SIMULATION OF VOLTAGE-SOURCE INVERTER DRIVE FOR STARTING OF LINEAR ENGINE-GENERATOR

By

SITI NORFADZIELAH BINTI AYUB

FINAL REPORT

A project dissertation submitted to the
Electrical and Electronics Engineering Programme
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical and Electronics Engineering)

Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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Approved by:

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(A.P. DR. Mohd Noh Karsiti)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
SEPTEMBER 2011

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 acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

....

(Siti Norfadzielah binti Ayub)

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ABSTRACT

The pulse width modulation inverters have been increasingly using to convert DC source to AC source. DC source is one type of energy that can be found in battery and AC is a type of energy that is mostly used to supply electrical appliances. When these inverters are used for power conversion, the integrated output voltage waveform is inevitably distorted. There are various techniques such as analogue filtering, harmonic elimination and so on to reduce the number of harmonics usually affecting the system performance. Pulse width modulation is a technique that uses a way to decrease a total harmonic distortion in inverter circuit. The simplest form of an inverter is the full-bridge inverter where a power bridge is controlled according to the sinusoidal pulse-width modulation (SPWM) principle and the resulting of PWM wave is filtered to produce the alternating output voltage. However the amplitude of AC signal cannot easily adjusted because it is affected by some parameters such as switching frequency, modulation index, frequency of output voltage and also DC source itself. Therefore, this project aims to investigate the effect of these parameters such as modulation index onto inverter's output and also linear engine-generator (LG) performance. The LG is an electric generator which is an electromechanical device capable to convert mechanical energy into electrical energy as the final usable output. It is made as platform to convert mechanical to electrical energy through a particular arrangement with a linear generator and operated as a brushless or permanent-magnet linear motor to provide the force to reciprocate the piston. The model of the inverter and electrical subsystem of LG were implemented using MATLAB/Simulink with the SimPowerSystem application.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

A free-piston linear engine-generator (LG) is made as platform to convert mechanical energy of the reciprocating translator or piston assembly to electrical energy through a particular arrangement with a linear generator. The LG will be operated as a brushless or permanent-magnet linear motor to provide the force to reciprocate the piston assembly. Inverters are divided into voltage-source inverter (VSI) and current-source inverter (CSI). The dc source in a VSI is a fixed voltage such as battery, fuel cells, solar energy and dc generator [1]. The mainly purpose of designing inverter is to convert DC voltage source from batteries to AC to run LG. There are many type of inverters such as half-wave inverter and full wave inverter and they are also can be designed to be single-phase full bridge (H-bridge), two-phase inverter and three phase inverter. In this project, full-bridge three phase inverter will be implemented as inverter where a power bridge is controlled by sinusoidal pulse-width modulation (SPWM).

This project aims to develop a sinusoidal pulse width modulation inverter that will be implemented to linear engine-generator electrical subsystem circuit. The model is implemented using MATLAB/Simulink software with the SimPowerSystem Block Set based on computer simulation. Computer simulation plays an important role in the design, analysis and evaluation of power electronics converter and their controller. MATLAB is an effective tool to analyse a PWM inverter. In PWM, the amplitude of the output voltage can be controlled by width of the modulating waveform. The effect of variation modulation index values will be investigated to validate the ideal value for better performance of LG.

1.2 Problem Statement

LG was designed as prime mover for electricity generator and to start this engine, LG will be energized electrically by using DC source from batteries. The inverters are used to convert DC source to AC source. However, the amplitude of AC signal from the output of DC-AC inverter cannot easily be adjusted because it is affected by many factors. This project investigated and validated the influence of parameters such as modulation index and output voltage frequency on linear engine-generator.

1.3 Objectives

The main objective of this project is:

- To investigate effect of parameter such as modulation index and frequency on displacement and motor force of linear engine-generator (LG).

In order to achieve the main objective, this study must achieve the following sub-objectives:

- To study the function of inverters and its parameters.
- To design three-phase inverter model using MATLAB/Simulink.
- To observe its effect on three-phase inverter and linear engine-generator (LG) through simulations.

1.4 Scope of Study

In order to achieve the above objectives, the scope of work of this study was carried out as following:

1. Study about inverters and basic operation of linear engine-generator (LG).
2. Modeling and simulation using MATLAB/Simulink.
3. Vary modulation index value and other parameters.

CHAPTER 2
LITERATURE REVIEW

2.1 Brushless Linear Motor

Linear motors also known as linear induction motors are a special class of synchronous brushless dc motor (BLDCM). Linear motor produces motion in a straight line rather than rotational motion. It works like rotary motor, but is opened up and rolled out flat. The electrical energy is converted to linear mechanical energy with a high level of efficiency through the electromagnetic interaction between a coil assembly and a permanent magnet assembly. In rotary motors, the rotor and stator require rotary bearings to support the rotor and maintain the air gap between the moving parts. In the same way linear motors require linear guide rails which will maintain the position of the forcer in the magnetic field of the magnet track. At the same time rotary servo motors have encoders mounted to them, to give positional feedback of the shaft. Linear motors need positional feedback in the linear direction and there are many different linear encoders. By using a linear encoder, position is directly measured from the load and this again increases the accuracy of the position measurement [3].

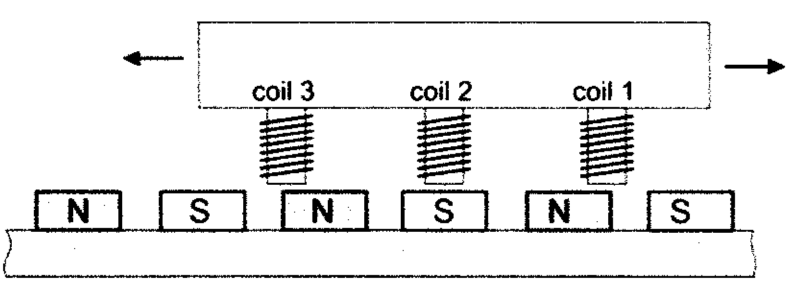


Figure 1: Magnets position on a flat surface

2.2 Basic Operation of Linear Motor

The category of application of the LG during starting is same as permanent-magnet BLDCM operation. The theory and concepts of BLDCM can apply equally well to a brushless linear motor and also to provide the force for reciprocating motion. Linear engine is made as platform to convert mechanical to electrical energy through a particular arrangement with a linear generator. Basically, the linear engine designed as prime mover for electricity generation as a practical method to start the engine to energize the LG electrically using stored electrical energy in batteries [1,2].

The electrical power is supplied to the linear engine to produce a reciprocating motion and operate as a linear motor. There is no usable of mechanical power or torque output and also none of the rotating components of conventional engine. A linear electric generator produces electricity directly from the linearly reciprocating motion of a single-moving assembly of one or more piston that connected to a linear shaft [1].

Current that was injected into the stator coils will create a magnetic field of the permanent magnets on the translator shaft. Hence, a motor force is created will push on the translator shaft with a certain magnitude. However, the direction of the translator's motion will depend on the relative position of the permanent magnets with respect to the fixed stator coils [1].

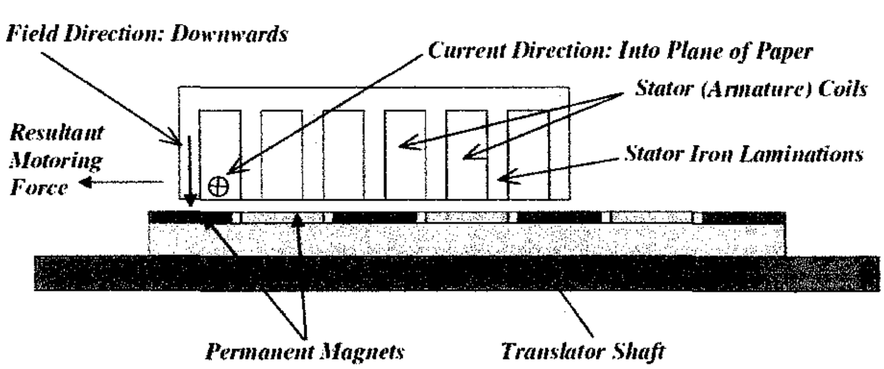


Figure 2: Interaction of Magnetic Fields in Linear Generator [1]

2.3 Inverter

Inverters or power inverters are used in wide range applications, as in situation where low voltage DC sources such as batteries, solar panels or fuel cells that must be converted to AC power for most electrical appliances. There are many type of inverters have been developed and the most common of inverters are square wave inverter, modified square wave inverter and pure sine wave inverter. The three different wave signals represent three different qualities of power output.

2.3.1 Square Wave Inverter

Square wave inverters were the first types of inverter made using square wave as output form and are obsolete. The square wave inverter has two output states which are alternately positive and negative creating a square wave waveform. The amplitude of the output waveform is directly related to the DC input voltage and cannot be adjusted except controlling the DC source. The advantages of this inverter include low switching loss and easy to control. However, they are not very efficient because the square wave produce higher harmonic that cannot be used in many appliances.

2.3.2 Modified Square Wave Inverter

Modified square wave inverters or modified sine wave were the second generation of power inverter and considerable as improvement of square wave inverter. The modified square wave is designed to minimize the harmonics. These popular inverters represent a compromise between the low harmonics of a true sine wave inverter. The disadvantage of this inverter is causing a reduction in product reliability and efficiency while abnormal heat will be produced.

2.3.3 Pure Sine Wave Inverter

Pure sine wave inverters represent the latest inverter technology. The waveform produced by these inverters is the same as or better than the power delivered by the utility. The harmonics are virtually eliminated and the appliances can operate properly with this inverter. However, this type of inverter produce pure sine wave at cost of efficiency loss and at much higher price compared to modified sine wave inverter.

2.4 Pulse Width Modulation

Pulse-width modulation (PWM) is commonly used technique for controlling power to electrical devices and practical by modern electronic power switches. PWM inverters are quite popular in industrial application and this technique is characterized by constant amplitude pulses. The width of this pulse is however modulated to obtain inverter output voltage control. Output voltage from inverter can also be adjusted by exercising a control within inverter itself [5]. The most efficient method of doing this is by pulse-width modulation control use within an inverter. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components.

The advantages possessed by PWM techniques are [4, 9]:

1. The output voltage control with this method can be obtained without any additional components.
2. With the method, lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

A number of PWM schemes are used to obtain variable voltage and frequency supply. The most widely used PWM schemes for three-phase voltage source inverter use sinusoidal pulse-width modulation (SPWM).

2.5 Sinusoidal Pulse-width Modulation

The control objective of sinusoidal pulse-width modulation (SPWM) is to produce a controllable ac output from an uncontrollable dc voltage source. Even though the desired output voltage waveform is purely sinusoidal, practical inverters are not purely sinusoidal but include significant high frequency harmonics [6]. That is why inverter normally employs a high-frequency switching technique to reduce such harmonics. Two alternative control methods are uniform pulse width modulation (PWM) and sinusoidal PWM. Sinusoidal PWM is widely used in motor drive applications with high frequency operation.

Figure 3 shows circuit model of three phase PWM inverter. A basic three-phase inverter consists of three single phase inverter switches each connected to one of the load terminals.

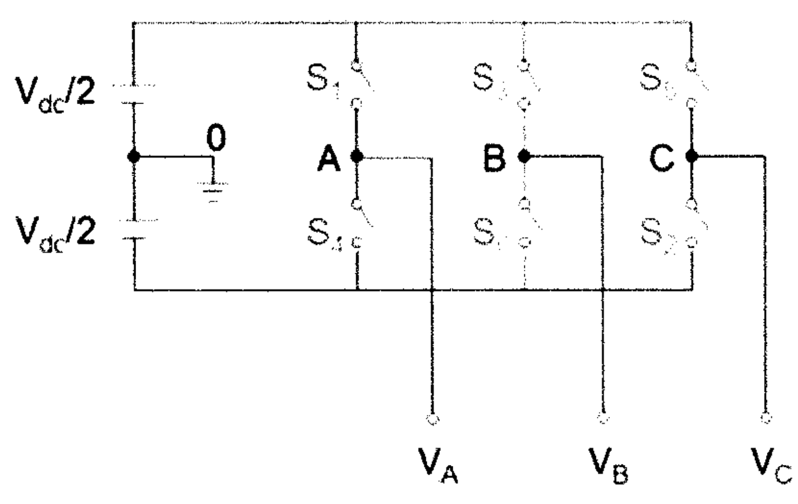


Figure 3: Three-phase PWM inverter

Sinusoidal pulse width modulation (SPWM) generated by comparing amplitude of triangular wave called as carrier wave signal (V_{tri}) and sinusoidal reference wave known as control signal ($V_{control}$). Basically the magnitude and frequency of sinusoidal control signal are controllable but the triangular signal magnitude and frequency are kept constant. The three of phase sinusoidal wave ($V_{control}$) is 120^o apart to produce a balance three phase output [7].

The figure 4 shows waveform of carrier wave signal (V_{tri}) inverter output line to neutral voltage ($V_{A0,}$ $V_{B0,}$ V_{C0}), inverter output line to line voltages ($V_{AB,}$ $V_{BC,}$ V_{CA}) respectively.

