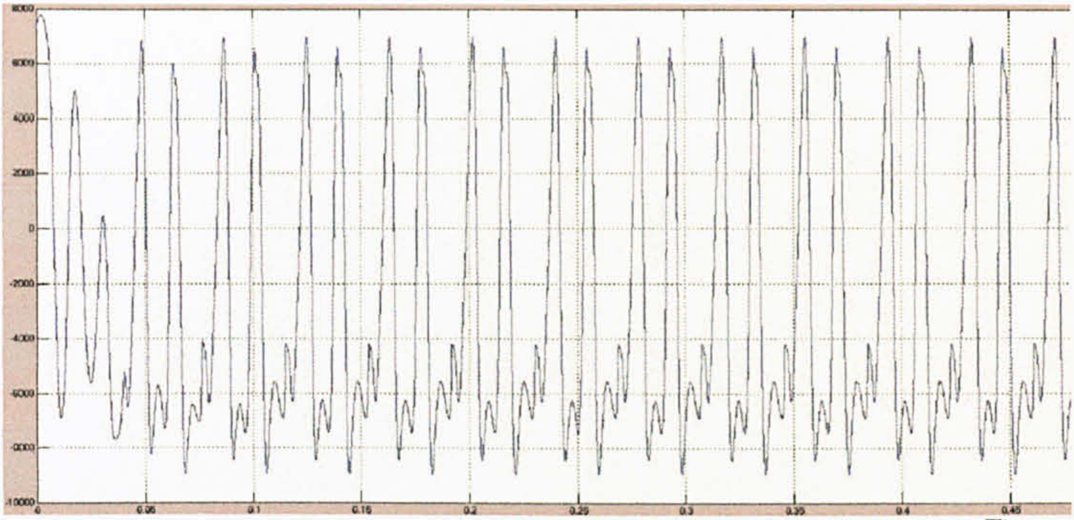


Figure 25 Displacement versus Time (90V)

4.3.1.6 Results of 150V AC Amplitude

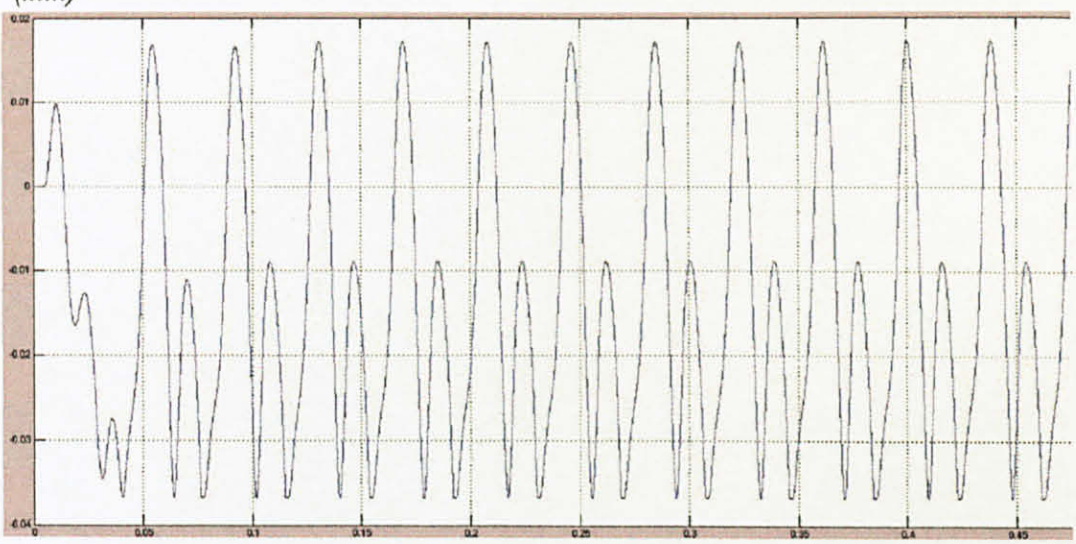
Force (N)



Time, t

Figure 26 Motor Force (150V)

Displacement (mm)



Time, t

Figure 27 Displacement versus Time (150V)

4.3.2 Choice of Suitable Voltage

After analyzing the result, it can be concluded that if value of voltage increase, hence the magnitude of motor will increase and the movement of piston will stay longer before it stop at some point. To choose the suitable voltage value, there are some parameters should be considered:

a) Consistency of waveform (Force)
b) Piston's ability to move (in time)
c) Heating factor

To satisfy the requirements, the value of 60V is an ideal value to use in this project. Even though the magnitude of 60V motor force is less than the range 90V and 150V, but it gives consistent and stable force value versus the period of time. It differs compared to the other voltage values which changing up and down rapidly in short of time. 60V of AC voltage source will enable the pistons to move from right to left. Although it would stand less than 90V and 150V sources, but it is still sufficient for the piston to move at the required condition.

Moreover, as voltage increases, the heating process will occur. Heating could damage the internal condition of the piston. As refer to the result, value of 60V is the turning point where the heating process will start to occur.

Furthermore, the usage of 60V at the car system is very practical compared to others. The weight of the batteries in the car system needs to consider wisely. In addition, the more voltage used, the more battery needed subsequently will increase the cost. In a nutshell, the value of 60V is very practical and fulfills the above requirement.

4.3.3 Variation of frequency

For frequency variation, the values are varied in the range of 21Hz-32Hz while the voltage amplitude is fixed at 60V. Once again, graphs of motor force and displacement versus time were captured from the simulation and shown in Figure 28 – 37.

