CHAPTER 1

INTRODUCTION

1.1 Background Of Study

Linear motor is one type of motor that operates in linear motion and it has started to replace the rotating motor in many fields of applications. In operating the linear motor, a motor driver is needed to provide for the power drive the motor. It also needs a controller to control the linear motor's motion and speed.

Linear motor has been used in real life applications such as the MagLev (Magnet Levitation) train, MagneRail linear motor, food slicing and bottle capping in food manufacturing factories. In MagLev train, linear motor technology is used for providing forward propulsion in the trains. MagLev means magnetic levitation where the train floats over a guide way using the basic principles of magnets to replace all the conventional steel wheel and track trains [1].

The application of linear motor is widely used all over the world since it operates very well compared to the common rotating motor. The advantages of linear motor are direct force, no backlash, fast response, much higher speed, less maintenance work and it is three-phase operating motor [2].

Direct force removes a major source of positioning error by eliminating the conversion of rotary (ball screws, timing belt, etc) to linear motor and this will increase accuracy repeatability. A rotary motor also can attain speed of 50 inches per second (converting rotary to linear motion) while the linear motor speeds reaching 400 inches per second (10 m/s) are possible.

There are different kinds of linear motor that available in market for various applications. The types of linear motors are moving coil, moving magnet, AC synchronous design, AC induction design, linear stepping design, brushed design and brushless design [3].

Therefore, it is planned to have a linear motor testing facility in UTP where a lot of experiments can be done on the linear motor, for example force control, positioning control and velocity control. For these controls, a very important parameter to observe is the current waveform of the three-phase of the linear motor.

This project is relevant to the study of Power Electronics and Electrical Machines. It is also relevant to the recent technology of applying linear motor in various fields such as in robot usage for manufacturing purposes, entertainment, and safety and so on. Besides, the installation of the linear motor can be the first step of developing and testing linear motor in UTP.

1.2 Problem Statement

A brushless linear motor operates by injecting current into the required phases at the right instant of time. When current is injected into a particular phase, it will produce a magnetic field on the windings or coils. This magnetic field will produce a force which interacts with the permanent magnets' magnetic fields. The force produced will move the translator to the right or left.

The process of current injection to produce maximum force and proper direction is called commutation. In a brushed DC motor, the permanent magnets are stationary while the coils will move. Switching of current into the different coils is performed by mechanical commutation by the use of commutator ring and brushes.

In a brushless linear motor, which is the present study, the permanent magnets move while the coils are stationary. Thus, switching of current injection into the static coils is achieved by electronic commutation by the use of an inverter bridge, commonly referred to as motor driver.

Electronic commutation has different techniques for current injection which are sinusoidal, trapezoidal, rectangular and six step commutation. Without this proper current injection, switching and commutation technique, a linear motor can not be operated successfully.

1.3 Objectives

The objectives of this project are listed as below:

1) Hardware configuration of brushless linear motor and its motor driver for experimental testing.

2) Software configuration of commutation, switching and current injection for the linear motor.

3) Designing and fabricating a Printed Circuit Board (PCB) for three-phase current transducer.

4) Testing and analysis of current injections to investigate the commutation strategies for the linear motor.

1.4 Scope Of Study

A linear motor can be operated as a servo motor for positioning and velocity control. There are three basics of servo used in modern servo systems: AC servo motor (based on induction design), DC servo motor (based on DC motor design) and AC brushless servo motor (based on synchronous design) [4].

This project involves installing the following hardware: a three-phase brushless linear motor and a motor driver (MOSFET Inverter Bridge). The brushless permanent magnet DC motor is a three-phase motor. After this hardware configuration is completed, software configuration will be implemented where this configuration is very important for the linear motor.

Software configuration is about communicating the motor driver (Accelnet Panel ADP) with the CME 2 software. This stage of configuration is important since it sets all the switching and commutation strategies so the linear motor can be run properly.

The brushless linear motor called Servotube Actuator model XTA 3810 while the motor driver used is digital servo drive for brushless or brush motor (Accelnet Panel ADP, model ADP-180-18-S). −S means this motor driver is able to receive sin or cos feedback. Both of these equipments are purchased from Copley Controls Corporation.

The study will be in two stages, where the first stage is to study and set up all the hardware including the wiring and connectors. The second stage is to communicate the CME 2 software with the Accelnet Panel ADP to drive and control the linear motor on its commutation.

After the current transducer is installed on the PCB, it will be used for observations of current waveforms in different commutation techniques and operation modes: position, velocity and force. By analyzing the current waveforms and comparing with the theory, it is hoped that much knowledge can be gained from the linear motor testing facility.

CHAPTER 2

LITERATURE REVIEW

2.1 Three-Phase Brushless Linear Motor

Naturally, much of motion involved in automation processing is linear. This motion and generation of linear force are conventionally produced through the use of hydraulics or pneumatics that is very complex, messy and quite expensive. Other technologies used to create linear motion is by rotating electrical devices that require a mechanical transmission to convert rotary to linear which will add more cost and complexity to the system plus extra possibility of wear and failures.

As technology evolves, there is new option in motion control. The recent technology introduced into the engineering world is the use of permanent tubular linear motor. This linear motor is more reliable and practical to be applied in linear automation since it directly translates the electrical energy into usable linear force and motion [5].

Even though this linear motor is slightly different than the rotating one, it actually has the same principle of operation: conversion of electric to mechanical energy. However, a linear motor commutate based on linear position while a rotary motor commutate based on angular position.

2.1.1 Commutation

Commutation is the process of switching current into the phases to result in the movement or motion of the motor. Most linear motors use three-phase of the brushless design. Brushless technology has no contacting parts and therefore it is more reliable in many aspects but the control of this type of motor will be a little complex [6].

If a common brushless motor is used in producing a force, the windings must be switched in polarity and amplitude relative to the permanent magnet's fields. However, if a brushed type motor is used, then the magnets are usually static which is known as stator. In a brushless motor, the magnets are on the moving shaft, either rotating or sliding. Commutation is cyclical (cycles repeat every revolution) with a rotary motor but with a linear motor, the cycles repeat over a fixed distance.

A brushless linear motor requires a drive to supply power to the motor's windings. In other words, some kind of feedback is needed from position sensor in order to make the commutation works properly as shown in Figure 1 below [7].
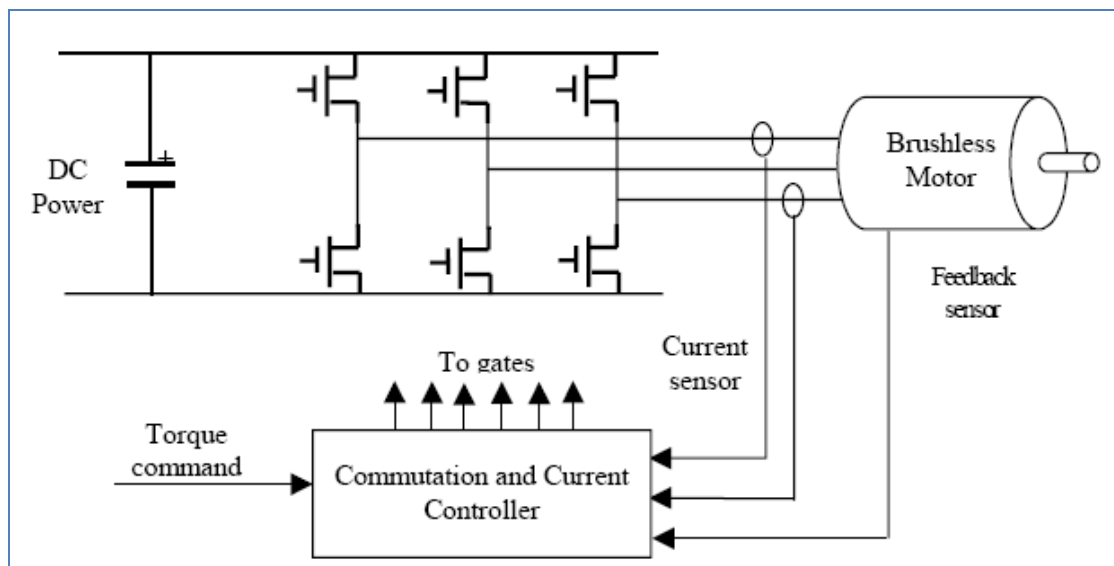