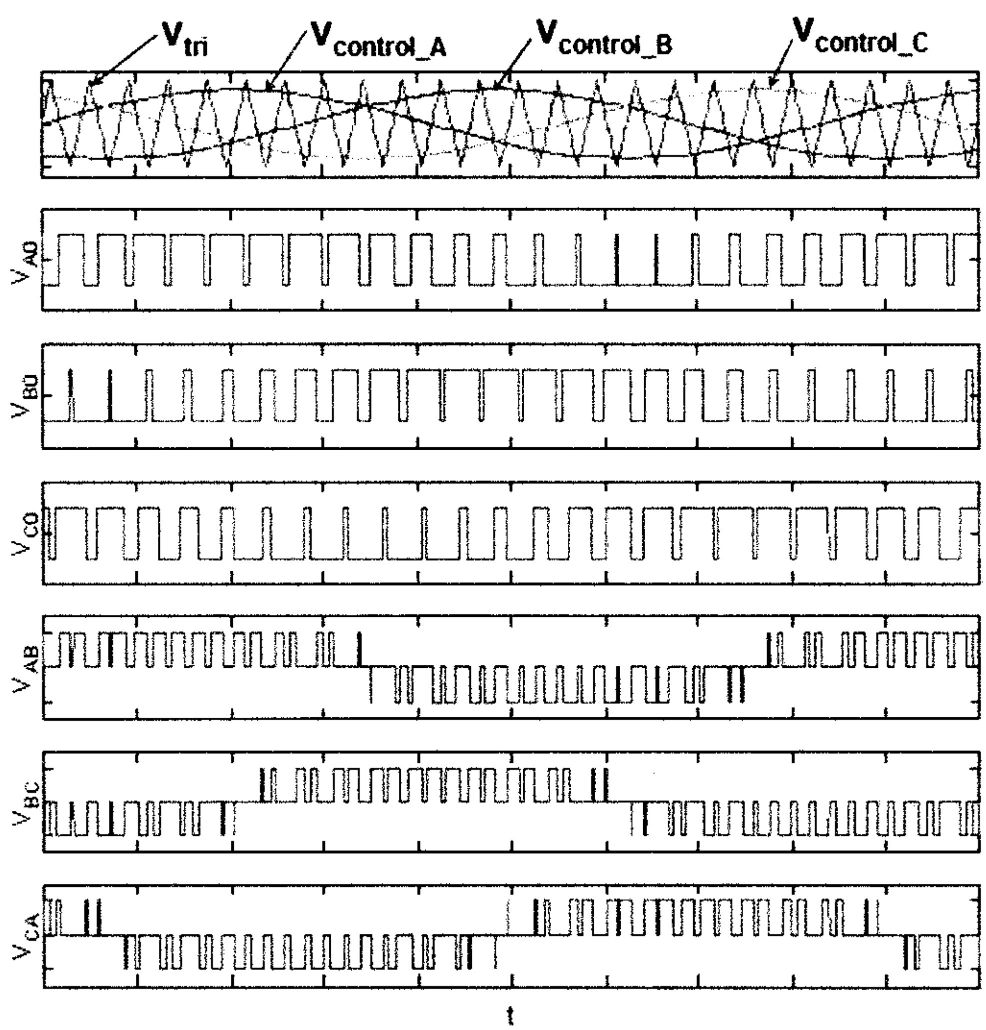


Figure 4: Waveform of three-phase SPWM inverter

As described in figure, the frequency of V_{tri} and $V_{control}$ is:

- Frequency of Vtri = f_s which is PWM frequency.
- Frequency of $V_{control}$ = f_1 is a fundamental frequency.

The inverter output voltages are determined as follows:

- When $V_{control} > V_{tri}$, $V_{A0} = V_{dc}/2$
- When $V_{control} < V_{tri}$, $V_{A0} = -V_{dc}/2$

Where $V_{AB} = V_{A0} - V_{B0}$, $V_{BC} = V_{B0} - V_{C0}$, $V_{CA} = V_{C0} - V_{A0}$

CHAPTER 3

METHODOLOGY

This project will be conducted according to this methodology to meet the objectives. The procedures and stages of the entire project are shown in the flowchart below:

3.1 Research Flowchart

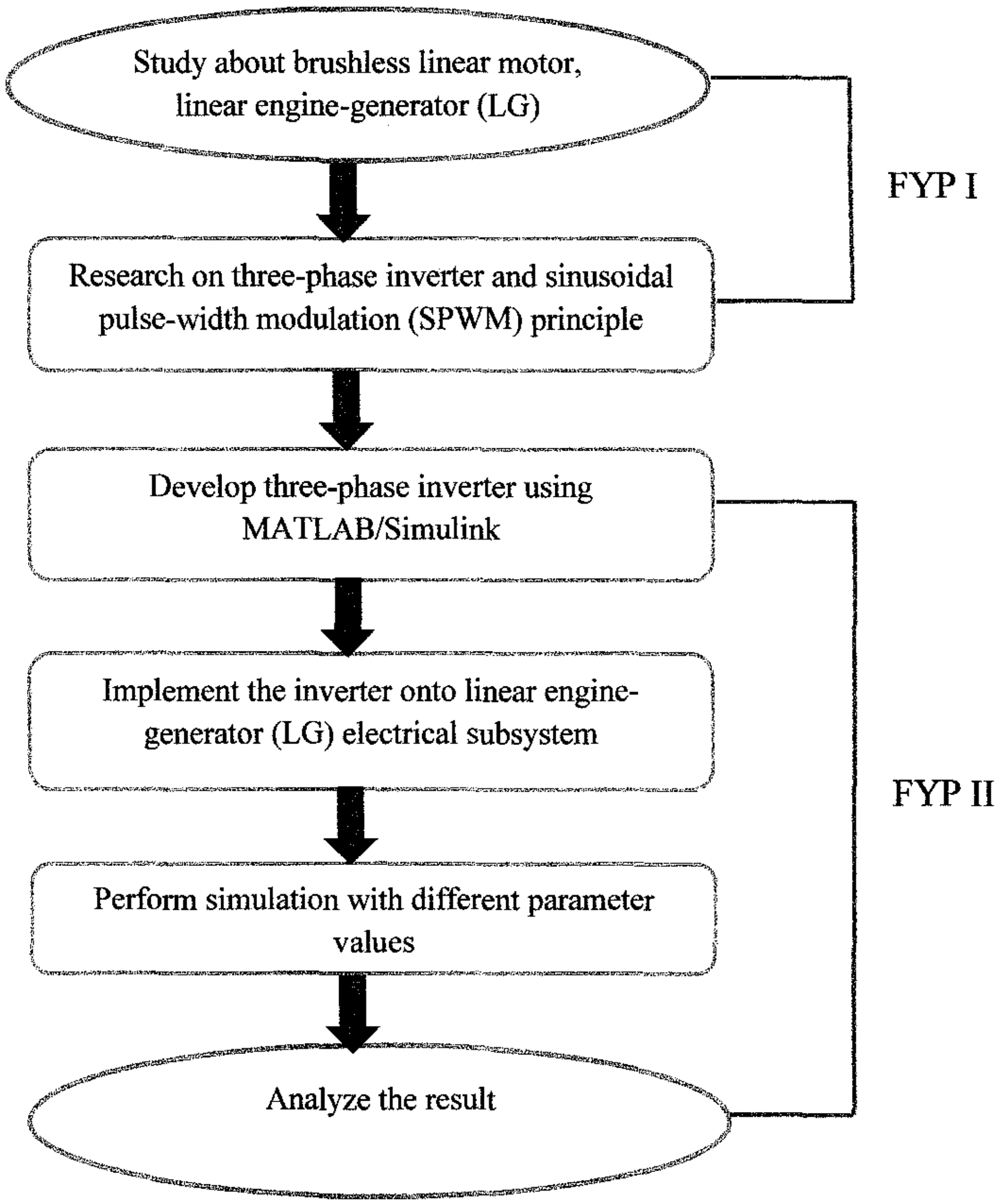


Figure 5: Methodology Chart

Step 1: To start this project, the concept of brushless linear engine-generator (LG) is studied. The category of application of the LG during starting process is same as permanent-magnet brushless dc motor (BLDCM) operation.

Step 2: Research on three-phase inverter and sinusoidal pulse-width modulation (SPWM) theories were carried out to understand its application in power electronics.

Step 3: Three-phase inverter circuit is developed using MATLAB/Simulink with the SimPowerSystem application. Three-phase inverter consists of three single phase inverter switches each connected to one of the load terminals.

Step 4: Linear engine-generator model consist of electrical and mechanical subsystem models. This work focuses the electrical aspect which is the three-phase inverter is implemented to simulate the electrical subsystem circuit for starting process.

Step 5: The simulation has been performed to investigate the effects of the parameters such as modulation index and frequency on inverter operation and LG performance.

Step 6: The result output and its effects on inverter operation and LG performance are evaluated.

3.2 Project Activities

3.2.1 Block diagram of Linear Generator

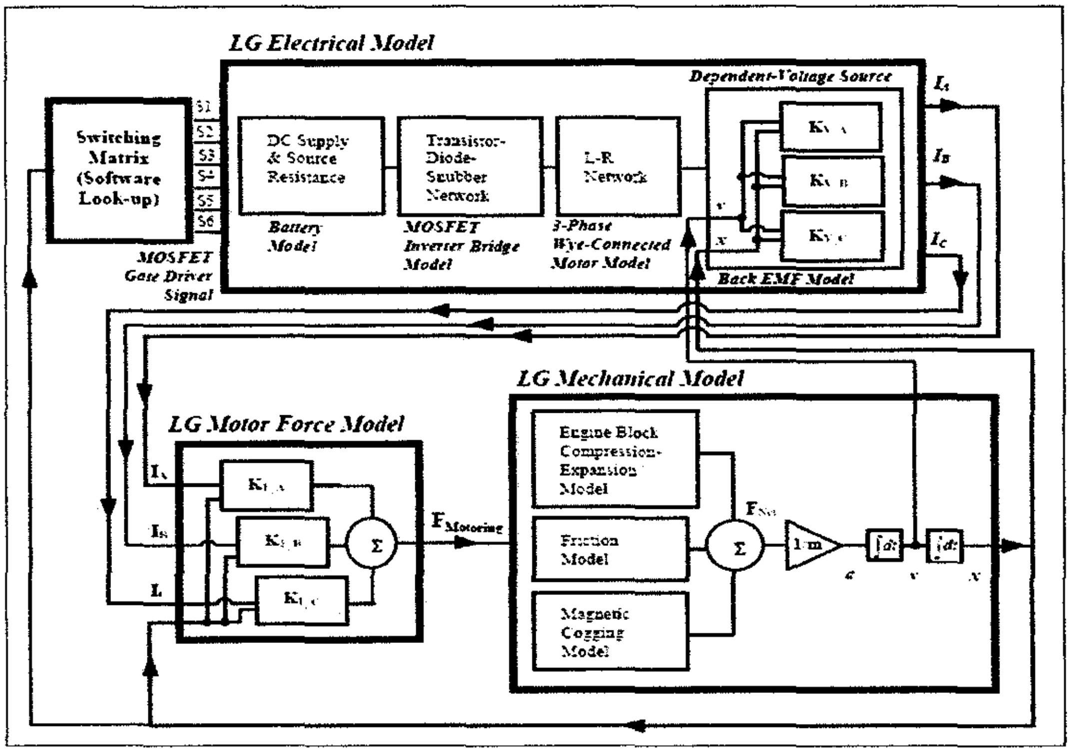


Figure 6: The block diagram of electrical and mechanical subsystems for LG [1].

Block diagram of linear generator consists of electrical and mechanical subsystem models. These models are combined to form an integrated LG model that will be implemented on MATLAB/Simulink.

From the block diagram in leftmost Figure 6 of electrical subsystem is a MOSFET gate driver signal which is providing the displacement point throughout commutation technique and inside of electrical system consists of battery model for DC source, MOSFET inverter bridge, three-phase wye-connected motor model and back emf model. The output of electrical model is three-phase current that will be the input for motor force model.

Each phase current is multiplied by K_f to produce motoring force and become the input for mechanical model. The integrated block diagram in mechanical model is to show the interrelation between motor force, velocity and displacement [1,2].

3.2.2 Electrical Modeling and Simulation

MATLAB/Simulink comprises of a range of blocksets such as power electronics, communications, control, power system and fuzzy logic etc. depending on application requirements. For inverter development, the power system blockset provides the required components such as a full-bridge, batteries, resistors, inductors, capacitors etc. and many more. Shown in Figure 7 is the power system full-bridge block which is at the heart of the inverter. It comprises of the dc voltage input, PWM inputs (pulses) for each of the six switches, and the full-bridge output.

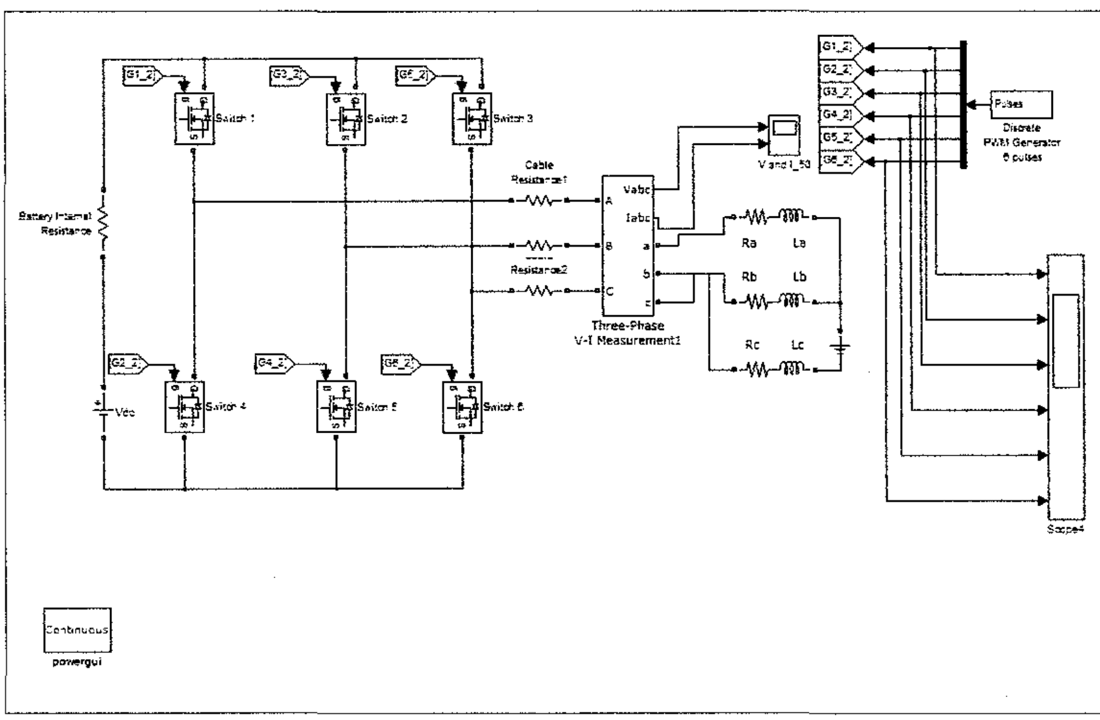


Figure 7: Three-phase full-bridge inverter circuit

This inverter is implemented to linear engine-generator (LG) electrical subsystem as shown in Figure 8 to produce AC from DC supply. The objective of this project, the variation of modulation index PWM input is carried out to observe the effects on LG performance. The electrical subsystem of LG is essentially made up of a DC voltage source model (in multiple of 12V and up to 12 batteries or 144V), a brushless motor drive model (MOSFET inverter bridge) and an inductive-resistive (LR) network model.