4.3.3.1 Results of 21Hz

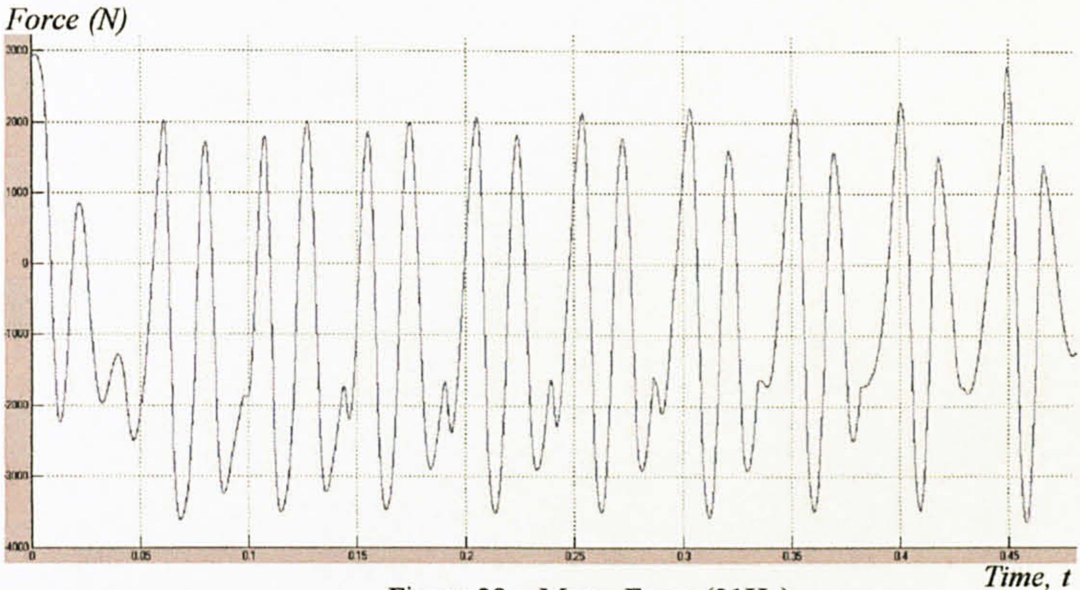


Figure 28 Motor Force (21Hz)

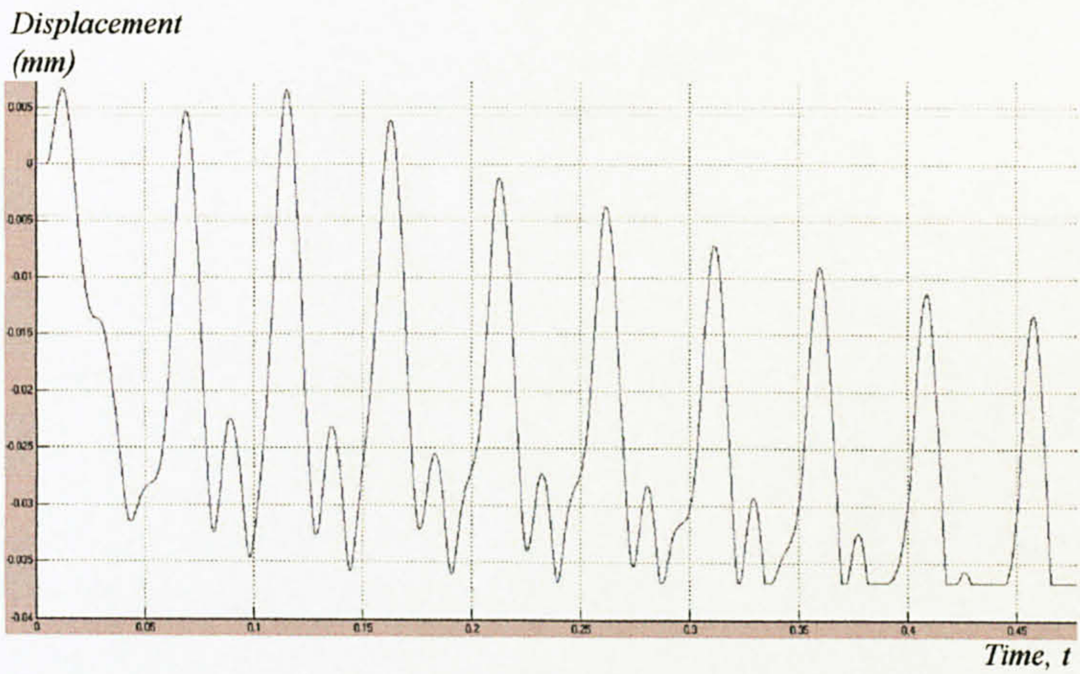


Figure 29 Displacement versus Time (21Hz)

4.3.3.2 Results of 23Hz

Force (N)