Figure 1: Brushless motor drive system

In order to have commutation, power is applied to the windings to produce force or torque and for the brushed type motor, the brushes and commutator accomplish this within the motor. This type of motor can be controlled by varying the DC power supplied to the motor. For the brushless type motor, it needs an integral relationship of amplifier or any controller to do this job.

There will be a position sensor equipped internally in the motor which feeds commutation position information to the amplifier or controller to control the polarity and amplitude of the voltage supplied to the coils based on the position of the magnets. The position information will be sent to the amplifier or controller depending on the design and specific type of the controller being used.
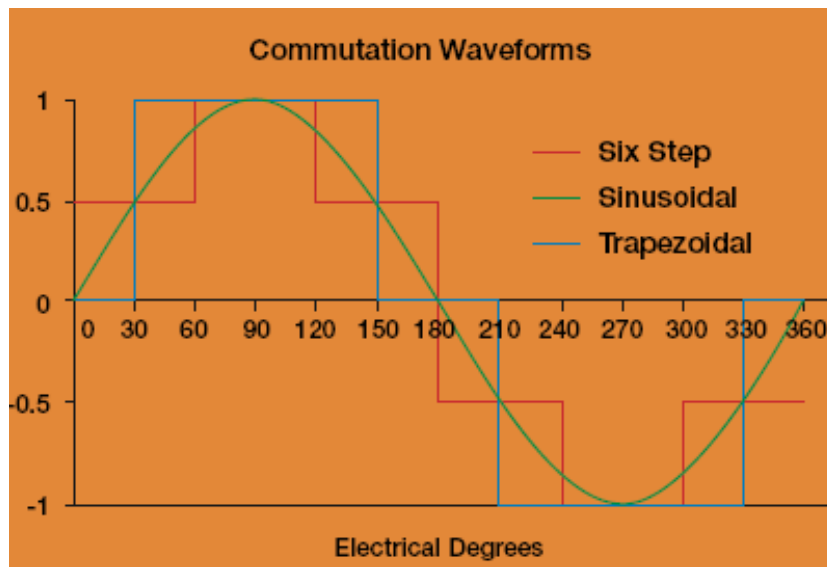

Figure 2: Commutation Waveforms

There are different schemes of electronics commutation and current controls for a brushless linear motor such as six-step, sinusoidal and trapezoidal commutation as shown in Figure 2 above. Basically, trapezoidal is the simplest form of commutation compared to the others plus it is the cheapest one among the three. Six-step commutation looks more like the trapezoidal commutation but it has a disadvantage where it has disturbance forces when running in high temperature and this will make the motion not smooth.

2.1.1.1 Six-step Commutation

Six steps commutation is one of the simplest commutations for three-phase brushless linear motor. Each phase voltage is activated for 120° (electrical degree) as in Figure 3 where each phase voltage is positive (negative) when top switch is ON (OFF) and the bottom switch is OFF (ON). No voltage is injected when both of switches are OFF where the actual terminal voltage is governed by the back EMF voltage of the motor [7].

In other words, each phase voltage at a time takes one of three states – positive, negative or floats. At every sector, only one phase is energized positive and one of the other is energized negative in order to maintain the path.
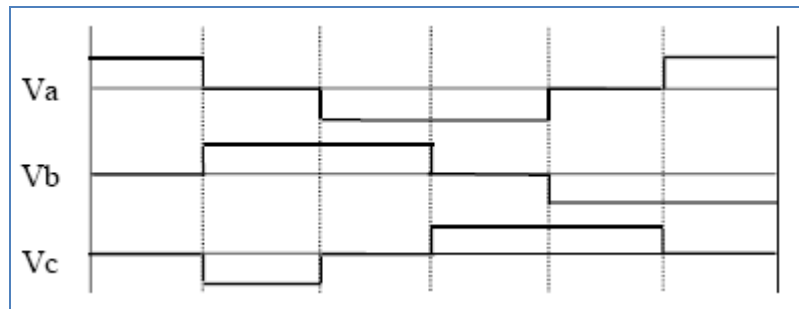

Figure 3: Six-step phase voltages

2.1.1.2 Sinusoidal Commutation

This commutation is basically done by two methods: the first one is rectangular commutation using digital Hall Effect devices which generate pulses as the motor passes over the magnetic poles of the magnet track.

The signals, which are correct for the commutation, will then be combined with the demand signal to properly commutate the motor. This method has lower cost compared to the other method but noise can be easily taken into consideration on the hall-effect commutation.

The other method is by using a sinusoidal encoder. When a change of state is detected in the digital Hall signal, the incremental encoder signals can then be used to digitally determine where in the commutation cycle the motor is. Commutation is basically done by producing a sin (θ) phase A command signal, a sin (θ + 120) phase B command signal, a sin (θ + 240) phase command signal and multiplying these by the current command. This is shown in Figure 4.
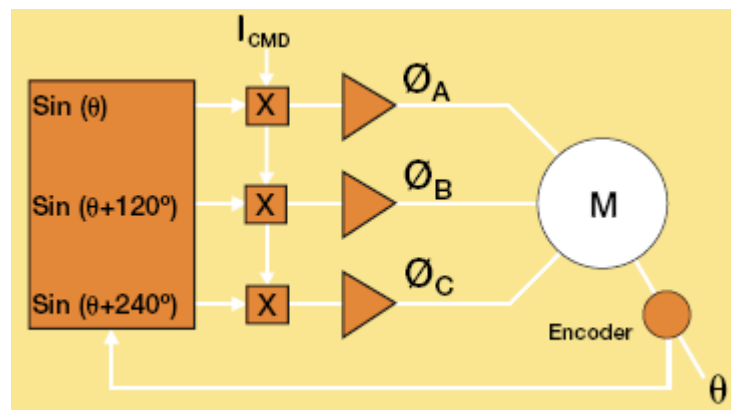

Figure 4: Sinusoidal Commutation

This method gives the best results, faster settling time and tighter servo loops. The noise can also be easily filtered out from the system which makes the system more reliable. When sinusoidal commutation is used in a linear motor, the motion is smoother and it is driven efficiently with less heat production.