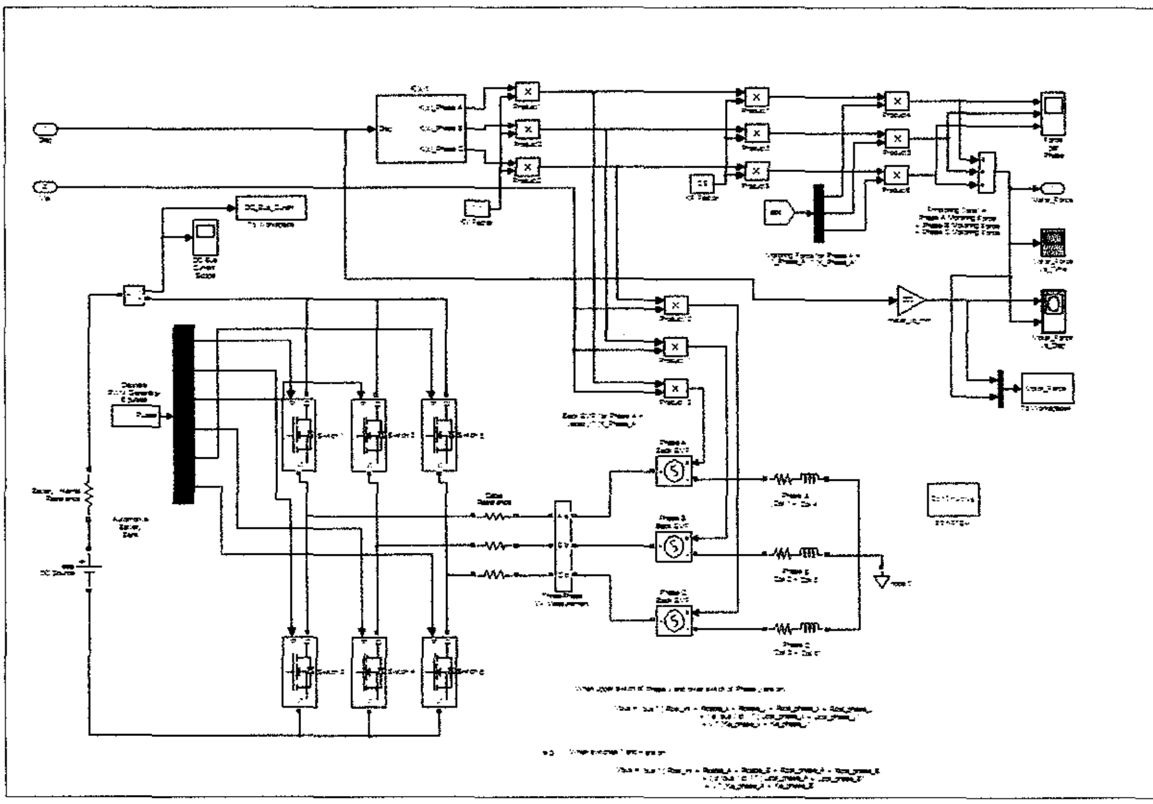


Figure 8: Electrical modelling of LG

3.2.3 PWM Generator

The PWM Generator block generates pulses for carrier-based pulse width modulation (PWM) converters using two-level topology. The block can be used to fire the forced-commutated devices (FETs, GTOs, or IGBTs) of single-phase, two-phase, three-phase, two-level bridges or a combination of two three-phase bridges.

The pulses are generated by comparing a triangular carrier waveform to a reference modulating signal. The modulating signals can be generated by the PWM generator itself, or they can be a vector of external signals connected at the input of the block. One reference signal is needed to generate the pulses for a single- or a two-arm bridge, and three reference signals are needed to generate the pulses for a three-phase, single or double bridge.

The amplitude or also known as modulation, phase, and frequency of the reference signals are set to control the output AC voltage of the bridge connected to the PWM Generator block [10].

The pamarameters of PWM generator source block is shown as below:

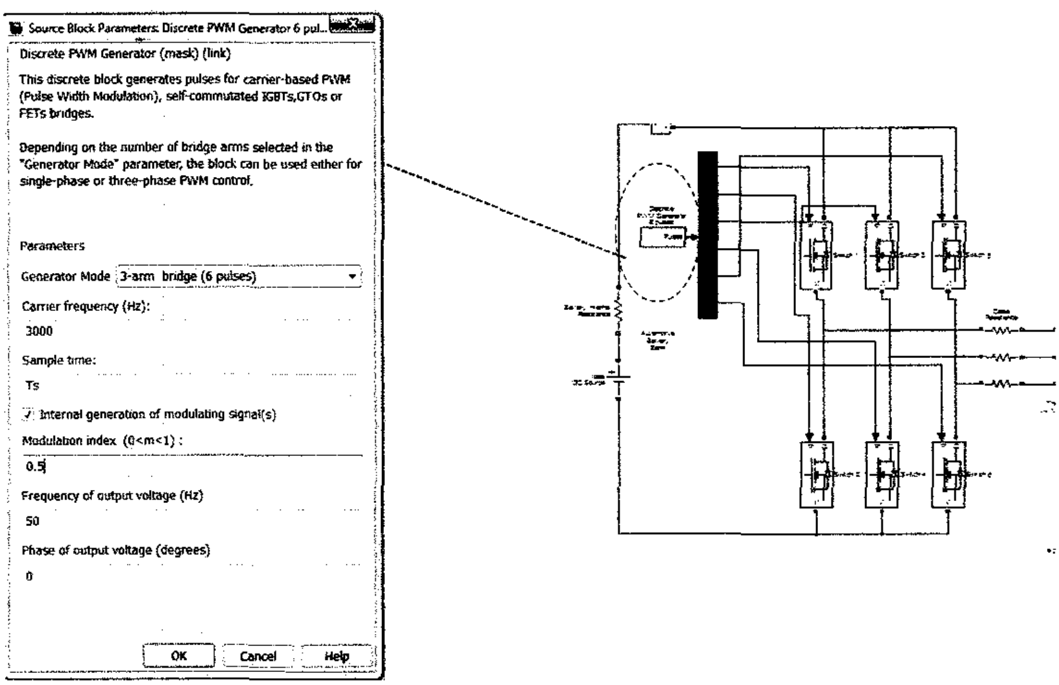


Figure 9: Dialog box and parameters

a) *Carrier frequency* also known as switching frequency or carrier triangular signal. The technique generates a fixed frequency usually 2 kHz - 30 kHz controlled on-time of voltage pulse.

b) *Internal generation of modulating signal* is selected to generate the modulating signal. Otherwise the external modulatin signal are used for pulse generation.

c) *Modulating index* $(0 < m < 1)$ must be greater than 0, and lower or equal to 1. This parameter is used to control the amplitude of the fundamental component of the output voltage of the controlled bridge.

d) *Frequency of output voltage* is used to control the phase of the fundamental frequency of the output voltage of the controlled bridge. The value for this parameter was fixed 26Hz because it was found as ideal operating frequency for LG [1].

e) *Phase of output voltage* is used to control the phase of the fundamental component of the output voltage of controlled bridge.

Parameters of simulated inverter design are summarized as below:

Parameters	**Value**
DC line voltage	144 V
Battery internal resistance	0.035 Ω
Cable resistance	0.025 Ω
Coil resistance	0.2Ω, 0.0019H
Frequency of output voltage	26 Hz
Carrier frequency	3000 Hz

Table 1: Specification of inverter design

3.2.4 Modulation Index

Modulation index is defined as the ratio of frequency deviation to frequency of the modulating signal and can describes the ratio of peak value of the reference signal over peak value of the triangular waveform. The amplitude and frequency modulation indices are defined as follows [8]:

$$m_a = \frac{V_{P,ref}}{V_{p,tri}}$$

$$m_f = \frac{f_s}{f_o}$$

$V_{p,ref}$: Peak value of the reference signal

$V_{p,tri}$: Peak value of triangular waveform

f_s : Frequency of triangular waveform or also known as the carrier frequency

f_o: Desired inverter output frequency which is equal to the reference frequency

In this project, the effect of changing modulation index is investigated. Different modulation index values are tested: 0.5, 0.6, 0.7, 0.8 and 0.9.

3.3 Tool and Equipment

This project is mainly about the modelling and simulation of three-phase inverter. The software used to run the simulation is MATLAB/Simulink with the SimPowerSystem application. All the circuits are redrawn in the Model window and the result of the simulation are viewed at scope window. The advantages of using MATLAB/Simulinks are faster response, availability of various simulation tools and functional block. Since there is no prototype model required, MATLAB/Simulink is an effective tool and plays an important role to achieve the objectives of the project.

3.4 Gantt Chart and Key Milestone

Gantt chart is a project schedule to illustrate the start and finish date of a project in duration 14 weeks. Gantt chart is provided to ensure that the project ordering is consistent and all milestones in Gant Chart colour-corded to distinguish upcoming, overdue and complete task (Appendix A).

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The simulation has been conducted in order to achieve the objective of the project. Previous final year project student has performed simulation the effect of supplying three-phase voltage source without any inverter used (Refer Appendix B). Different AC voltage amplitudes are tested to observe the effect on motor force and displacement of linear engine-generator (LG). In this case, DC-AC inverter cannot easily adjust amplitude AC signal because it is affected by parameters such as input voltage, modulating signal, frequency output voltage and so on, while the amplitude of ideal AC source can be selected in any value.

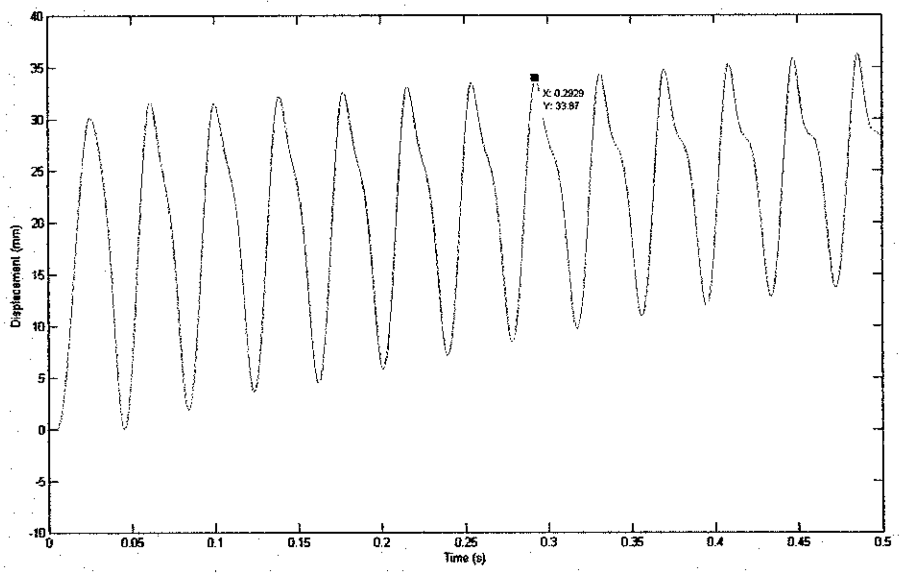
In this project, to investigate the effect of parameters on inverter operation, three-phase inverter is simulated in MATLAB/Simulink. The simulation has been done for different values of modulation index and voltage output frequency. For modulation index variation, the values are varied from 0.5, 0.6, 0.7, 0.8 and 0.9 which is the voltage supply (Vdc) is fixed at 144V and frequency of output voltage equal to 26Hz. The frequency of 26Hz is chosen as fixed value because it was found in previous research for LG reciprocation as ideal value for starting frequency.

Further simulation on different output voltage frequencies were performed to observe its effect on LG performance. The values are varied in the range of 21Hz-32Hz. The graphs of motor force versus time and displacement versus time are illustrated as follow:

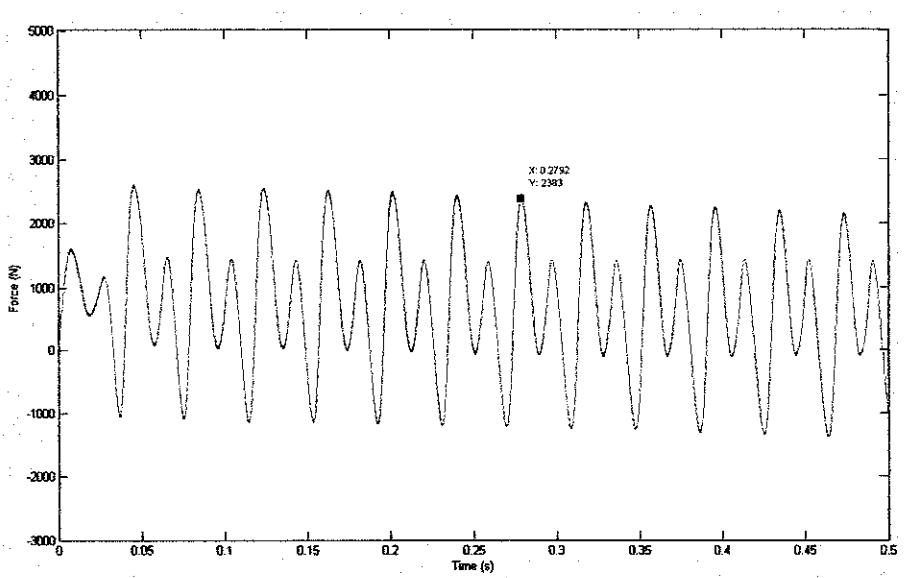
4.2 Results of Variation Modulation Index

In this project, the modulation index values are varied from 0.5-0.9 and the output voltage frequency value is fixed to 26Hz.The result for motor force and displacements versus time from simulations are shown below.