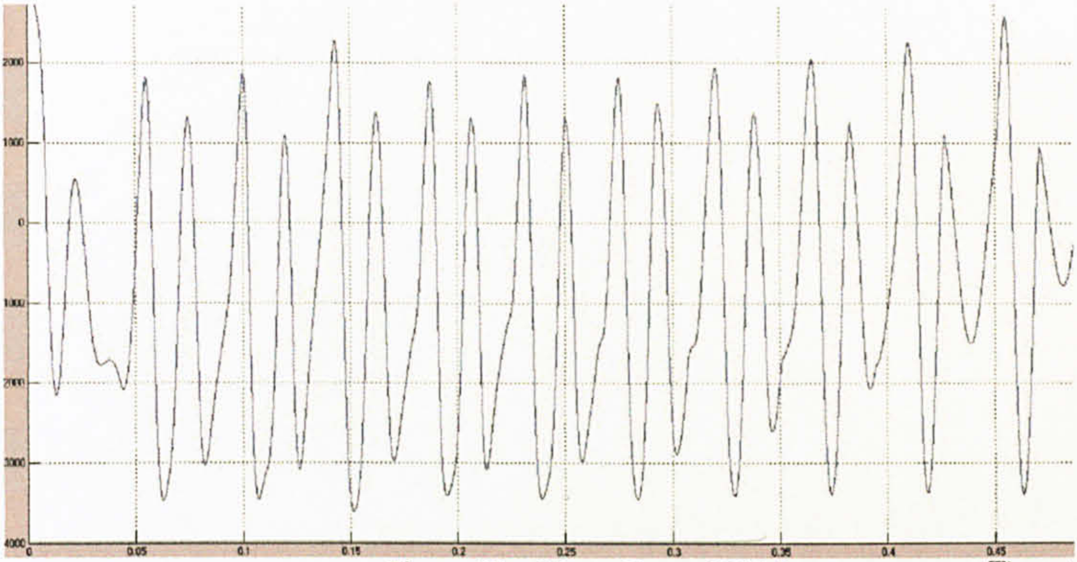
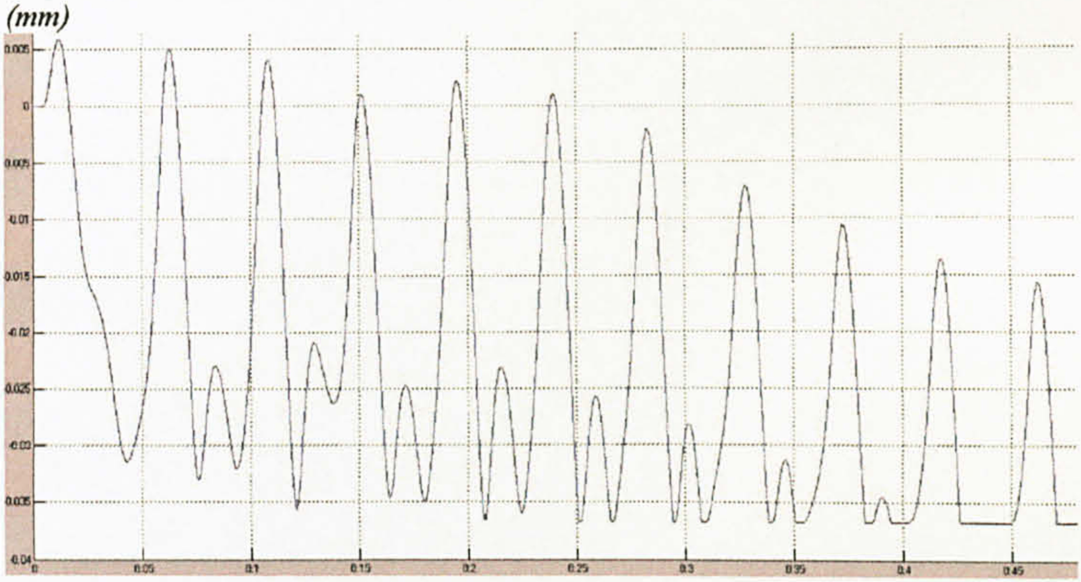


Figure 30 Motor Force (23Hz) *Time, t*

Displacement (mm)



Time, t

Figure 31 Displacement versus Time (23Hz)

4.3.3.3 Results of 26Hz

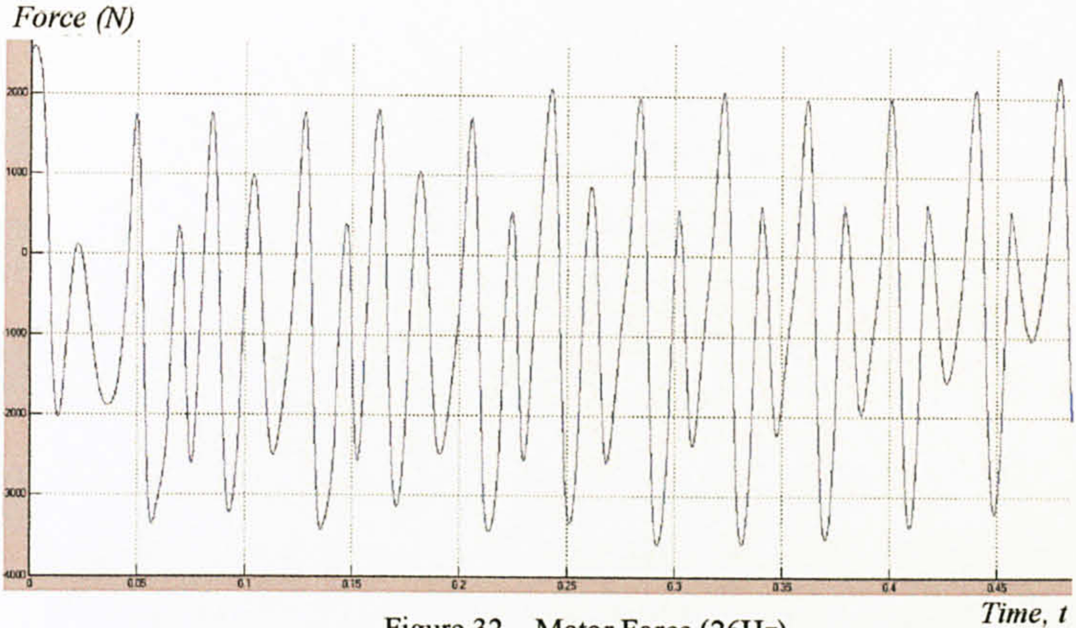


Figure 32 Motor Force (26Hz)