2.1.2 System Architecture

Apart from commutation, other aspects of the linear motor operation include the supply of power itself which is provided by the motor drive (a power electronics stage called an inverter bridge which consists of several power transistor) and motor controller which provides for motion, velocity and torque control. Such a system is usually called a servo control system, making it a servo linear motor. The following are different architecture of arrangement of the linear motor, motor drive (or servo amplifier) and servo controller.

2.1.2.1 System One

A position signal is fed into the controller which then provides the commutation signals to the amplifier, allowing the amplifier to drive the motor properly. This type of control system is compatible with virtually every permanent-magnet brushless motor and it is a simple architecture and has enough ability to deliver signals to the controller even though it is not very accurate [5].
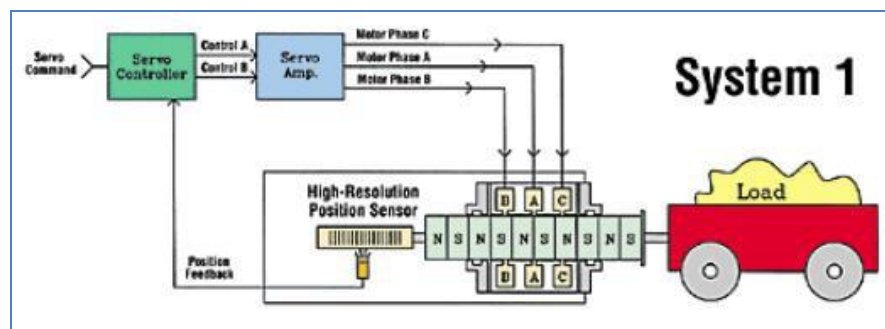

Figure 5: Illustration of System One

2.1.2.2 System Two

This system is the same as System One but with an additional control loop. The second control loop will monitor the force or load, where it allows the controller to close a position loop and force loop while providing commutation signals to the amplifier. With this additional loop, the system is not limited for controlling based on positional information only. The system may use other sensors such as force, velocity or torque for controlling the system [5].
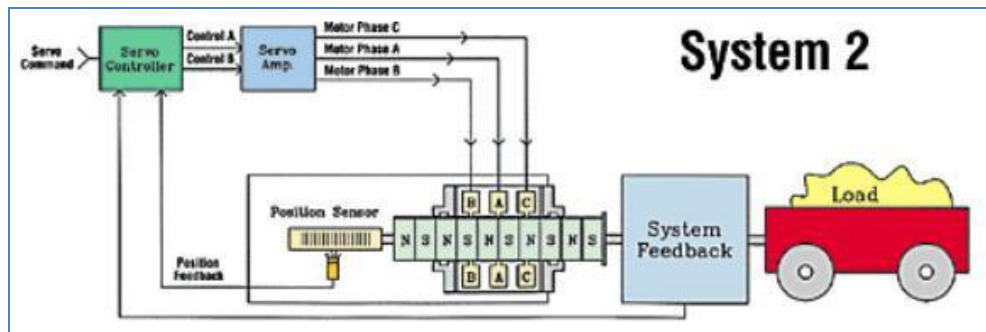

Figure 6: Illustration of System Two

2.1.2.3 System Three

In addition to position signals which are supplied to the controller, a commutation signal is required by the servo amplifier to properly phase the drive current. With this system, the commutation feedback is sent to the amplifier instead of the controller for commutating the motor and at the same time any process control feedback like force, velocity or high resolution position is sent to the controller to maintain control over whatever parameter is needed by the system [5].
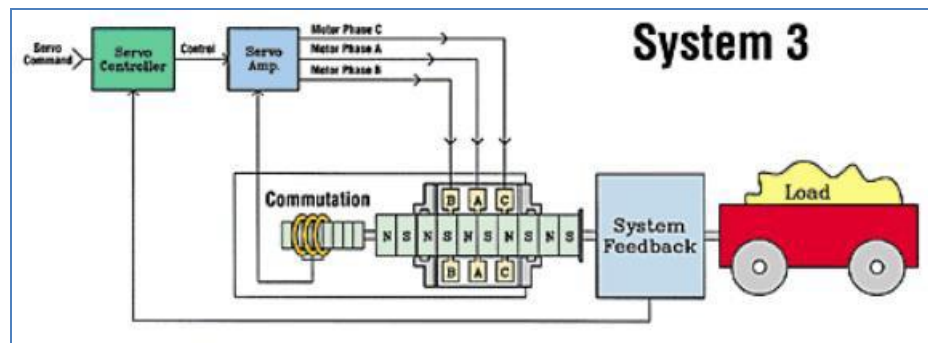

Figure 7: Illustration of System Three

This system tends to use a less expensive controller while maintaining the control over the process in a manner similar to that offered by System Two. It also allows the use of a variety of feedback devices. A high-resolution feedback can be attached to the load or motor, and achieved with any type of position or force feedback device. It does not need an initialization phasing move as in System One and System Two.

2.1.2.4 System Four

This system requires position-based information which will be obtained from a resolver, to be supplied to the servo amplifier. The amplifier will then generate an A-B quadrature signal for the controller and the commutation signal for phase control. The resolver is mainly attached to the motor and it generates angular position data. Data received by the amplifier will then be processed to produce a quadrature A-B signal, mimicking an encoder for positional feedback to the controller [5].
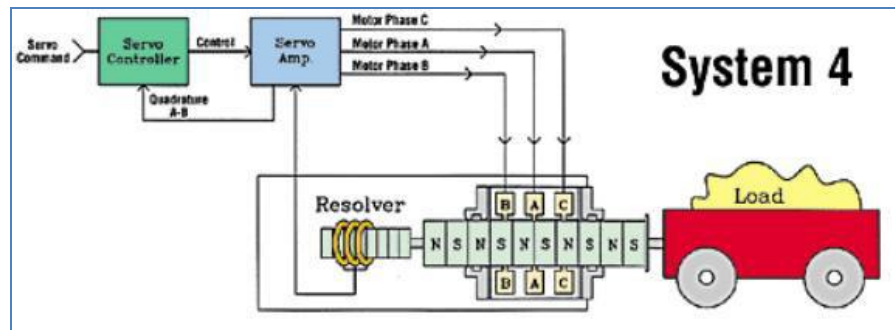

Figure 8: Illustration of System Four

Basically, this system saves cost since it uses one type of feedback device. It is easy to be implemented and simple to control plus it is a very good system for non-critical applications. However, it is not suitable for applications with high speeds and accuracies since it has a time delay which is caused by the processing of the resolver information.

2.2 Servotube Actuator

A servotube actuator is one type of linear motor which offers an optimal solution for industrial position control. It is faster than a ball-screw plus clean reliability of linear forcer and it is cost effective in applications requiring greater flexibility and control. It operates with maximum velocity of up to 5.3 meters per second and its range of motion is between 33 mili-meters to 318 mili-meters [8].