3.2.1 Result of m=0.5



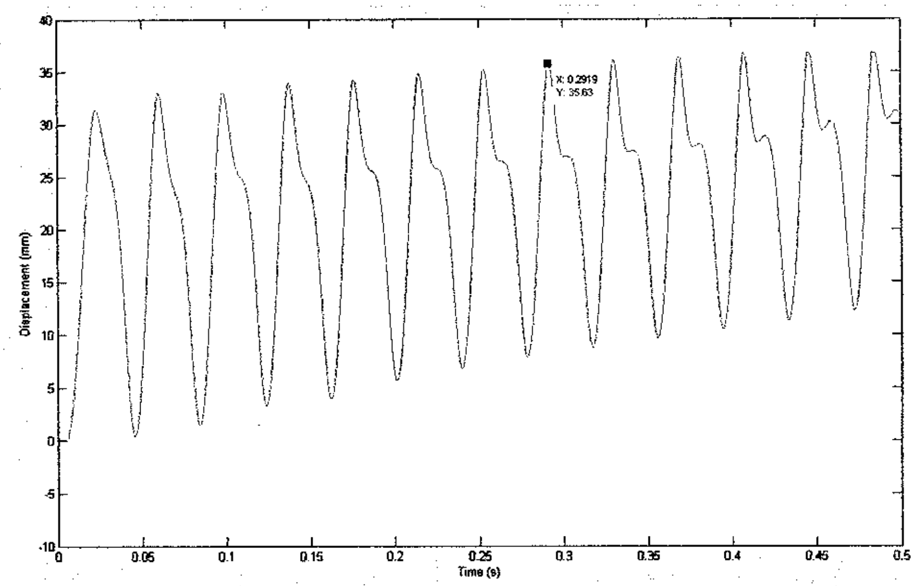
a) Displacement versus Time (m=0.5)



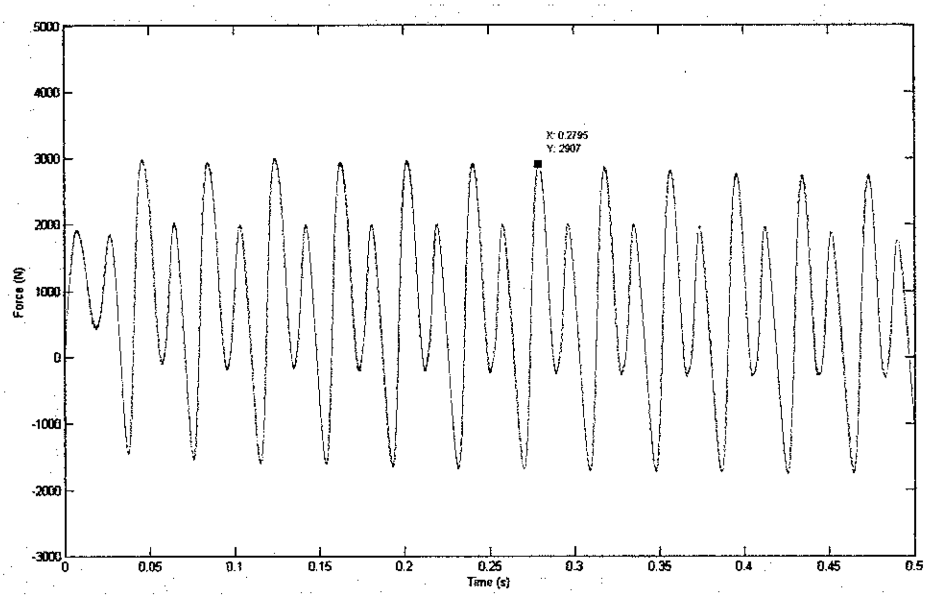
b) Motor Force versus Time (m=0.5)

Figure 10: Result of m=0.5 for Displacement vs Time and Motor Force vs Time Vdc=144V, f=26Hz

3.2.2 Result of m=0.6



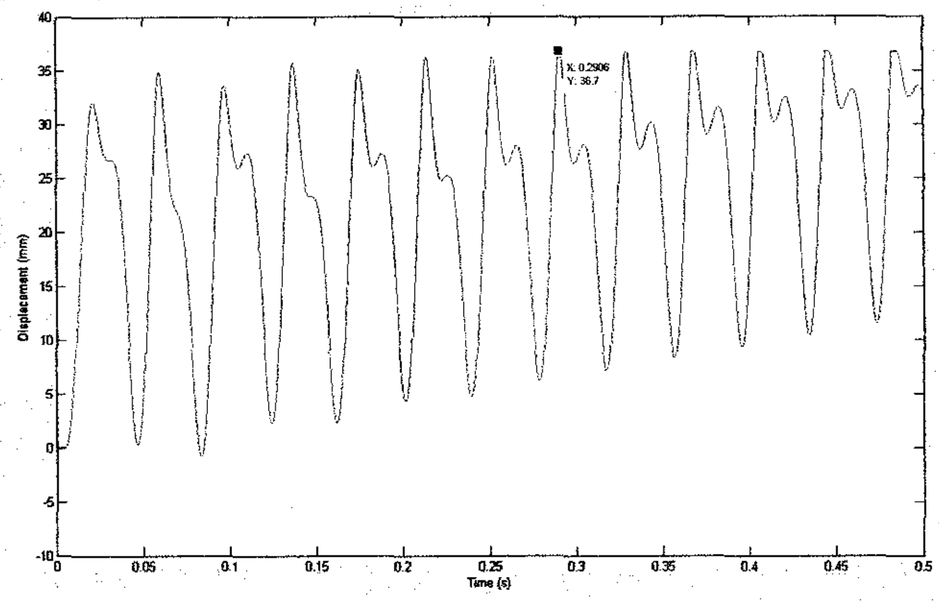
a) Displacement versus Time (m=0.6)



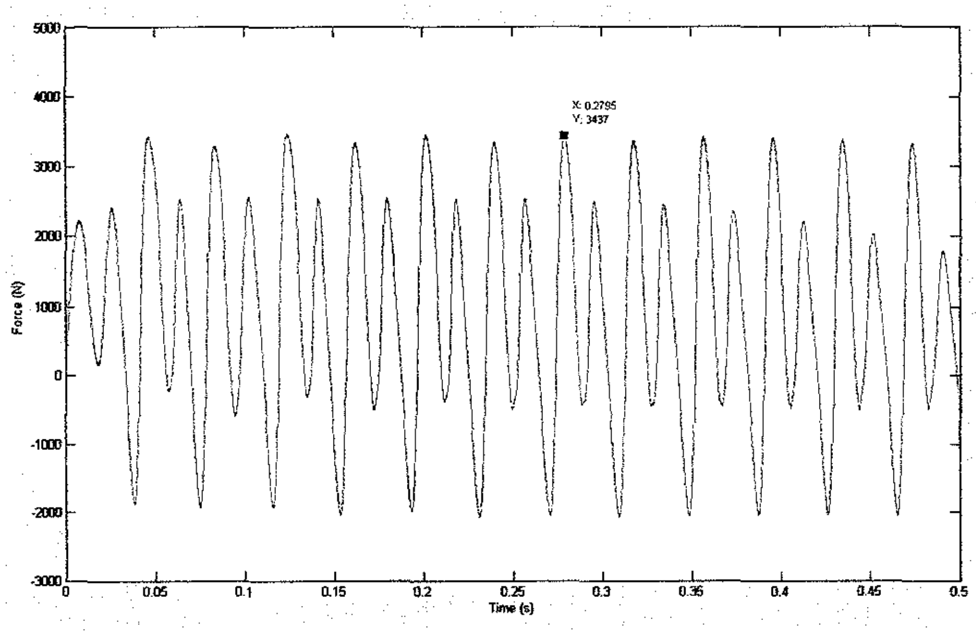
b) Motor Force versus Time (m=0.6)

Figure 11: Result of m=0.6 for Displacement vs Time and Motor Force vs Time Vdc=144V, f=26Hz

3.2.3 Result of m=0.7



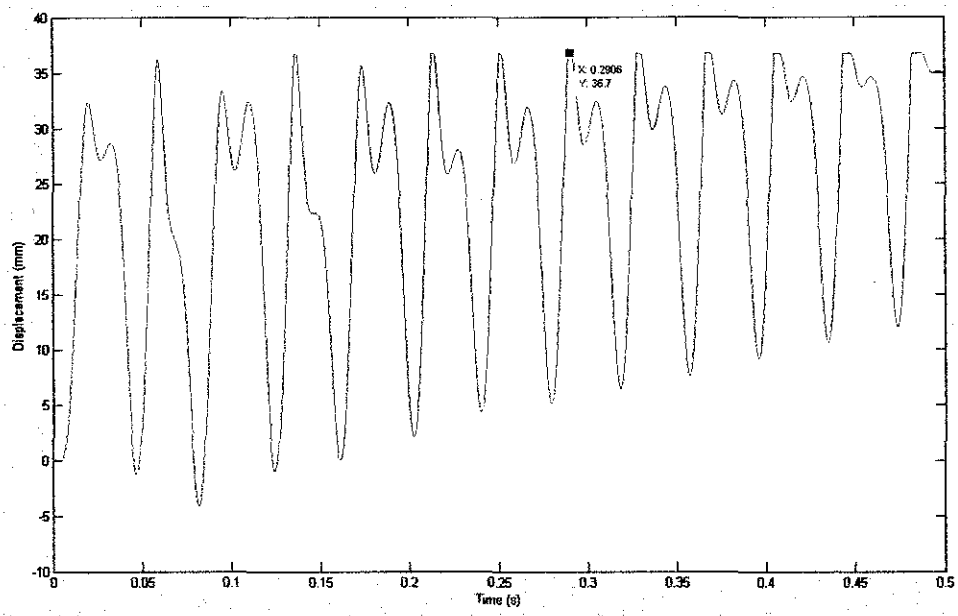
a) Displacement versus Time (m=0.7)



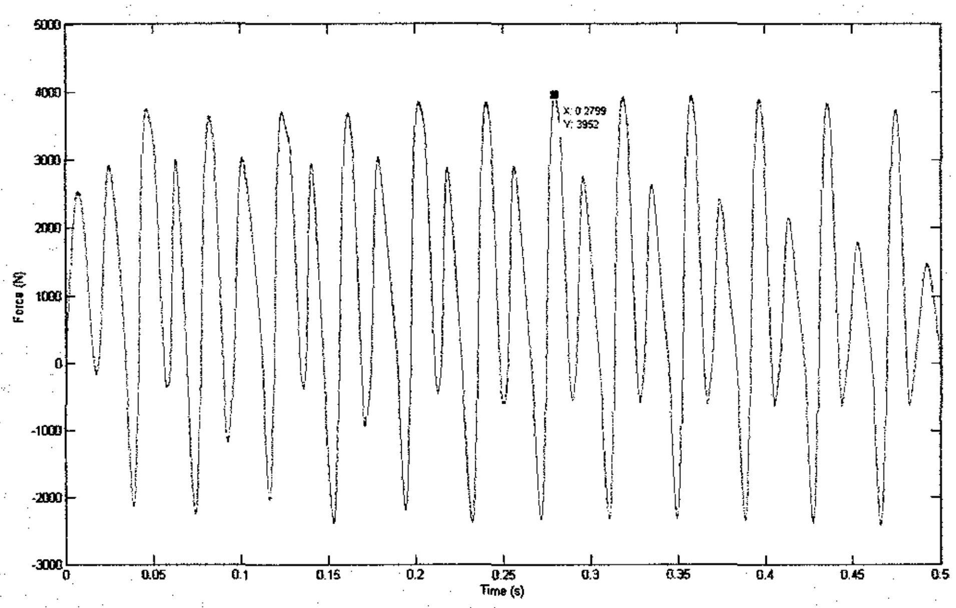
b) Motor Force versus Time (m=0.7)

Figure 12: Result of m=0.7 for Displacement vs Time and Motor Force vs Time
Vdc=144V, f=26Hz

3.2.4 Result of m=0.8



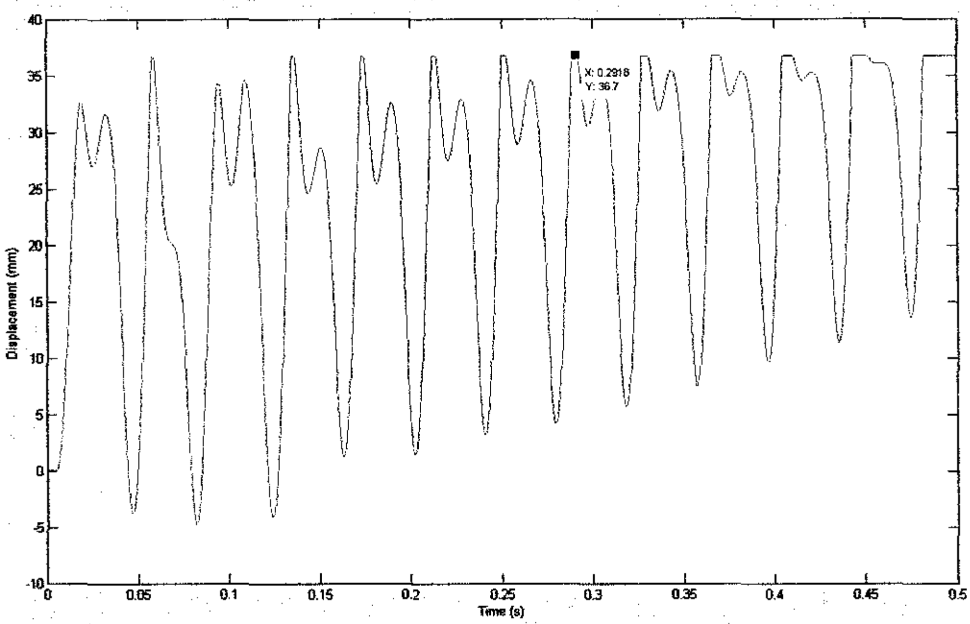
a) Displacement versus Time (m=0.8)



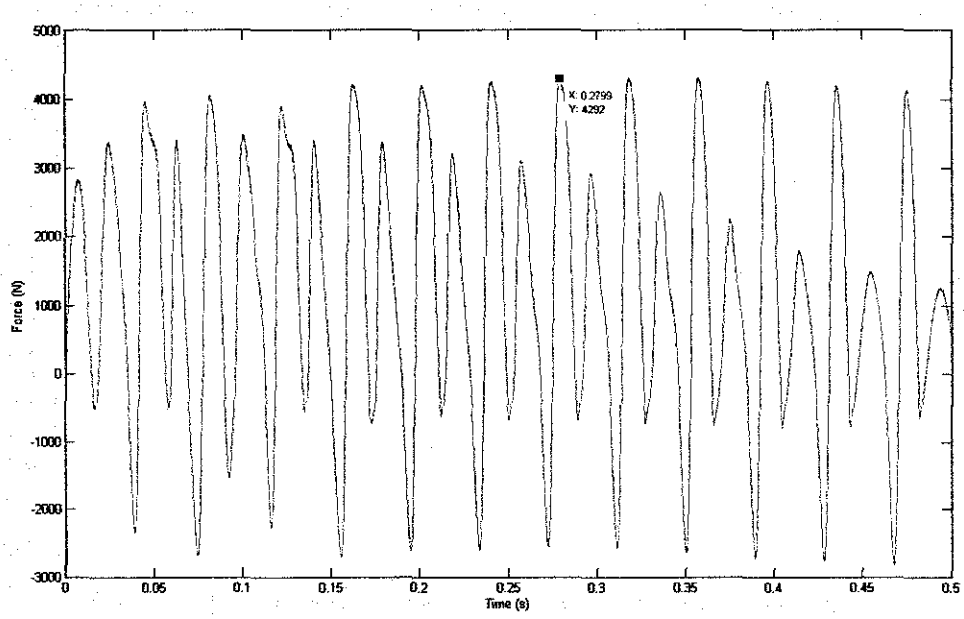
b) Motor Force versus Time (m=0.8)

Figure 13: Result of m=0.8 for Displacement vs Time and Motor Force vs Time Vdc=144V, f=26Hz

4.3.5 Result of m=0.9



a) Displacement versus Time (m=0.9)



b) Motor Force versus Time (m=0.9)

Figure 14: Result of m=0.9 for Displacement vs Time and Motor Force vs Time
Vdc=144V, f=26Hz

4.3 Discussion for Variation of Modulation Index

The effect of variation modulation index value on output current (Refer Appendix D) is shown in table below:

Modulation Index (m)	0.5	0.6	0.7	0.8	0.9
Output Current (A)	92.0	110.5	127.7	146.2	164.2

Table 2: Current amplitude of three-phase inverter

Based on results output illustrated in Figure 10-14, the maximum stroke length, is summarized in table, while Table 3 summarized the maximum force value for right and left position.