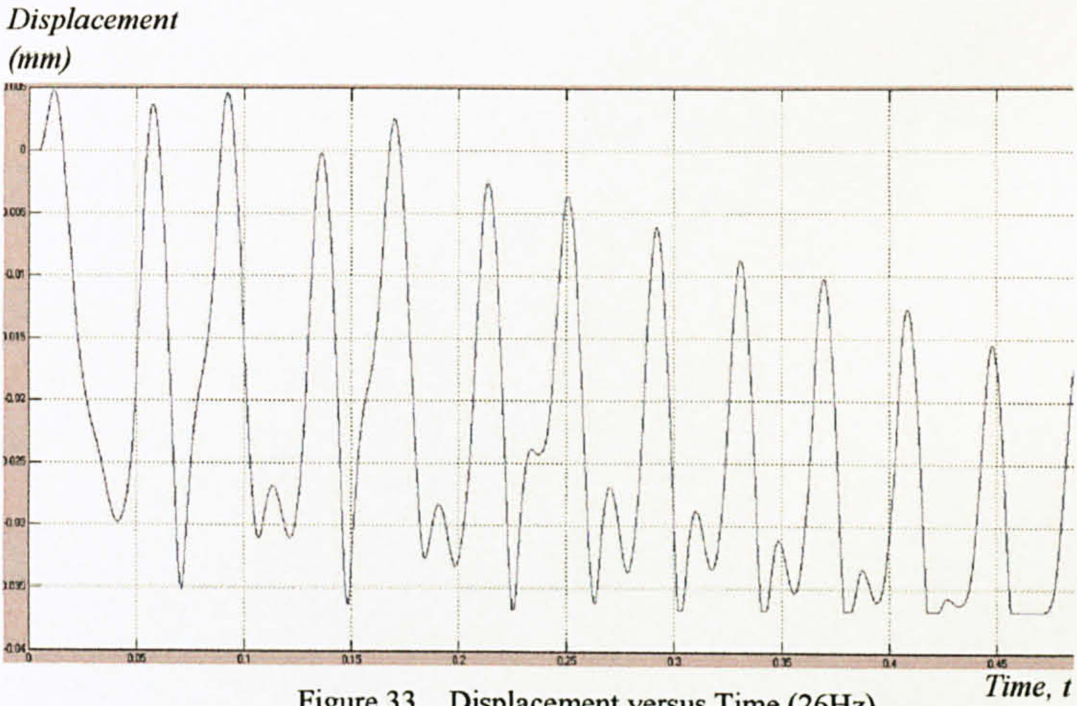


Figure 33 Displacement versus Time (26Hz)

4.3.3.4 Results of 29Hz

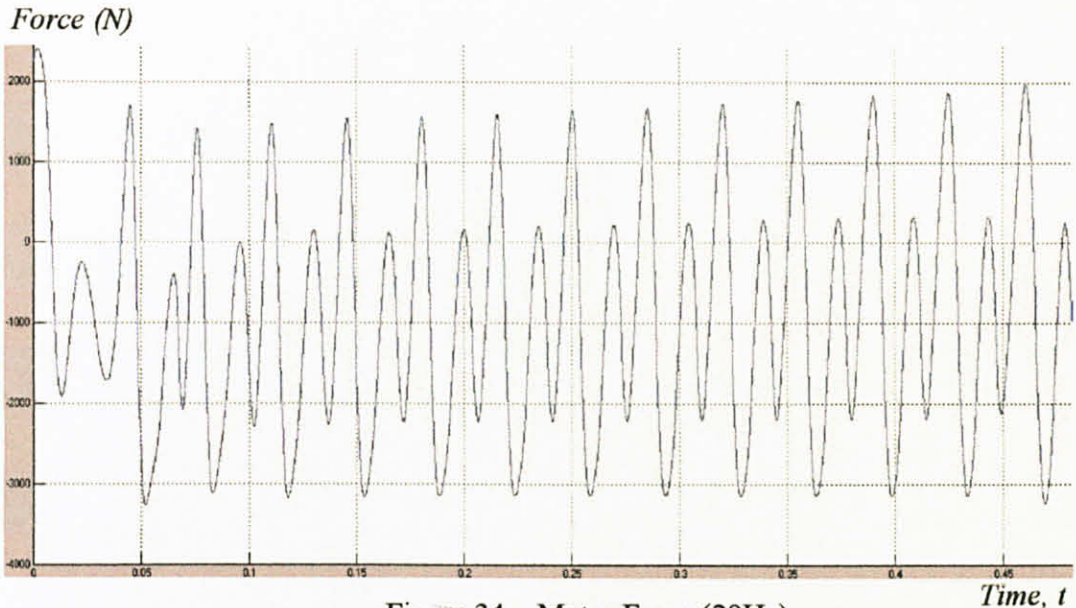


Figure 34 Motor Force (29Hz)

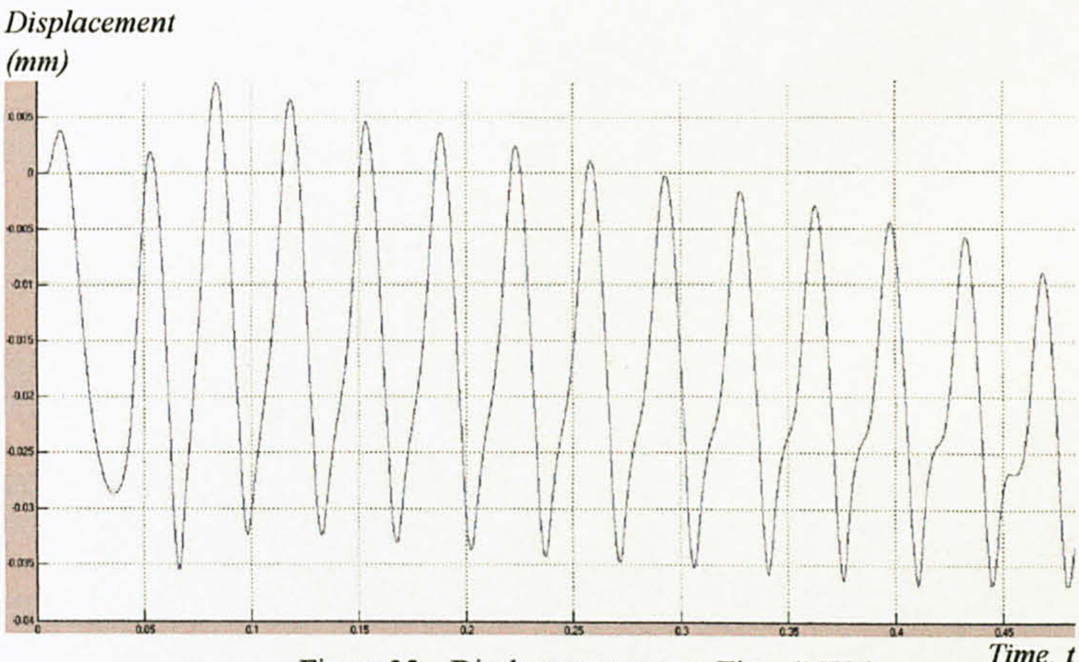


Figure 35 Displacement versus Time (29Hz)