The servotube actuator is an ideal example for any linear work such as push, pull, lift material handling, packing, and automated assembly applications. The motor is equipped with a built in position sensor so no external encoder is required. The following Figure 9 shows how the servotube actuator works: the force can be obtained from the body of the motor or by its moving shaft.
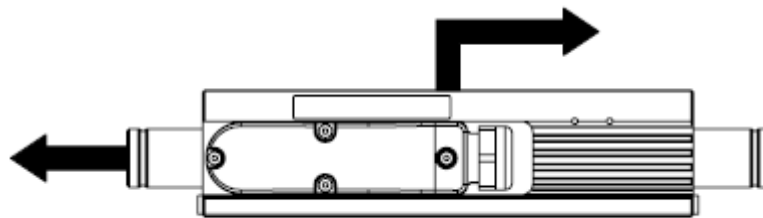
Figure 9: A servotube actuator's motion

2.2.1 Position Sensor

The position sensor outputs are analogue which are differential sine and cosine signals. The following Figure 10 shows the relationship between the forcer phase back EMF and position sensor outputs for one direction of motion (as shown by the arrow). It shows that +SIN or −SIN is always in phase with the forcer phase U.
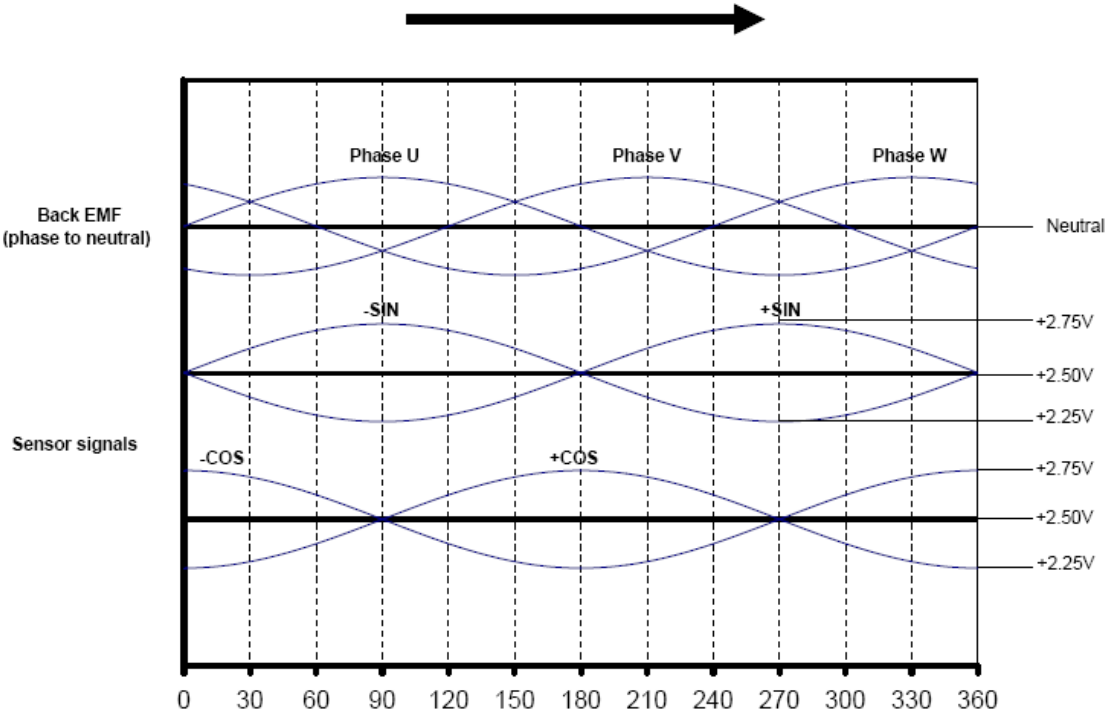

Figure 10: The relationship between forcer phase back EMF and position sensor outputs for one direction

2.3 Current Transducer

After the linear motor is successfully configured, analyses will be done on the input current waveforms for three modes: current, velocity and force modes. The analyses will be done on the waveforms taken from the Accelnet Panel's (motor driver and controller) input to the linear motor by the use of a current transducer to capture the current waveforms.

A transducer is basically a device which is usually electrical, electronic, electro-mechanical, electromagnetic, photonic or photovoltaic which it converts one type of energy or physical attribute to another form of energy for various purposes including measurement or information transfer [9].

In this project, the current transducer is used to read out the input signal waveforms from the Accelnet Panel ADP while it is commutating the linear motor. A current transducer is a device that functions the same as current sensor where it detects the electrical current (AC or DC) from a wire and the device will generate a signal proportional to the sensed current. The current transducer is actually a current transformer that has two windings: primary and secondary windings as shown in Figure 11 below.

The primary winding is wound with a thick wire and consists of a small number of turns. It is connected in series with the conductor in which the current is measured, while the other winding: secondary winding is wound with a thin wire and consists of large number of turns compared to the primary's turns. It is used to form a current in the secondary that is proportional to the primary current. The current is then rectified and introduced at the transducer output.

Figure 11: Current transformer

2.3.1 Current Transducer HXS 50-NP

This transducer is used in the project to capture current waveforms of all three phases' input signals of Accelnet Panel ADP to the linear motor. Each phase of the motor (Phase U, phase V and phase W) will have its own transducer and the waveforms will be displayed on an oscilloscope or captured by a data acquisition (DAQ) system for further analyses.

Current transducer HXS 50-NP (Figure 12) is basically used for electronic measurement of currents: DC, AC, pulsed and a mixed, with a galvanic isolation between the primary circuit (high power) and the secondary circuit (electronic circuit). This transducer is manufactured by LEM (Experts for Electrical Measurement) whose products are widely used in many applications.

The transducer needs 5-Volt power supply and it has low power consumption. It is small in size and space-saving plus it has high immunity to external interference. It is usually used on AC variable speed drives, static converters for DC motor drives, UPS (Uninterruptible Power Supply), SMPS (Switched Mode Power Supplies) and battery supplied applications.
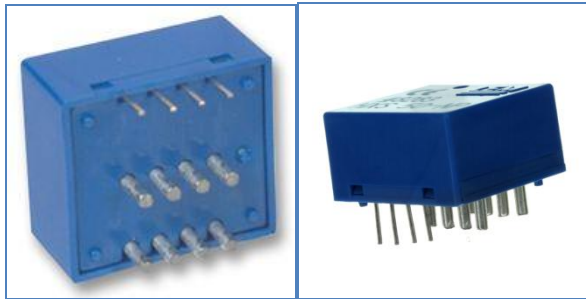
Figure 12: Current transducer HXS 50-NP

The current transducer is basically connected to power supply, an external optional reference voltage and it will produce an output. The device has eight pins that are directly connected to the internal windings whose pins are numbered from one to eight as shown in the Figure 13 below. The pins can be connected in three ways which depends on the required number of primary turns. According to Table 1, different number of primary turns will give different maximum primary current and maximum nominal current.
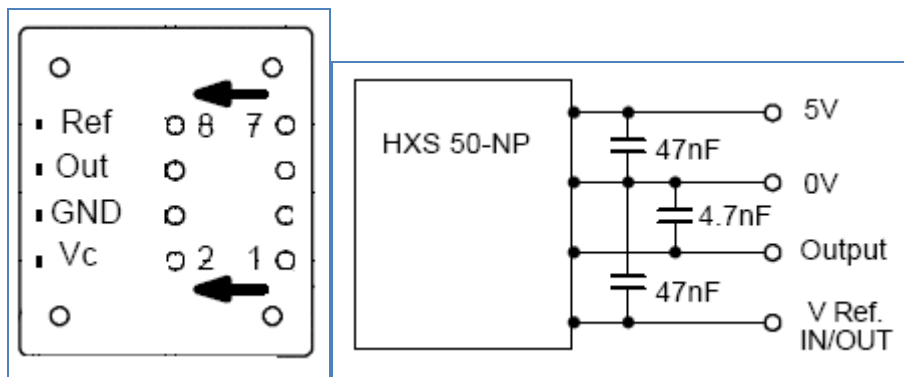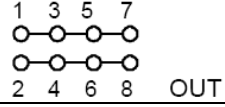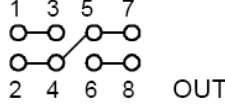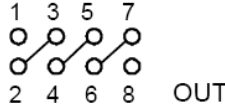