Modulation Index (m)	0.5	0.6	0.7	0.8	0.9
Max. Force (Right)	2383 N	2907 N	3437 N	3952 N	4292 N
Max. Force (Left)	1247N	1701N	2070N	2322N	2570N

Table 3: Summary of maximum force value for variation modulation index

Modulation Index (m)	0.5	0.6	0.7	0.8	0.9
Max. Stroke length (mm)	33.87	35.63	36.70	36.70	36.70

Table 4: Summary of maximum stroke length for variation modulation index

From the result displays in Table 2, as the modulation index increases, the amplitude of output current also increase. It is because the transistors of inverter act as a gate to allow a precise amount of the current to flow to the load. As this gate is rapidly switched on and off, the amount of current which flow is dependent upon the ratio between on and off time. The larger this ratio (modulation index) is the more current flow.

When these inverters are implemented to electrical system of LG, increasing of modulation index value caused motor force left and right position increase. The output of LG electrical model which is three-phase current will be the input for motor force model. Thus, the total for each phase current multiplied by respective K_f (motor force constant) will increase. The resultant motoring force can then be determined using Lorentz force law and the duality between electromotive force V and magnetic force F, [1]:

$$F(t) = K_F(x).I(t)$$

where K_F is conventionally known as the force constant of a motor rotating at constant speed. For three-phase LG, the total motoring force resulting from current flowing through individual coils is given by [1]:

$$F(t) = \sum_{n=1}^{3} K_F(x)_{phase_n} \cdot I_{phase_n}(t)$$

so that when phases A and B are energized, the total motoring force as a function of time is given by [1]:

$$F(t) = K_F(x)_{phase_A} \cdot I_{phase_A}(t) + K_F(x)_{phase_B} \cdot I_{phase_B}(t)$$

F(t) is the instantaneous motoring force and the final output of the integrated LG electrical subsystem model made up of the LG electrical model and motor force model. I(t) is the instantaneous current, as the input of LG motor force model that is obtained as the final output of the integrated LG electrical subsystem model.

As shown in Figure 6, the back emf model contains profile K_v against displacement for each phase of LG. Since the resultant back emf voltage is a function of velocity, this parameter is also is an input of the back emf model, in addition to displacement. Each phase current of the output *LG Electrical Model* block is multiplied by the respective K_F profile to produce the final motoring force, $F_{motoring}$, which is a summation of the individual contributions of force. Each force is in turn due to the interaction between the permanent magnet's magnetic field and the field due to the current flowing through the respective phases being energized [1].

The resulting of $F_{motoring}$ is the input to the mechanical model and in this integrated block diagram shows the inter-relation between motoring force with velocity and displacement (Refer Appendix B).

For dynamic mechanical equation of LG during starting, based on Newton's second law of motion as equation below [1]:

$$\sum F_x = ma_x = m\frac{d^2x}{dt^2}$$

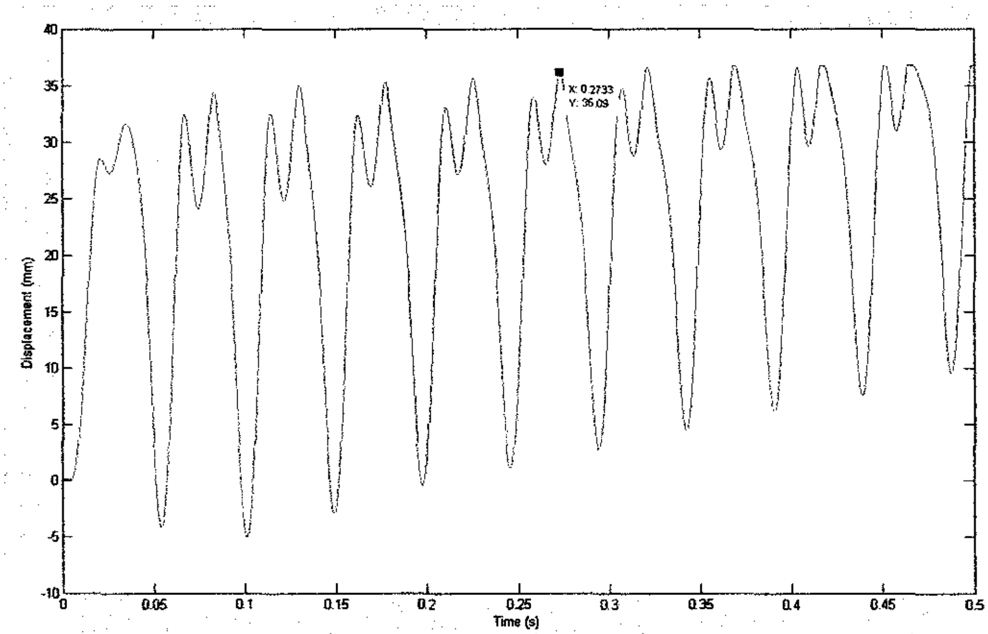
Let m be the total mass of the translator including piston and magnets, and a its acceleration. F_x represents motoring force that is acquired from current injection into LG coils.

From the equation above, when the value of the current injected to the coils increase, motoring force will increase and hence the stroke length of the translator also increase. In previous research, the maximum possible top dead centre (TDC) position or piston distance from the cylinder head for free-piston LG is 36.7mm [1]. As the result shown in Table 4, when the modulation index value increases, the stroke length also increases until the piston assembly actually hits the cylinder head at 36.7mm. It can conclude that the ideal value of modulation index is 0.7.

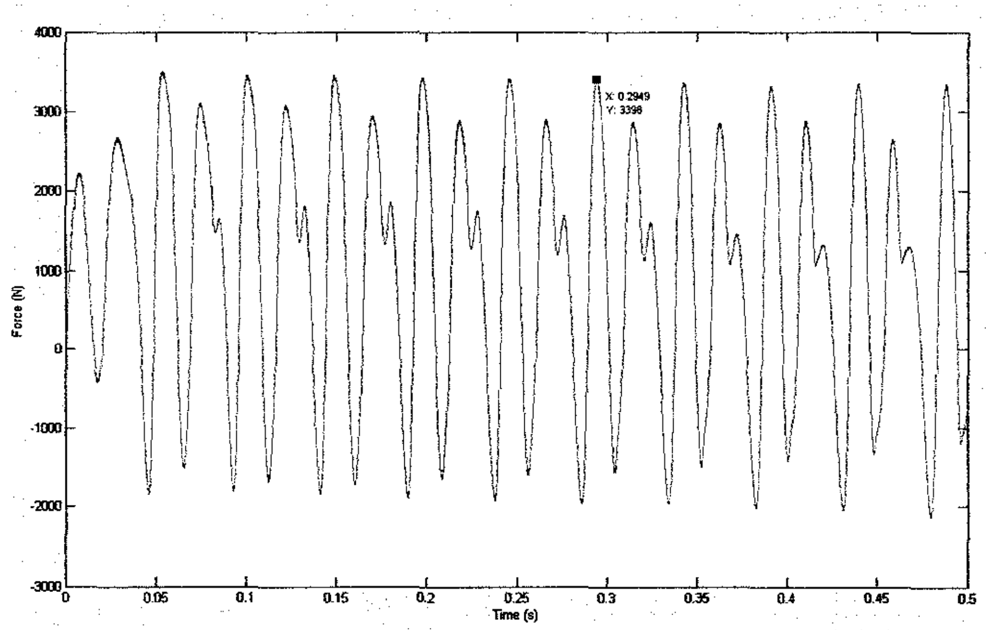
4.4 Results of Variation Frequency of Output Voltage

For frequency of output voltage variation, the value are varied in the range of 21Hz-32 Hz while voltage supply is fixed 144V and m=0.7.

4.4.1 Result of f=21Hz



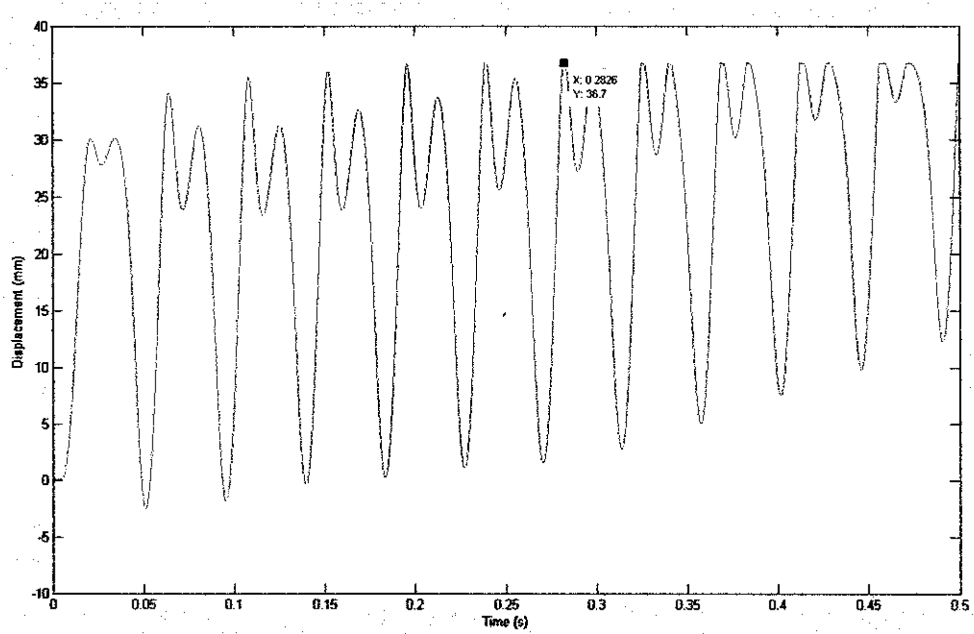
a) Displacement versus Time (f=21Hz)



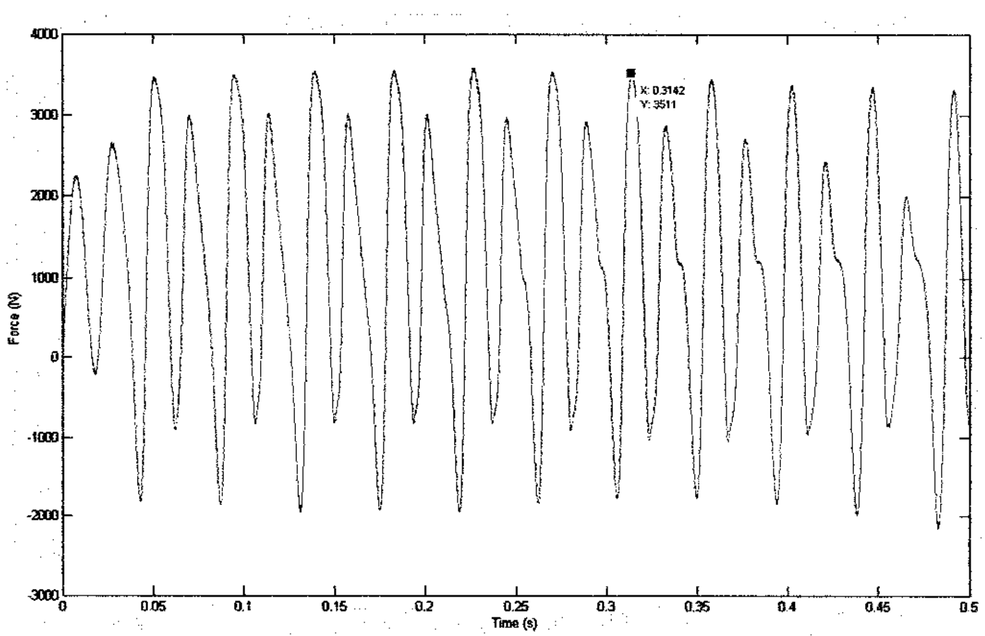
b) Motor Force versus Time (f=21Hz)

Figure 15: Result of f=21Hz for Displacement vs Time and Motor Force vs Time Vdc=144V, m=0.7

4.4.2 Result of f=23Hz



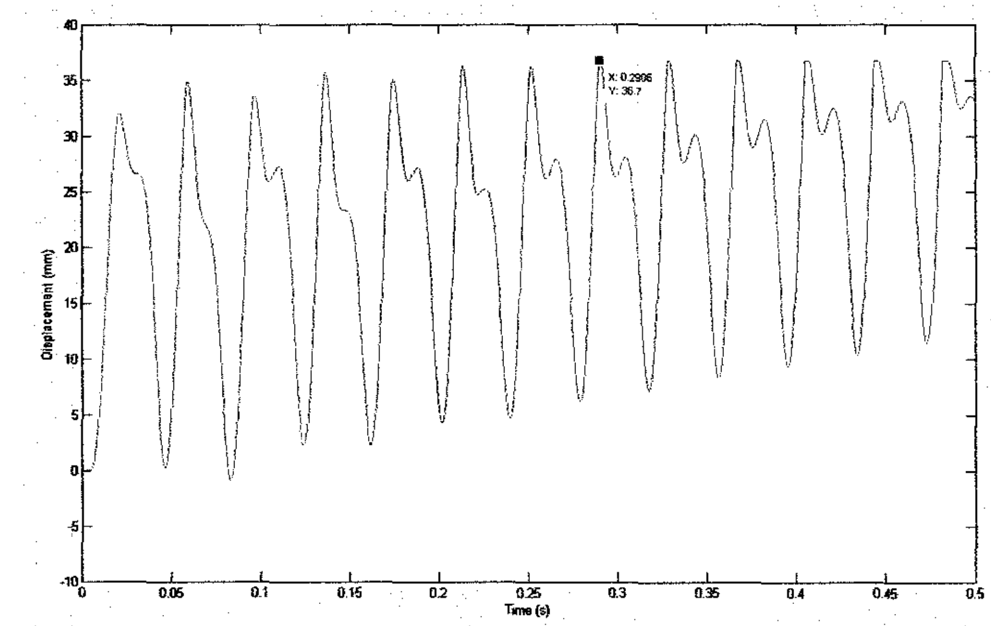
a) Displacement versus Time (f=23Hz)