4.3.3.5 Results of 32Hz

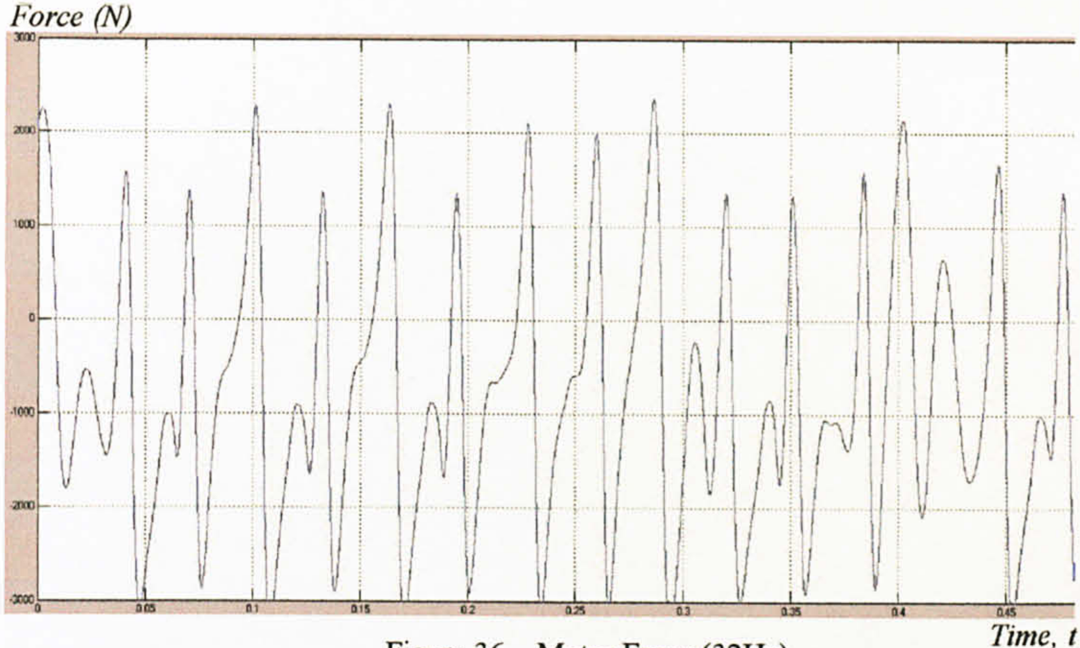


Figure 36 Motor Force (32Hz)

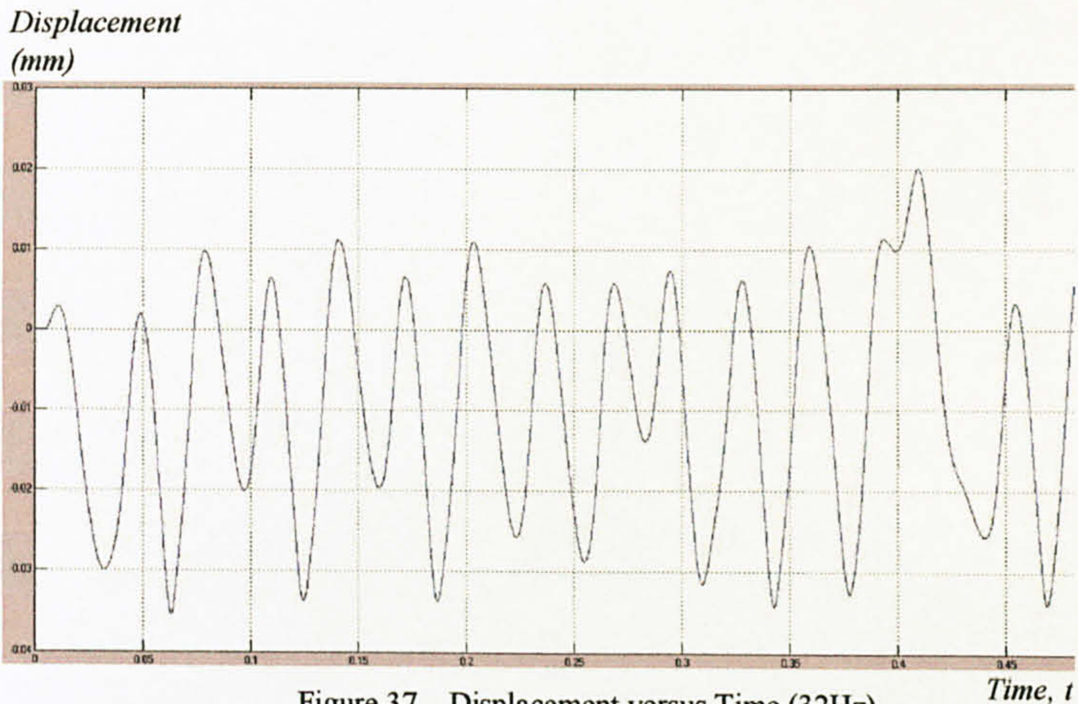


Figure 37 Displacement versus Time (32Hz)

4.3.4 Choice of suitable frequency

Based on the result, it can be seen the pattern of motor force and displacement versus time. Frequency will not affect the value of motor force because it's related to the time domain, not the amplitude. To decide which frequency is most suitable, the analyzing process was carried based on the displacement versus time graphs. The starting value is 26Hz. As the value increase to 26Hz, it's starting to get clean sinusoidal waveform and constant value of displacement against time. From the reading, the piston was pushed nearly identical from right to left. As the frequency value increase to 32Hz, it is hardly to see the improvement of the pattern as the reading goes unstable and the value of displacement starting to decrease. For conclusion, 26Hz was chosen as it gives stable reading of displacement.