Figure 13: Electrical connection of HXS 50-NP

Table 1: Options of connectivity for current transducer

| Number of primary turns | Primary current | | Primary resistance, Rp (m ohm) | Primary insertion inductance, Lp (µH) | Recommended PCB connections |
	Nominal, Ipn (A)	Maximum, Ip (A)			
1	50.000	150.000	0.050	0.025	IN 1 3 5 7 ○-○-○-○ ○-○-○-○ 2 4 6 8 OUT
2	25.000	75.000	0.200	0.100	IN 1 3 5 7 ○-○ ○-○ ○-○ ○-○ 2 4 6 8 OUT
4	12.500	37.500	1.000	0.400	IN 1 3 5 7 ○ ○ ○ ○ ○ ○ ○ ○ 2 4 6 8 OUT

The third option will be used for this project where the number of primary turns is four and the maximum nominal current is 12.5 amperes. This value will be used to calculate the output voltage of the current waveforms based on the following formula:

$$V_{out} = V_{ref} \pm (0.625)\left(\frac{I_p}{I_{pn}}\right) \quad Volt$$

where V_{ref} is constant at 2.5 Volts, I_p is supplied current and I_{pn} is maximum nominal current. This calculated output voltage will then be verified with the output voltage obtained from the oscilloscope.

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

In order to achieve the objectives of this project, some research is done on some resources from books and technical papers to obtain information on the servotube actuator (linear motor), Accelnet Panel ADP (motor driver and controller), current transducer and CME 2 Software.

All the connections from the motor to the Accelnet Panel ADP are done in the laboratory. Then, the configuration on CME 2 software will be started. Basically, the CME 2 is used to communicate the motor with the Accelnet Panel ADP as its driver.