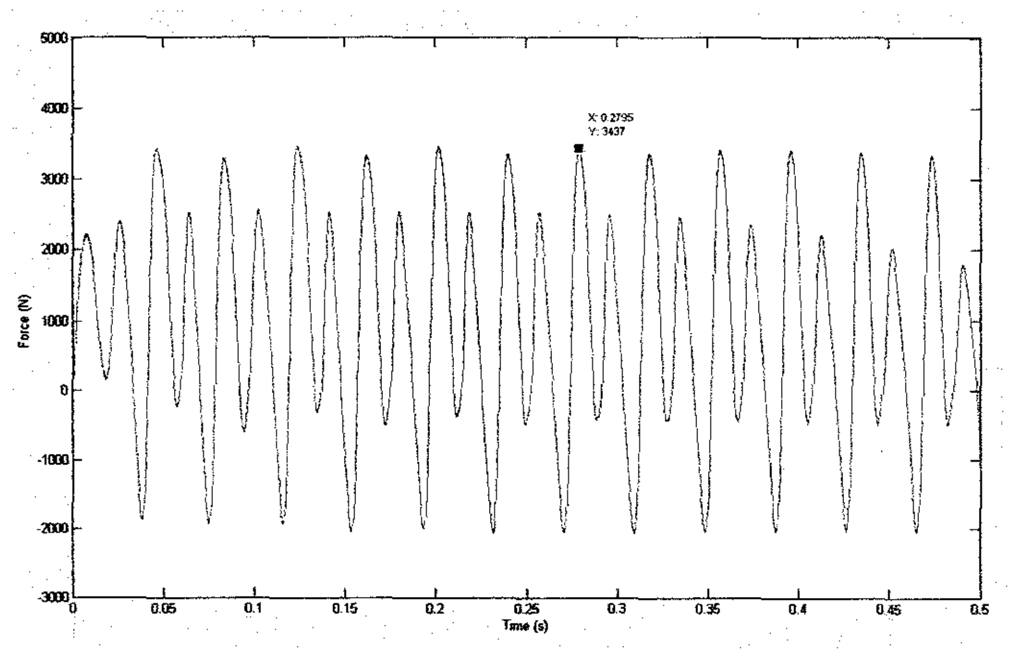
b) Motor Force versus Time (f=23Hz)

Figure 16: Result of f=23Hz for Displacement vs Time and Motor Force vs Time
Vdc=144V, m=0.7

4.4.3 Result of f=26Hz



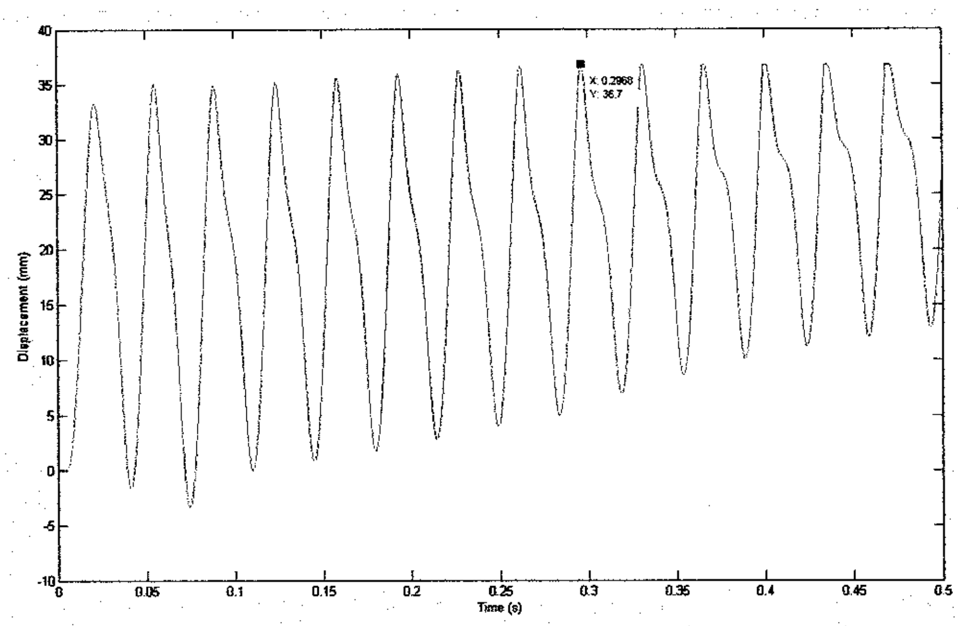
a) Displacement versus Time (f=26)



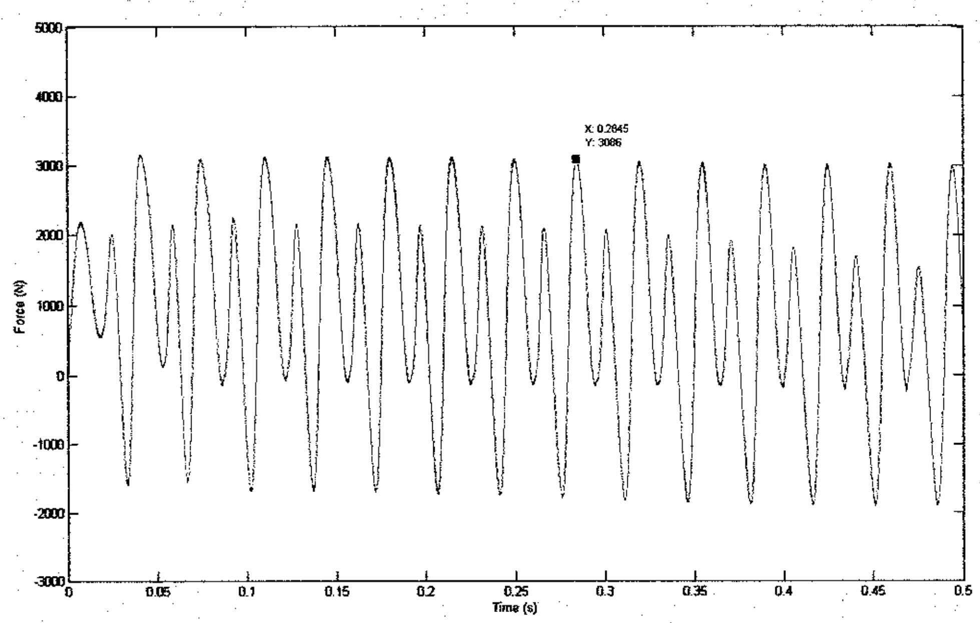
b) Motor Force versus Time (f=26)

Figure 17: Result of f=25Hz for Displacement vs Time and Motor Force vs Time Vdc=144V, m=0.7

4.4.4 Result of f=29Hz



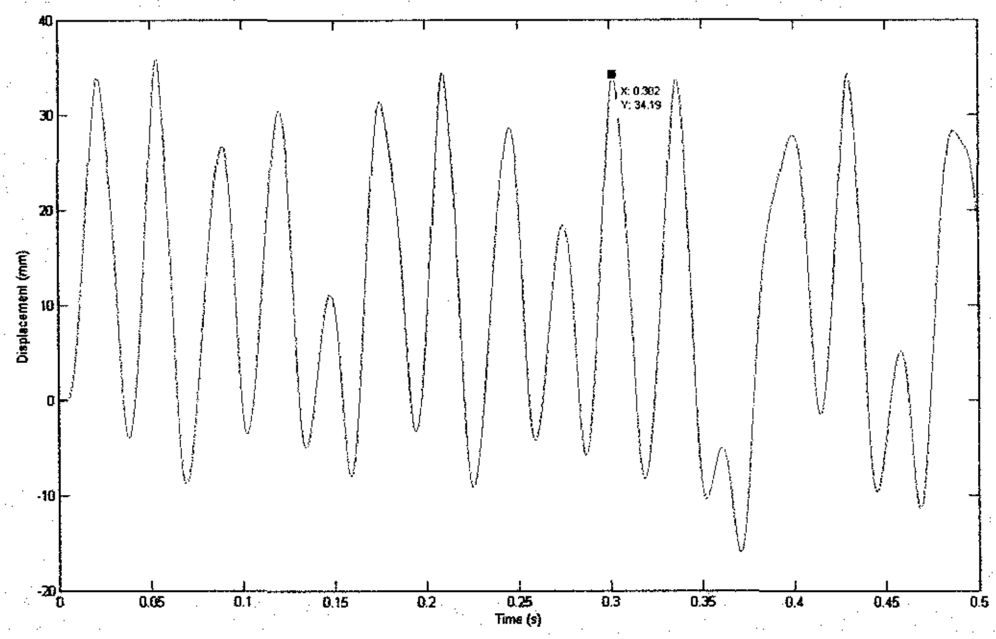
a) Displacement versus Time (f=29Hz)



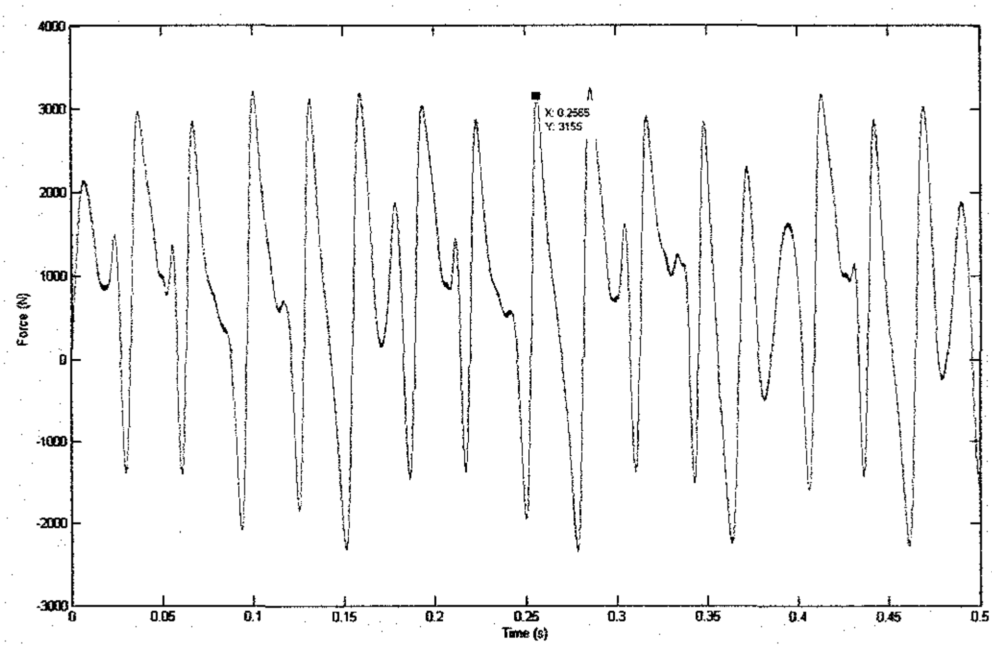
b) Motor Force versus Time (f=29Hz)

Figure 18: Result of f=29Hz for Displacement vs Time and Motor Force vs Time Vdc=144V, m=0.7

4.4.5 Result of f=32Hz



a) Displacement versus Time (f=32Hz)



b) Motor Force versus Time (f=32Hz)

Figure 19: Result of f=32Hz for Displacement vs Time and Motor Force vs Time Vdc=144V, m=0.7

4.5 Discussion for Variation Frequency of Output Voltage

The effect of variation frequency of output voltage value on output current (Refer Appendix E) is shown in table below:

Frequency (Hz)	21	23	26	29	32
Output Current (A)	146.4	137.4	127.9	119.2	110.7

Table 5: Current amplitude of three-phase inverter

Table 6 illustrates the summary of maximum force value for left and right position.

Frequency (Hz)	21	23	26	29	32
Max. Force (Right)	3398N	3511N	3437N	3086N	3261N
Max. Force (Left)	1928N	1843N	2070N	1816N	2331N

Table 6: Summary of maximum force value for variation frequency of output voltage

Frequency (Hz)	21	23	26	29	32
Max. Stroke length (mm)	36.09	36.70	36.70	36.70	34.19

Table 7: Summary of maximum stroke length for variation frequency of output voltage

The second part of this project is simulation of variation frequency of output voltage in ranges 21Hz-32Hz. Figure 15-19 illustrates the result of simulation output. Table 5 represents the amplitude of the output current for three-phase inverter without back emf. As the frequency increase, the amplitude of current will decrease. The current decreases with increase in modulating signal frequency at a constant gate voltage.

Based on the result output displayed in Table 6, the motor force decrease when the current decrease because it follow Lorentz force law states that the motor force equal to current multiplied by motor constant. However, changing the frequency of the output voltage not effect too much for motor force performance until it reach at f=32Hz. The graph on Figure 19 at f=32Hz shows unstable output due to the harmonics effects.

From the result in Table 7 shows that for all different frequency used, the translator reaches at maximum stroke length about the same for frequencies 23Hz, 26Hz, and 29Hz. However, the capability of piston to move at maximum length is drop at 32Hz due to harmonics. From the graph in Figure 16 and Figure 17, the result output for motor force at f=26Hz smoother as compared to motor force at f=23Hz. So the ideal output voltage frequency is equal to 26Hz because at this value, the translator able to reach at maximum stroke length.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In power electronics system, simulations are mainly performed to analyse and design the three-phase circuit and linear engine-generator (LG) circuit configuration. MATLAB/Simulink software is used through this project in order to perform the simulation and study the effect of changing these parameters to LG.

Since the amplitude of AC signal from the output of DC-AC inverter cannot easily be adjusted because it is affected by many factors of parameters, this project is carried out to study and validate the effect of changing these parameters. As the variation of modulation index and frequency of output voltage have been performed through the simulation, it can be concluded that these parameters have effect to the LG system performance such as motor force and stroke length or displacement.

Besides that, tuning simulation of these parameters will not only assist in validating the linear engine-generator (LG) output but will also help to understand more the behaviour of LG system under different parameter values.

5.2 Recommendation

For the future work, the optimization of the modulating index and other parameters can be studied. The effect of modulation index and frequency of output voltage are investigated in this project and the optimal value of these parameters can be obtained using optimization method.