4.4 PWM Switching

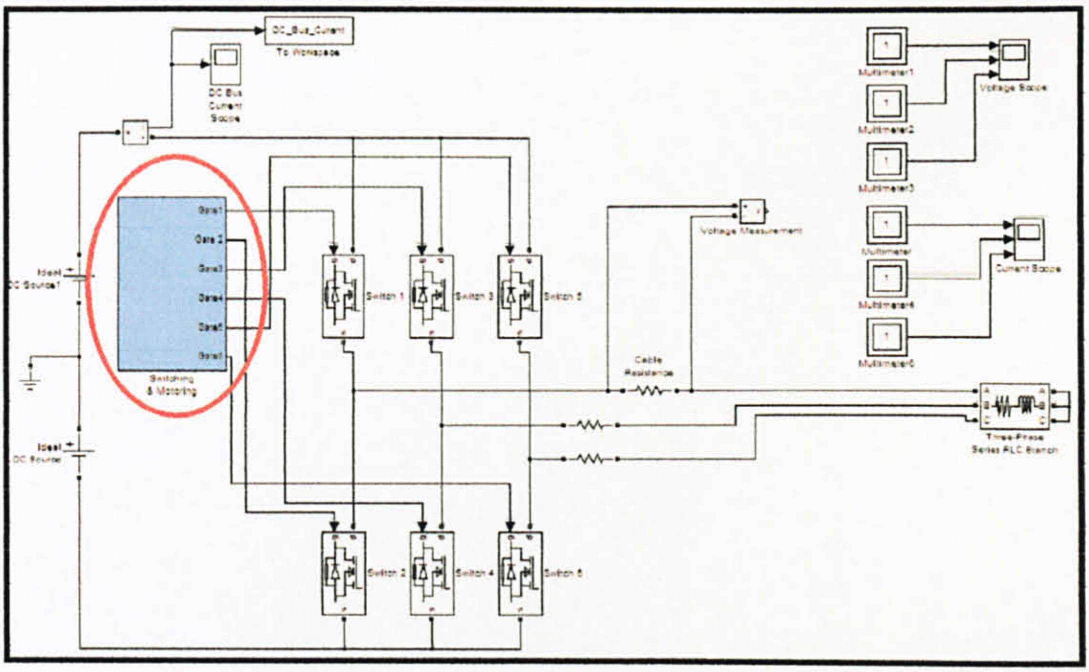


Figure 38 PWM Configuration

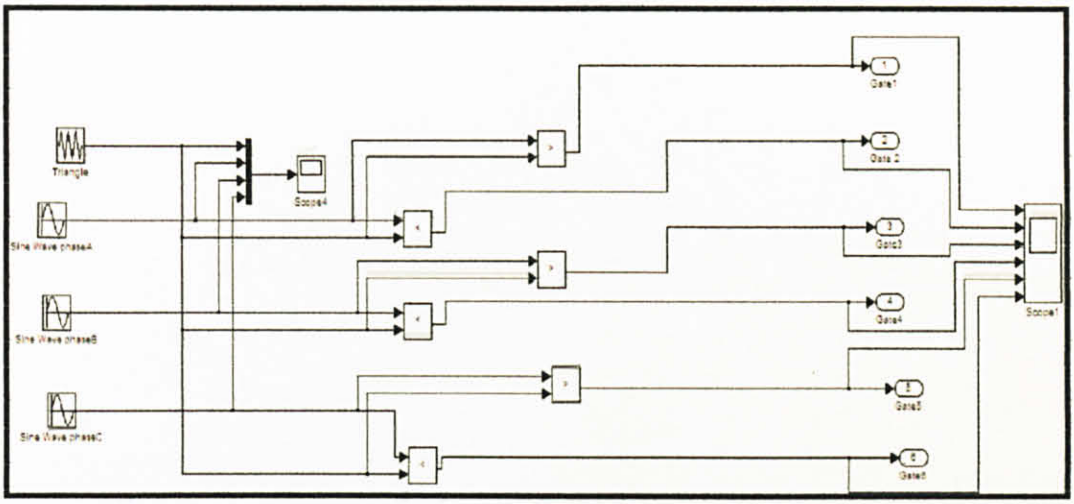


Figure 39   Configuration Inside the Gate Signal

Figure 38 and 39 shows the simulation models in producing the voltage waveform for PWM switching method.

4.4.1 PWM Result

At this stage of this project, this part on producing AC sinusoidal voltage from fixed DC bus produced the expected result of voltage and current waveform

Details of Triangular Wave (carrier wave):

a) Frequency : 2kHz
b) Amplitude: -1 to 1 unit

Details of Sinusoidal Wave (signal wave):

a) Frequency : 163.36rad/sec
b) Amplitude : -0.9 to 0.9 unit
c) Phase 120° apart: 0 rad/s (phase A) , 2.1 rad/s (phase B) and 4.2rad/s (phase C)