3.2 Project Work

The project activity flow is shown in Figure 14 below:

```
                    ┌──────────────┐
                    │    START     │
                    └──────────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │   Order and buy all the devices needed │
        └─────────────────────────────────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │ Configure the linear motor in the laboratory │
        └─────────────────────────────────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │ Testing the devices (Current transducer and │
        │        motor in the laboratory)         │
        └─────────────────────────────────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │     Analysis of Result & Discussion     │
        └─────────────────────────────────────┘
                           │
                           ▼
        ┌─────────────────────────────────────┐
        │            Report Writing              │
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                    │     END      │
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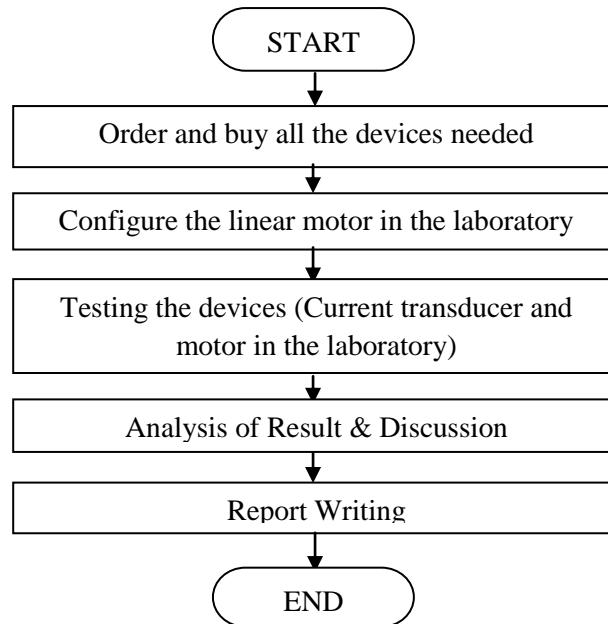
Figure 14: Project Activity Flow Chart

In order to achieve the objectives of the project, some researches were done in early stage on how the linear motor works, the equipment (hardware and software) needed for configuration and the expected results are studied. The studies were done on Servotube Actuator, Accelnet Panel ADP, CME 2 software and current transducer.

After all the equipments are obtained, the configuration is started with the configuration on linear motor and Accelnet's connections and the current transducer was tested in order to test its reliability and effectiveness in certain condition after all connections on the linear motor are completed.

The printed circuit board (PCB) design was started using Eagle software since the pins of the component can not be fitted with the common Vero-board or bread board. After the circuit was completed and current transducer was installed onto the PCB, second testing on the current transducer was done to ensure the component is working.

At the same time, familiarization on CME 2 software was done in the laboratory in communicating the computer and Accelnet via RS-232 and RJ-11 connectors. When the configurations on hardware are completed where the current transducer is placed in series in between Accelnet and linear motor, the configuration of CME 2 software is started.

When the linear motor is operated, the current waveforms driven the linear motor are observed and measured by using oscilloscope. The waveforms are obtained from the current transducer's output. The observation and measurement are done for few other modes; Current mode, position mode and velocity mode.

3.3 Equipments Required

3.3.1 Servotube Actuator