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[10] www.mathworks.com

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■						MIDSEMESTER BREAK							
2	Study about Brushless DC Motor (BLDCM) fundamentals			■	■	■	■	■								
3	Familiarize MATLAB/Simulink program						■	■								
4	Produce AC voltage from DC using PWM switching technique						■	■								
5	Submission of Extended Proposal						●									
6	Proposal Defence									■	■					
7	Simulation on DC/AC inverter using MATLAB/Simulink											■	■	■		
8	Submission of Interim Draft Report														●	
10	Submission of Interim Report															●

Table 1: Gant Chart FYP I

■ Process

● Suggested Milestone

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Develop three-phase inverter in MATLAB/Simulink	■	■	■					MIDSEMESTER BREAK								
2	Simulate the inverter with different parameters			■	■	■	■	■									
3	Submission of progress report									●							
4	Perform simulation of DC-AC inverter to linear generator									■	■	■	■	■			
5	Pre-EDX												●				
6	Submission of Draft Report													●			
7	Submission of Dissertation (soft bound)														●		
8	Submission of Technical Paper														●		
9	Oral Presentation															●	
10	Submission of Project Dissertation (Hard Bound)																●

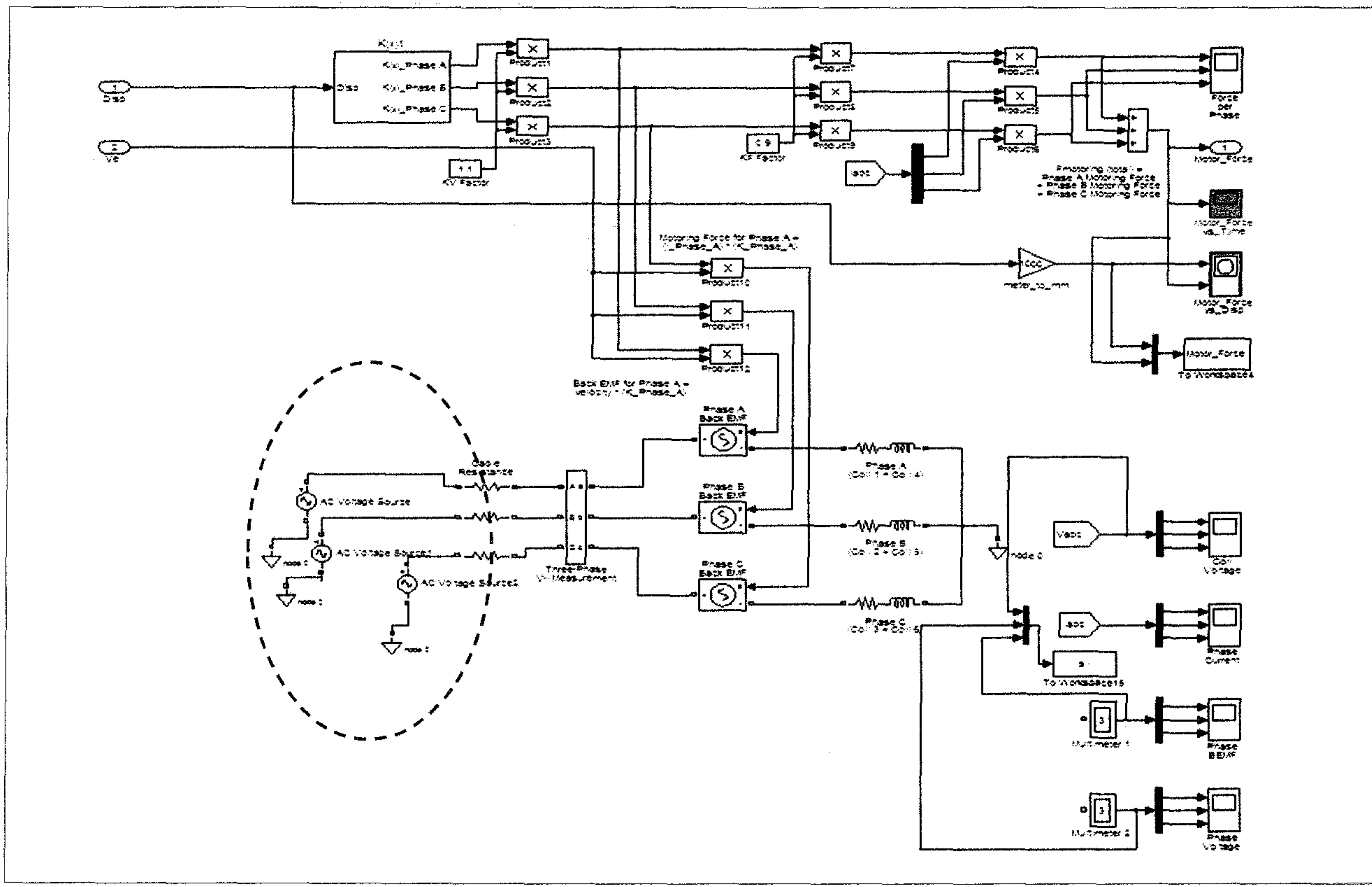
Table 2: Gant Chart FYP II

■ Process

● Suggested Milestone

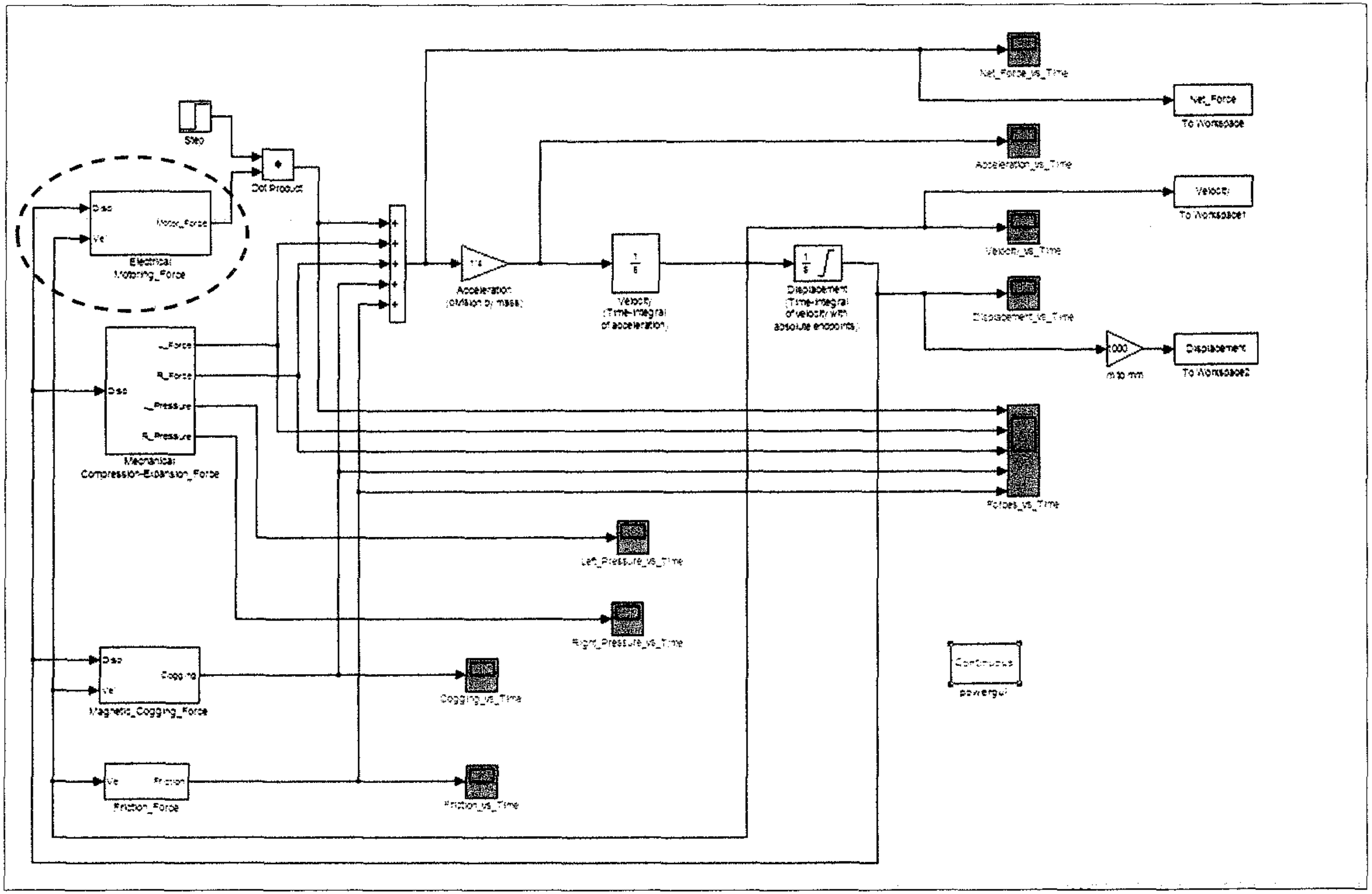
APPENDIX B

SIMULATION OF IDEAL THREE-PHASE AC VOLTAGE SOURCE


Disp
Vel
Phase A Back EMF
Phase B Back EMF
Phase C Back EMF
AC Voltage Source
Three-Phase V-I Measurement
Force per Phase
Motor_Force
Coil Voltage
Phase Current
Phase BEMF
Phase Voltage

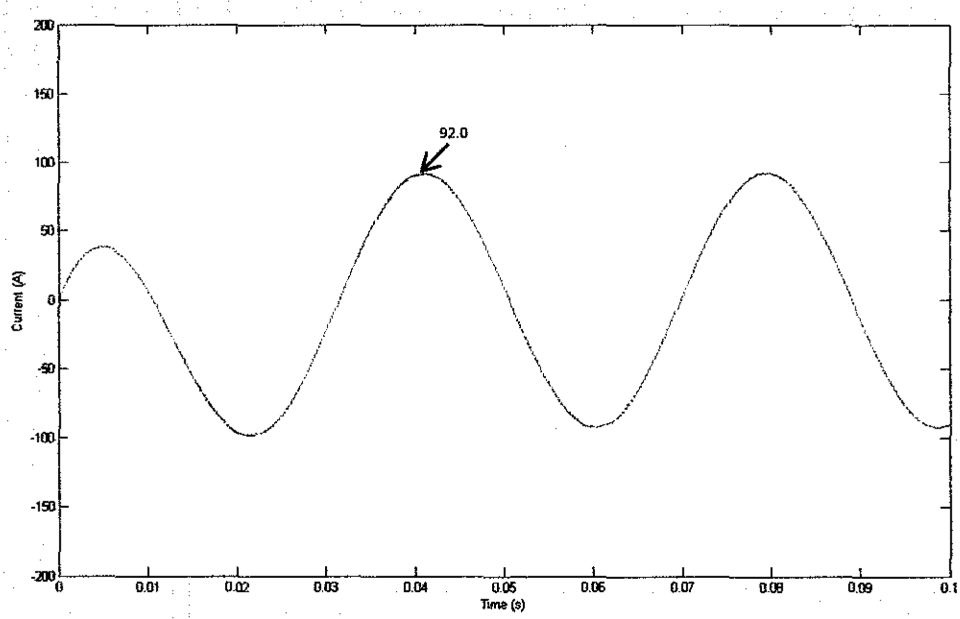
APPENDIX C

SIMULATION OF LINEAR ENGINE-GENERATOR (LG) MODEL

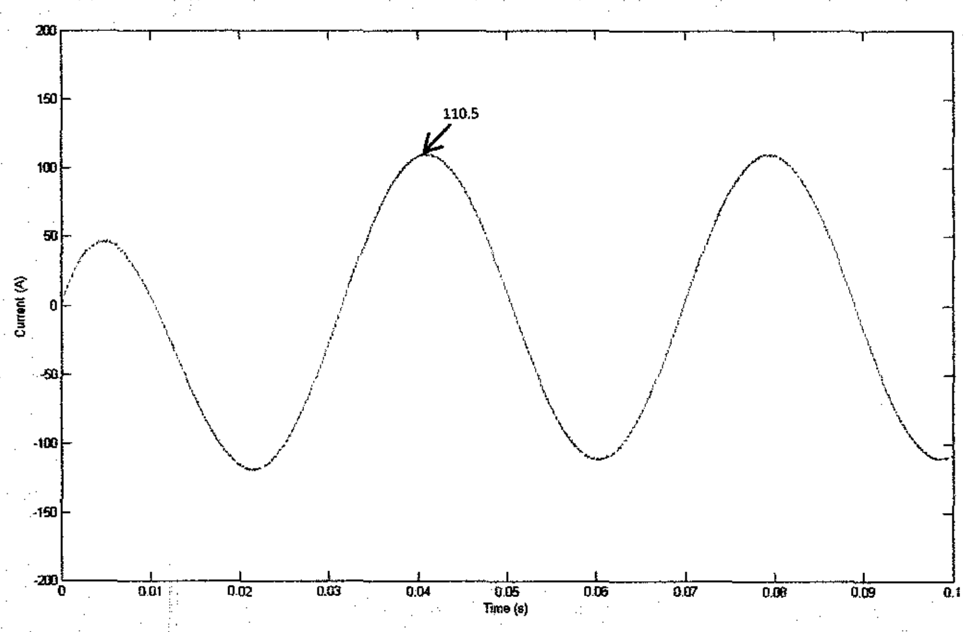

Step
Dot Product
Disp
Vel
Motor_Force
Electrical
Motoring_Force
L_Force
R_Force
L_Pressure
R_Pressure
Mechanical
Compression-Expansion_Force
Cogging
Magnetic_Cogging_Force
Friction
Friction_Force
Acceleration
(division by mass)
Velocity
(Time-integral
of acceleration)
Displacement
(Time-integral
of velocity with
absolute endpoints)
Net_Force_vs_Time
Net_Force
To Workspace
Acceleration_vs_Time
Velocity
To Workspace1
Velocity_vs_Time
Displacement_vs_Time
m to mm
Displacement
To Workspace2
Forces_vs_Time
Left_Pressure_vs_Time
Right_Pressure_vs_Time
Cogging_vs_Time
Friction_vs_Time
Continuous
powergui