4.4.1.1 PWM Voltage Waveform

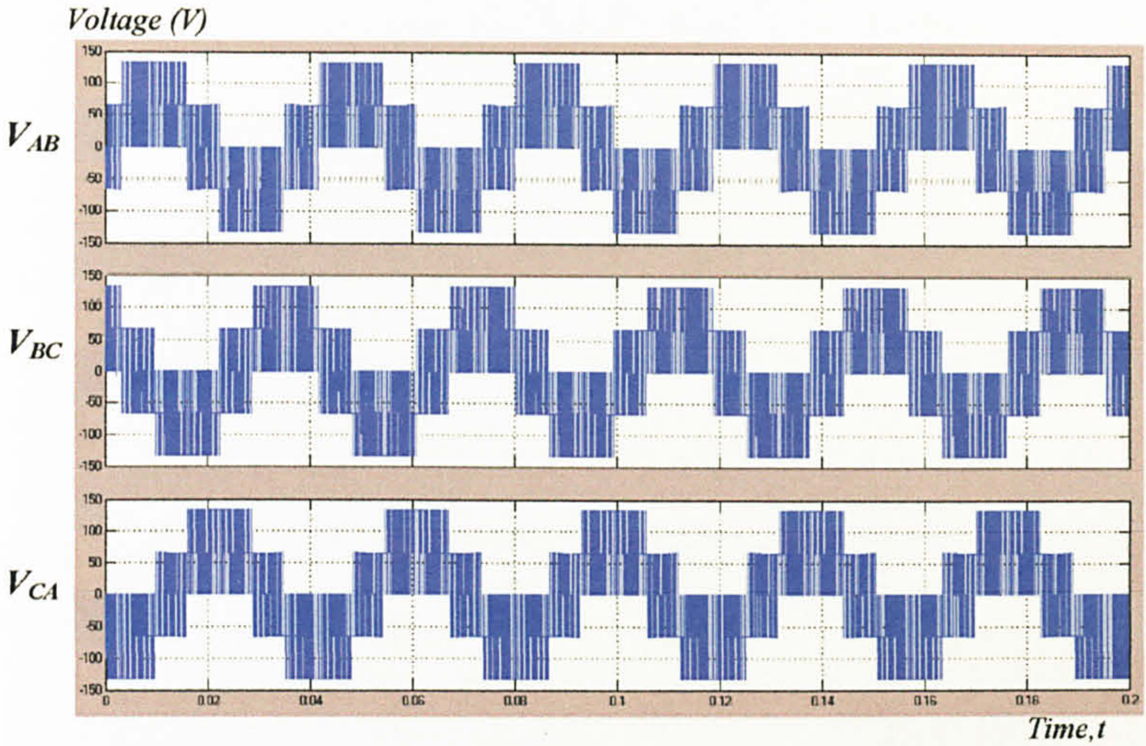
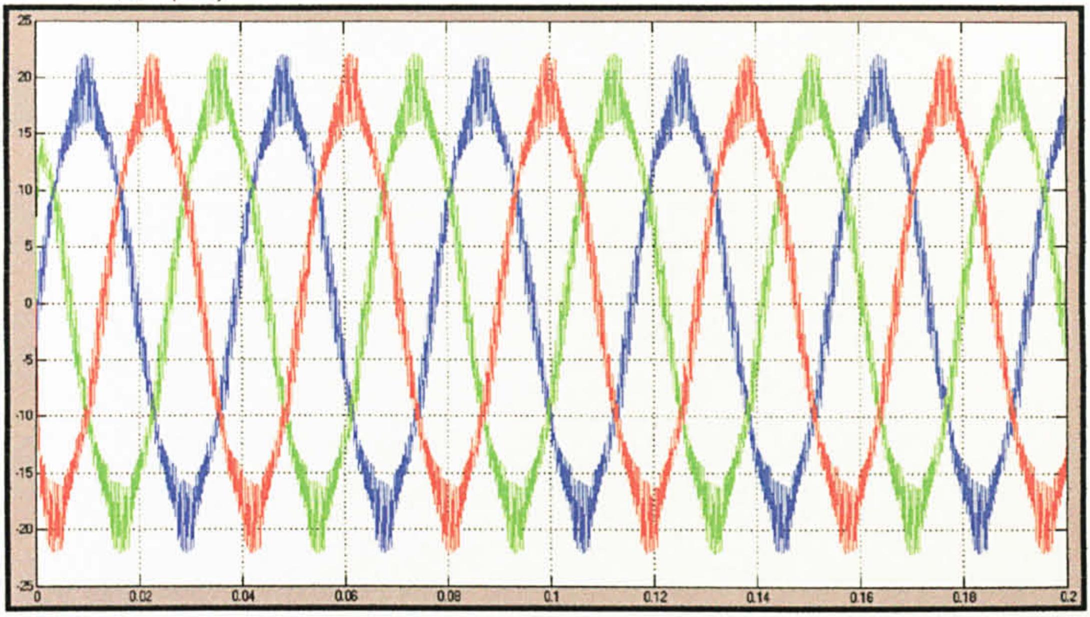


Figure 40 Inverter output voltage waveform generated from PWM switching method

For analysis, voltage waveform shown on Figure 40 consists of harmonics effect. Although the harmonics affect occurred, the pattern of voltage waveform still can be considered as following the desired voltage waveform (sinusoidal). Elimination of the harmonics effect is not covered for this project but only focusing on voltage level. For using 26Hz as signal frequency, it generates 133 Volts.

4.4.1.2 PWM Current Waveform

Current, A/ (mA)



Time, t

Figure 41 Current waveform generated from PWM switching method

Legend:

Blue: Phase A

Green: Phase B

Red: Phase C

For current waveform analysis, the simulated current waveform by using PWM switching method is identical to the desired current waveform (sinusoidal). The only different from the simulated is the existence of harmonics effect. It is hard to get the perfect and clean sinusoidal waveform without putting filter elements. It generates 22mA for 26Hz of frequency.