APPENDIX D

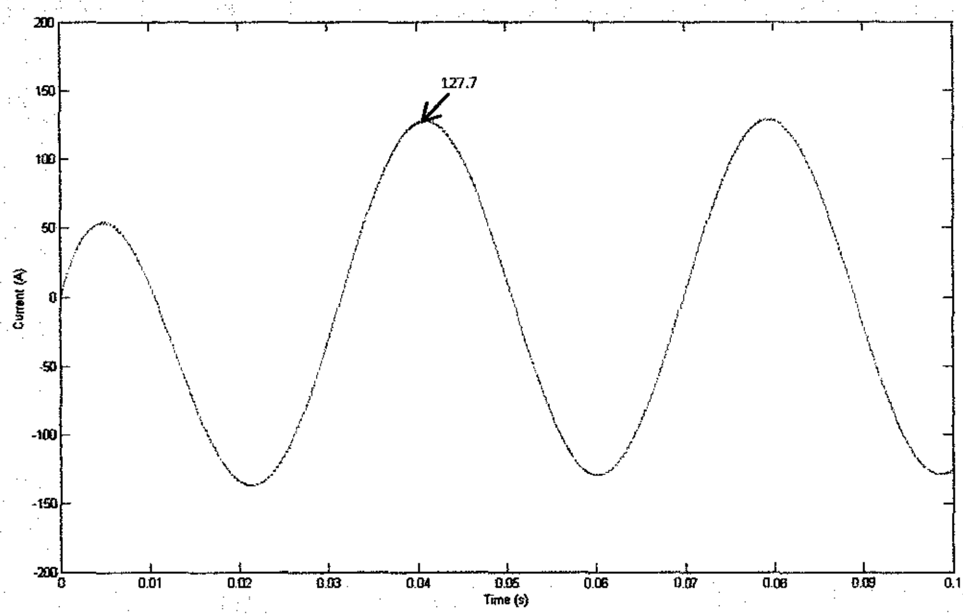
RESULT OF OUTPUT CURRENT BY VARIATION OF MODULATION INDEX



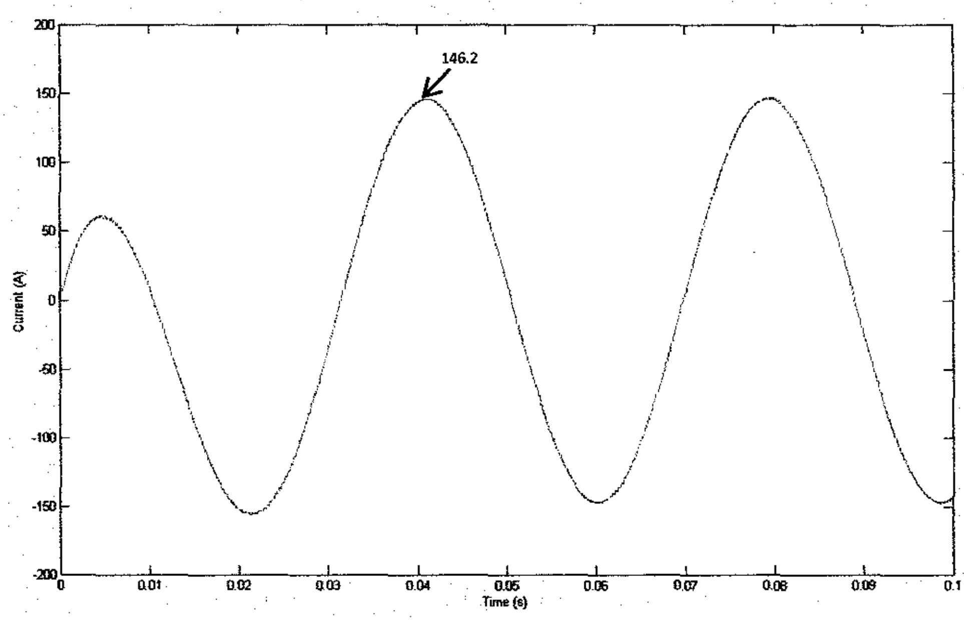
Vdc=144V, f=26Hz, m=0.5



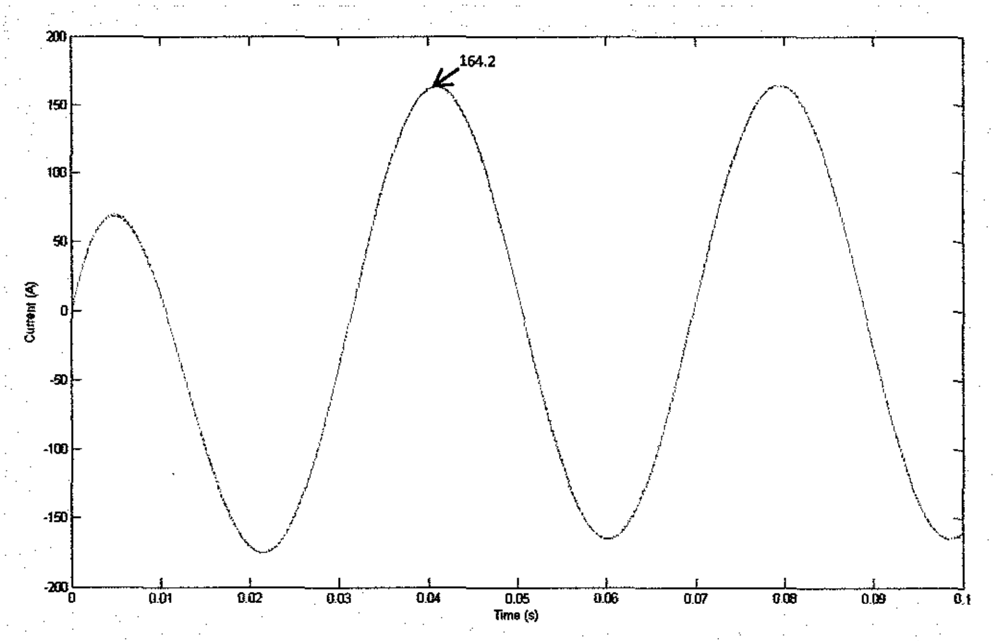
Vdc=144V, f=26Hz, m=0.6



Vdc=144V, f=26Hz, m=0.7



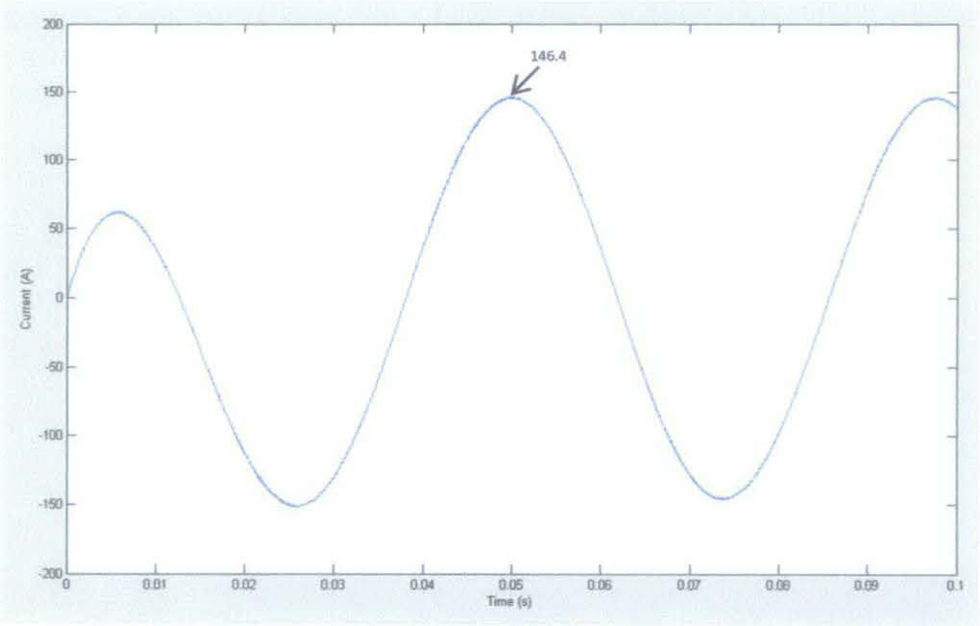
Vdc=144V, f=26Hz, m=0.8



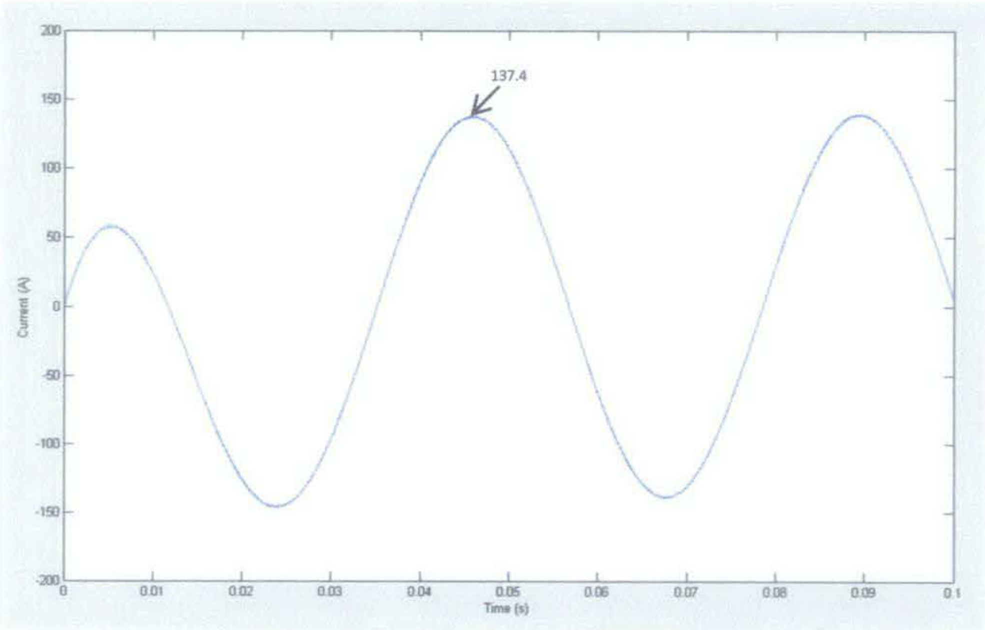
Vdc=144V, f=26Hz, m=0.9

APPENDIX E

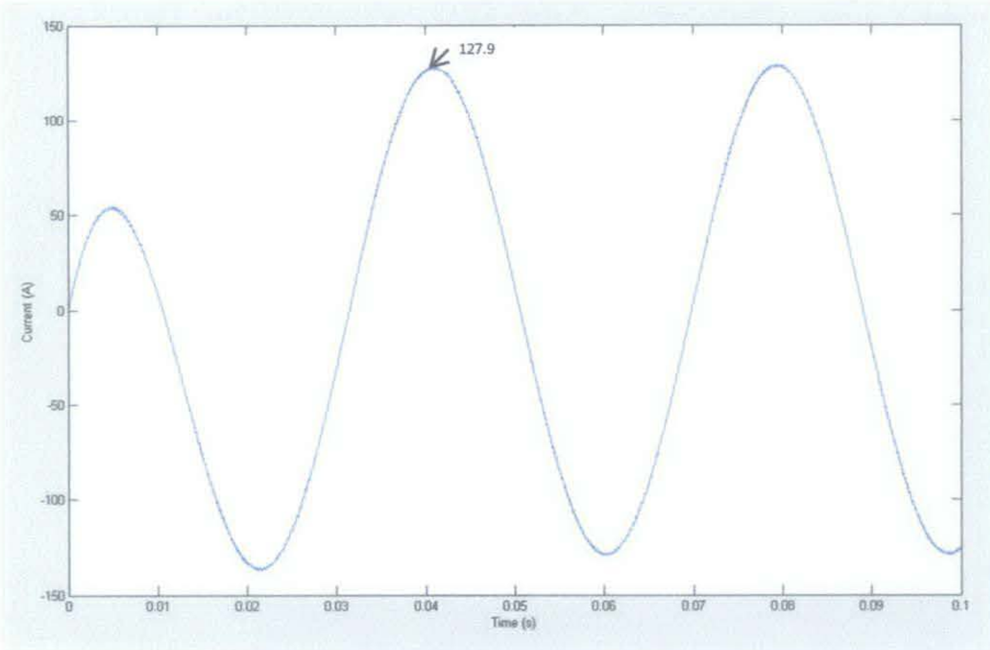
RESULT OF OUTPUT CURRENT BY VARIATION OF FREQUENCY OF OUTPUT VOLTAGE



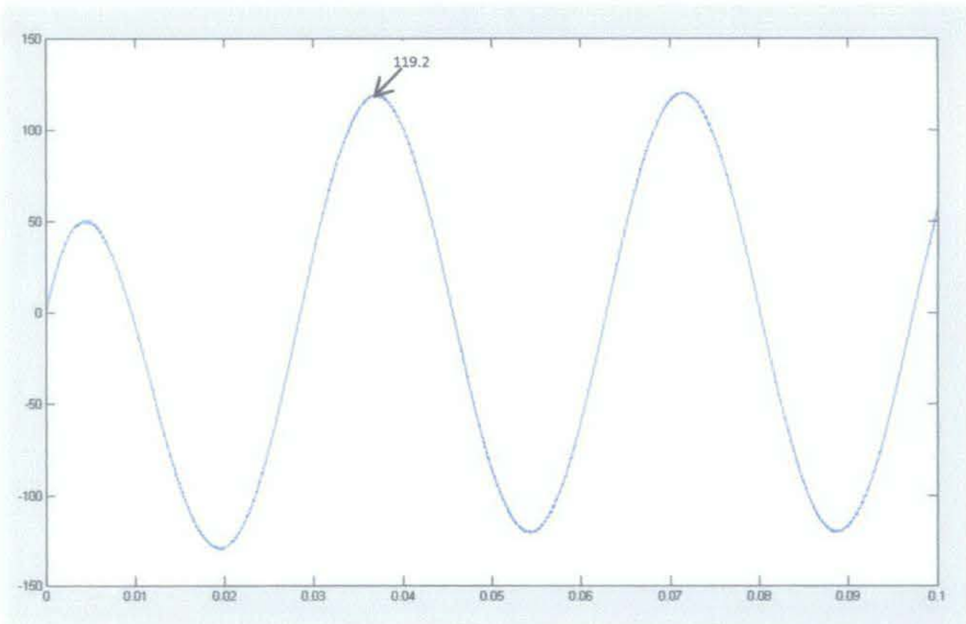
Vdc=144V, m=0.7, f=21Hz



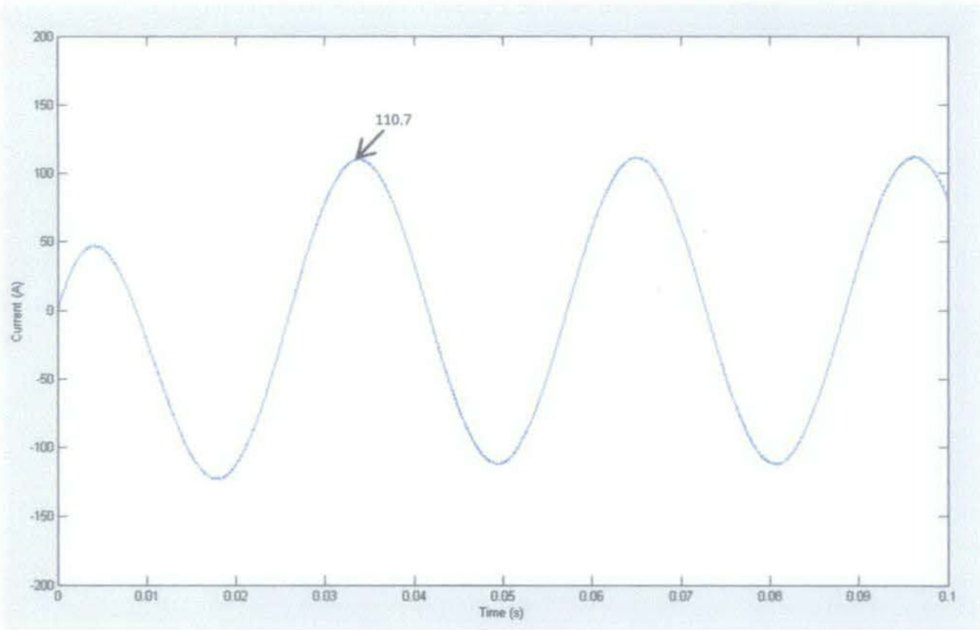
Vdc=144V, m=0.7, f=23Hz



Vdc=144V, m=0.7, f=26Hz



Vdc=144V, m=0.7, f=29Hz



Vdc=144V, m=0.7, f=32Hz