4.4.1.3 *Gate Signal*

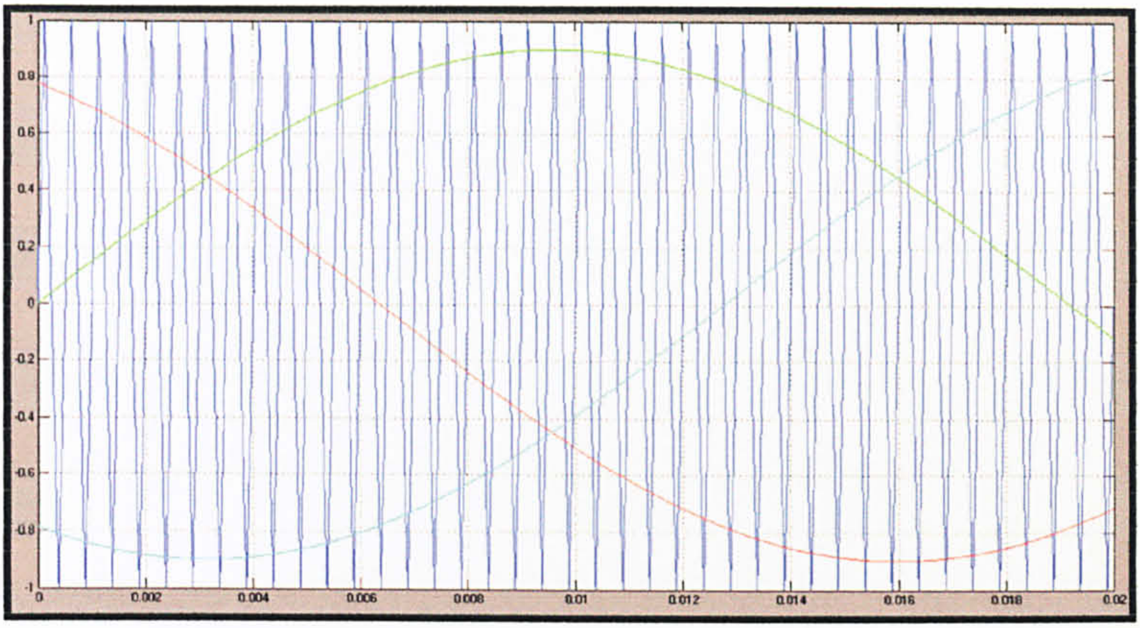


Figure 42 Comparison of Triangular and Sinusoidal waveform

Legend:

Green: Gate 1

Red: Gate 3

Blue: Gate 5

When the magnitude of the V_{tri} is larger than $V_{control}$, the PWM signal is off. Otherwise, when the $V_{control}$ is larger than V_{tri}, the PWM signal is on.

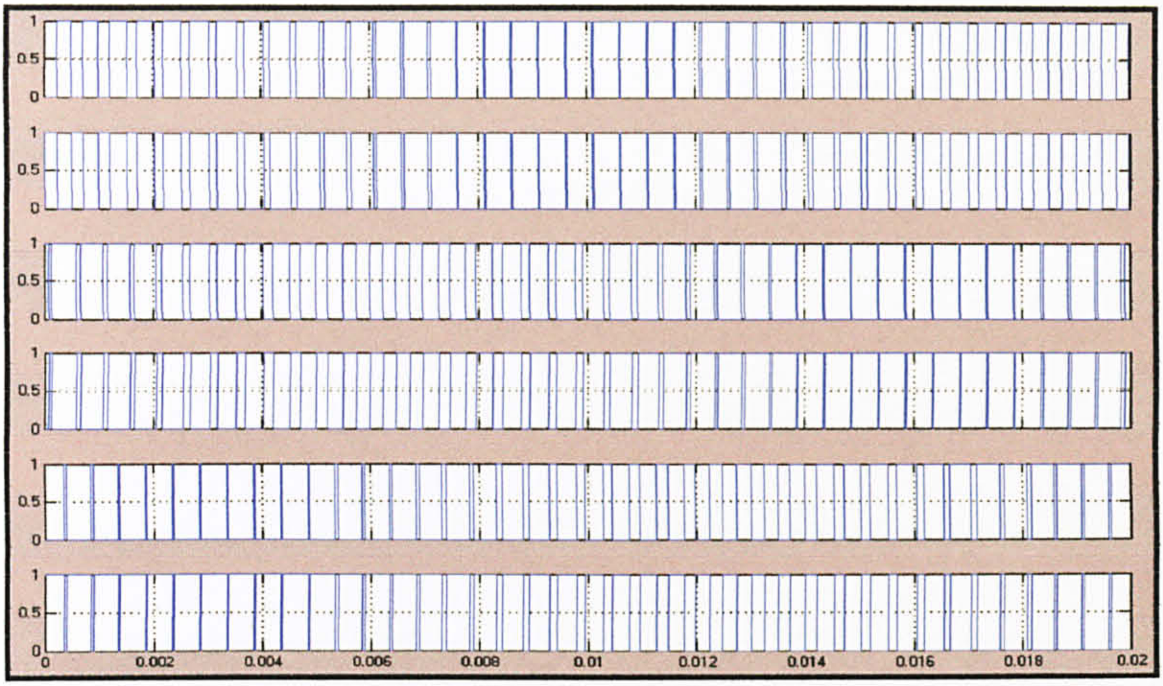


Figure 43 Gate Signal 1 until 6

Figure 43 is shown the result on which gates should be turn on at certain time.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This work investigates starting strategy for a 3-phase linear electric-generator (LG). The idea to start the LG is by injecting the certain amount of current into the stator coils that will produce motoring force which can effectuate the required reciprocating motion. Before that, the rectangular commutation of LG motor was studied and it can be classified into two types of switching strategy; six-step and square wave.

For sinusoidal commutation, it used two methods; by injecting the ideal AC voltage source to the electrical system and using Pulse Width Modulation (PWM) switching strategy. From the AC energization simulation, the suitable value of voltage and frequency are recorded. Frequency of 26Hz is used in the PWM switching strategy method. The objective of this energization is to observe experimentally the effect of supplying a 3-phase AC voltage source; to achieve the sinusoidal commutation. By supplying AC voltage, regardless of the position of the translator, the following results are obtained.

This project is only focusing on the electrical side where the electrical subsystem is redesigned from the rectangular commutation. This to ensure the objective of switching strategy by using sinusoidal commutation is achieved.

For the last part of this project is to design the model on PWM switching.
The models are validated with series of simulations. By using 26Hz of frequency, sinusoidal inverter output voltage (133V) and current (22mA) are obtained.

5.2 Recommendations

For future work, this work can be enhanced into the real application where it involves the usage of software and PXI controller by National Instruments hardware interfacing with the real model of engine.

Software P-Spice also can be used to design the circuitry of PWM. It will help to find the desired operating frequency and able to capture the pattern of sinusoidal waveform.

Furthermore, filter can be added into the program in order to eliminate the distortion effect. More clean voltage and current waveform can be obtained hence will lead to accurate interpretation of sinusoidal performance.

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