A servotube actuator is basically a device that converts electrical to mechanical in which an electrical input determines the position of the armature of a motor. As stated earlier in Chapter 2; Literature Review, this type of motor has been widely used all over the linear automation field since it offers better performance than the conventional technologies.

Three basic types of servo motors are used in modern servo systems: AC servo motors - based on induction motor designs, DC servo motors - based on DC motor designs and AC brushless servo motors - based on synchronous motor designs. In this project, the servo motor used is the brushless and powered by DC.

3.3.2 Accelnet Panel ADP

Accelnet is a high-performance, supplied with DC drive for position, velocity and torque control of brush and brushless motor. It is usually operated as distributed drive using the CANopen or DeviceNet Protocol, or it also can be used as a stand alone drive accepting analog and digital inputs from an external motion controller.

Drive commissioning is very easy and simple using CME 2 software which can be operated under Windows and it can communicate with the Accelnet via CAN or RS-232 link. Accelnet operates as a Motion Control Device where it supports some modes such as Profile Position, Profile Velocity, Profile Torque and Homing [10].

The model of Accelnet that will be used is ADP-180-18-S which (–S) means for sin or cos feedback. Besides that, the model comes with feedback options including digital quadrature A/B and absolute SSI encoders as standard. It can accept 12 inputs and processes them at high speed rate while there are 3 outputs port to be connected to the other devices.

3.3.3 Current Transducer

This device is used to change the output current from the motor to a current waveform for measurement and information transfer purpose as stated before this. The device was tested in the laboratory by supplying certain amount of frequency to observe the output of the transducer.

Basically, since the motor has three phases of inputs and outputs, there will be three current transducers will be used for the whole project to observe every single phase (Phase U, V and W).

3.3.4 CME 2 Software

In connecting the Accelnet and the computer via RS-232 or CAN bus, this software will be used since its configuration is very simple and fast. Connections are made once and the CME 2 does the rest thereafter. Motor data will be saved as as.ccm files and drive data will be saved as .ccx files. Drive data contains all drive settings plus motor data. Basically, the Accelnet will have a RJ-11 port and it will be connected to RS 232 on the computer.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

4.1.1 First Testing of Current Transducer

After the connections of the motor and Accelnet Panel ADP were completed, the testing on current transducer is done to make sure the device will properly work when it is installed on the PCB board. The following data are details for the testing on the transducer:

Equipment used: Current transducer, wire, function generator, digital oscilloscope, power supply, decade resistance box (Power resistance).

Power supply: 5 Volts

Number of primary turns: 4

Reference voltage, V_{ref}: 2.5 Volts

Maximum nominal current, I_{pn}: 12.5 Amperes

Primary resistance: 1 Ω

Measured primary resistance: 1.6 Ω

Frequency of input: 10 Hz

Maximum primary current, I_p: V / R

For the first testing, no frequency supplied from the Function Generator where the input voltage is 2.3 Volts. The following figures are the results:
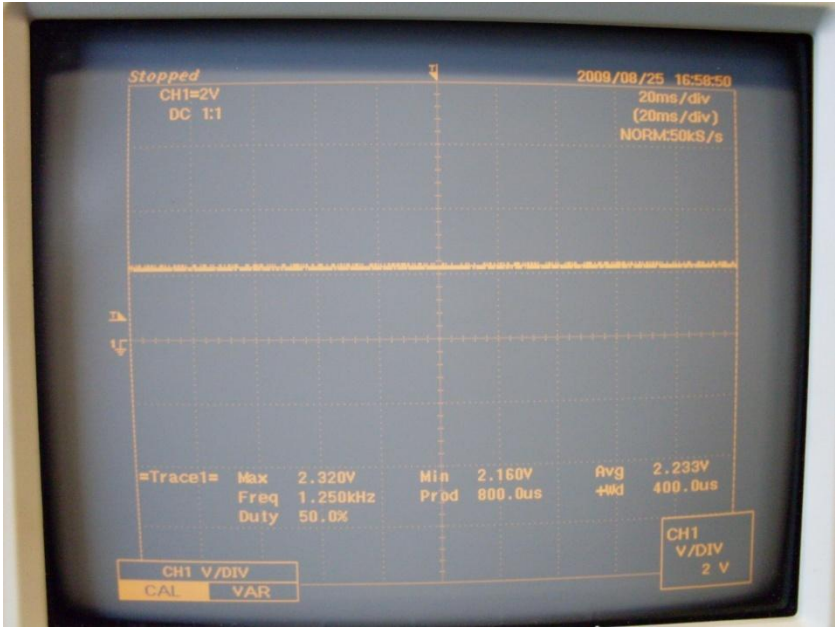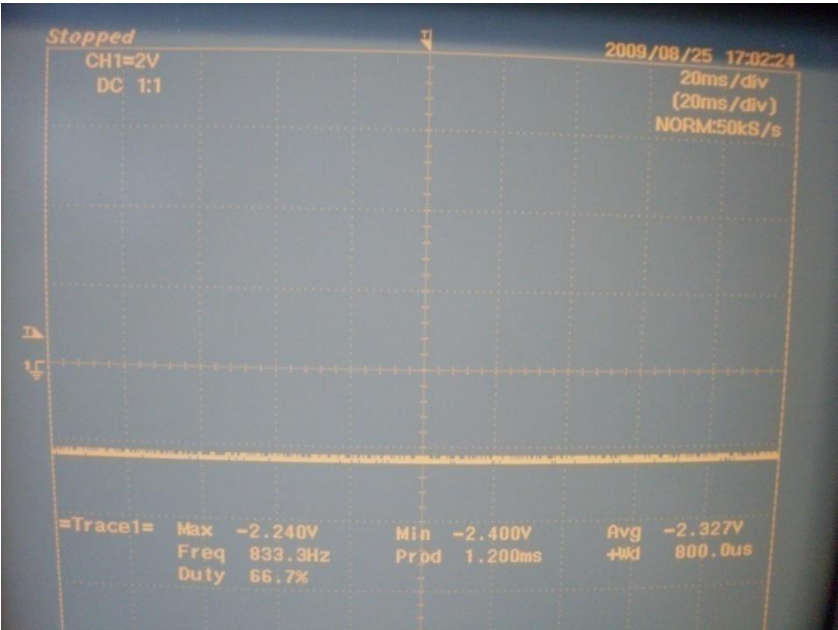

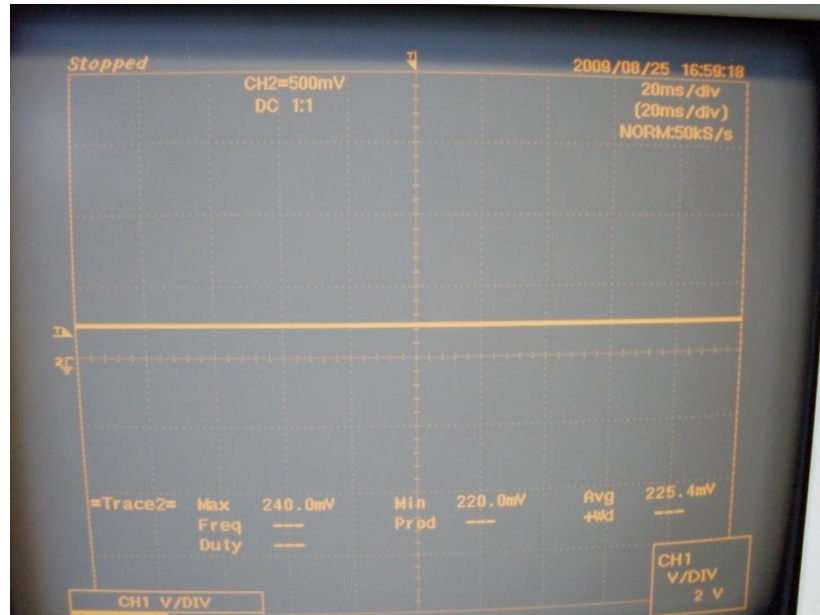Figure 15: Input 2.3 Volts

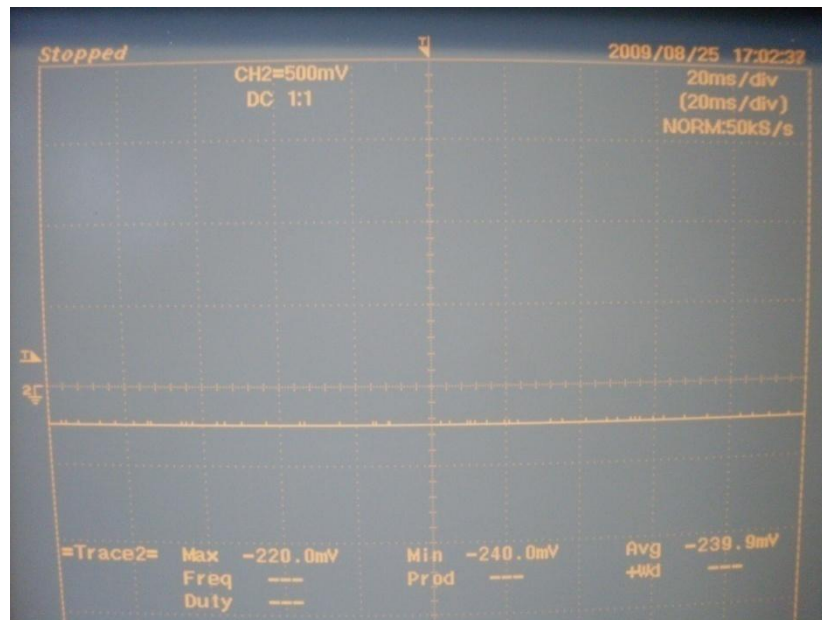Figure 16: Input -2.3 Volts

Figure 17: Output for 2.3 Volts

Figure 18: Output for -2.3 Volts

Based on the figures above, the input voltage is 2.3 Volts and – 2.3 Volts while the outputs are 240 mV and -220 mV respectively. The output basically can be calculated by formula $0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right)$.

The value of I_p:

$$\frac{V}{R} = \frac{2.3}{1.6}$$

$$= 1.4375 \text{ Amperes}$$

Therefore, the calculated output:

$$0.625 \cdot \left(\frac{I_p}{I_{pn}} \right) = 0.625 \cdot (1.4375 / 12.5)$$

$$= 898.44 \text{ mV}$$

Next testing is done by applying a 10 Hertz signal from the function generator while the other settings remain the same. The following figures are the results:
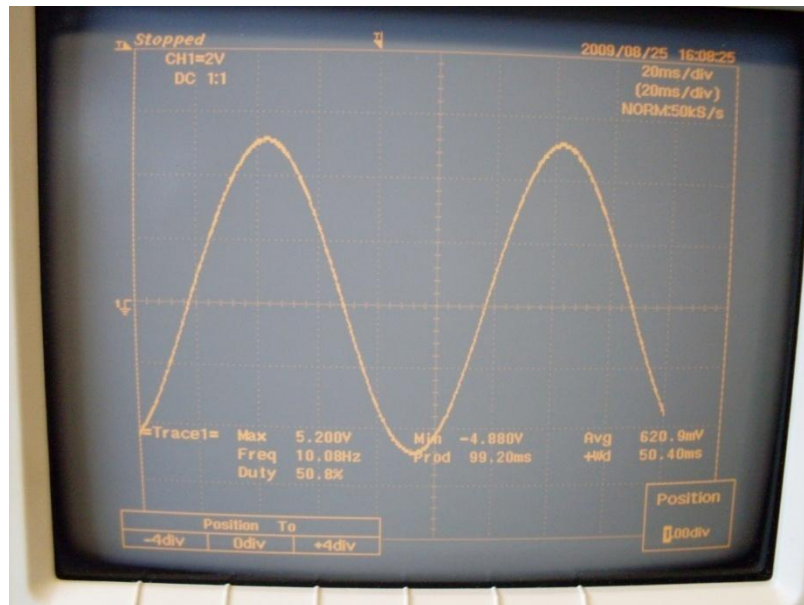

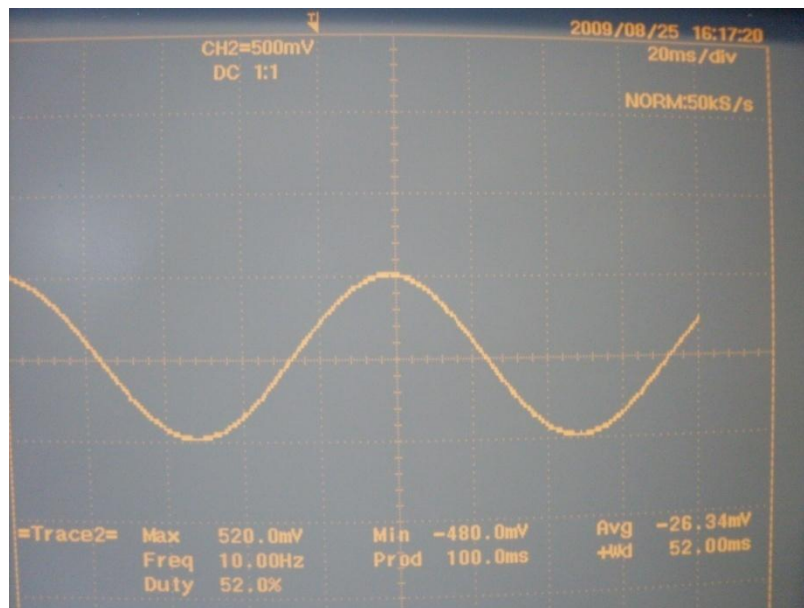Figure 19: Input of 5 V (Sinusoidal input)
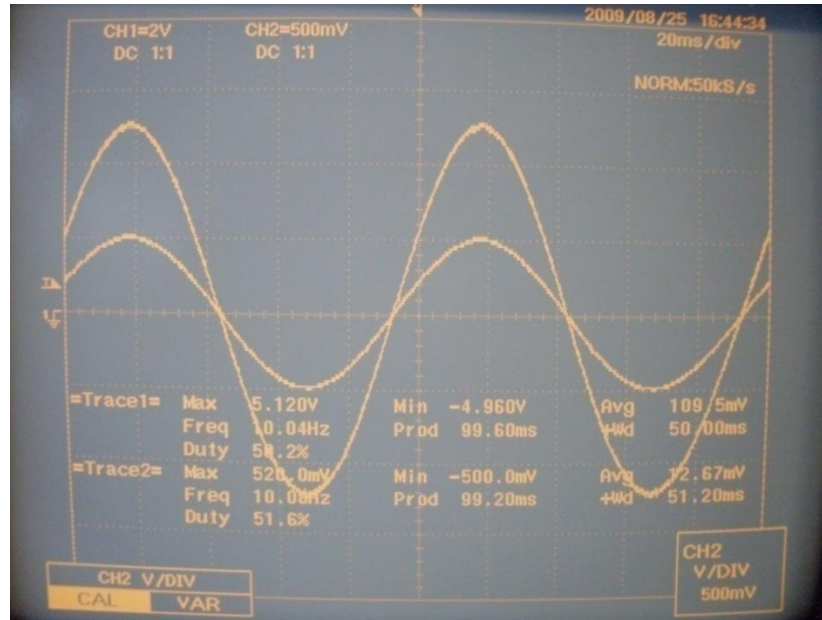

Figure 20: Output of 5V (Sinusoidal Input)

Figure 21: Comparison of Input and Output (Trace 1 – Input and Trace 2 - Output)

Based on the figures above, the input and output are sinusoidal waveforms where the frequency is 10 Hertz. The output's value of 520 mV and the calculated output is shown below by formula $0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right)$:

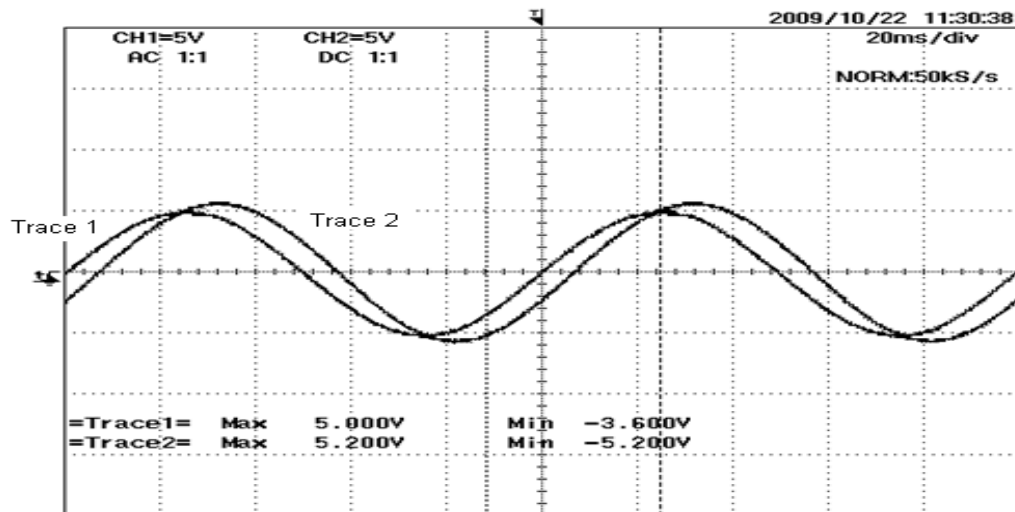Calculated primary current:

V / R = 5 / 1.6

= 3.125 Amperes

Therefore, the calculated output is:

$0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right) = 0.625 \cdot (3.125 / 12.5)$

= 156 mV

4.1.2 Second Testing of Current Transducer

After the Printed Circuit Board is installed with the current transducer, second testing on current transducer circuit is done. In this testing, the frequency of the input signals are varied to observe the respective output signals on the oscilloscope. The following are the results of the second testing as shown in Figure 22.
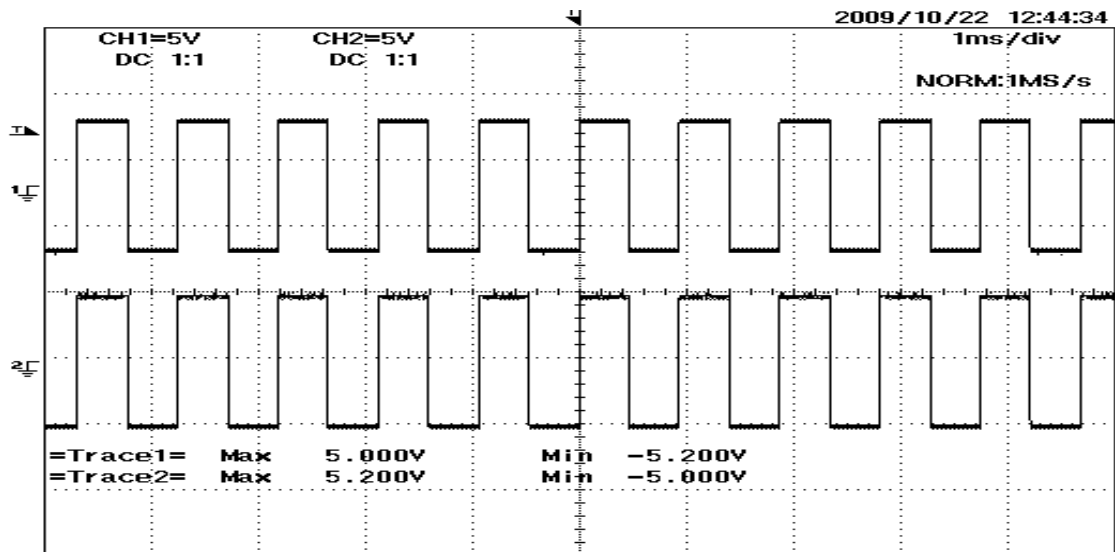

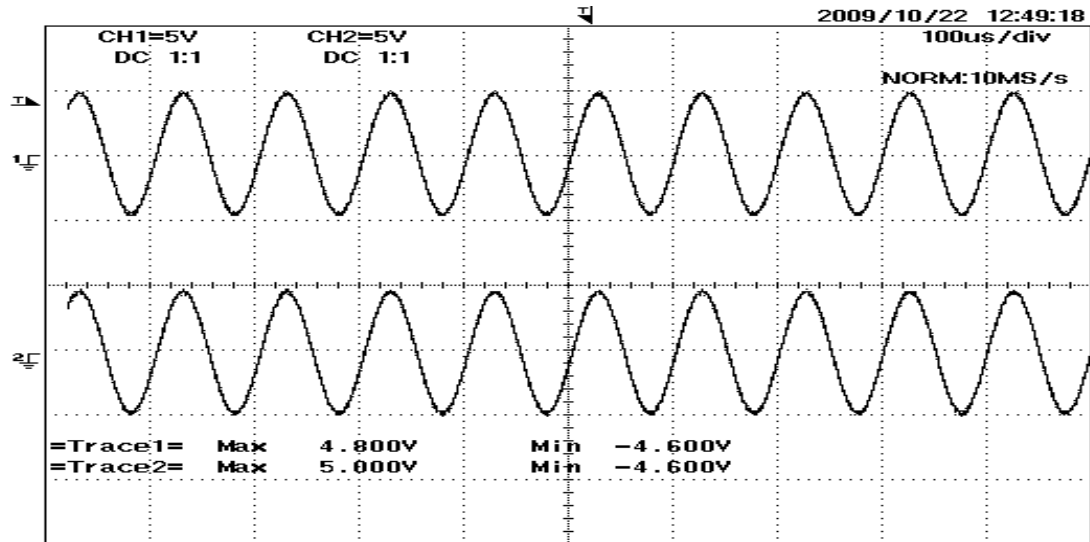a. Input and output signals for 10 Hz
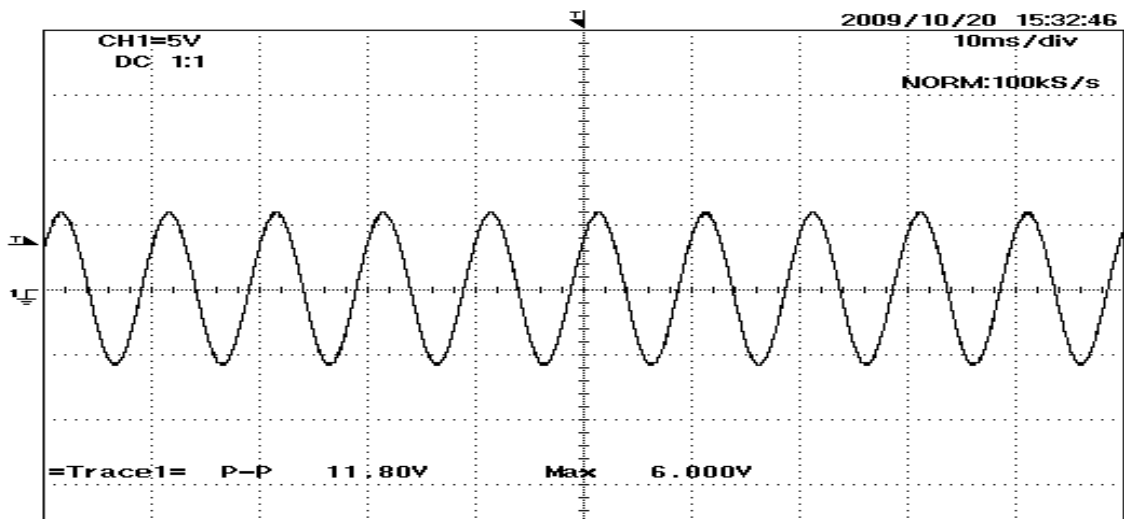
b. Input signal for 100 Hz
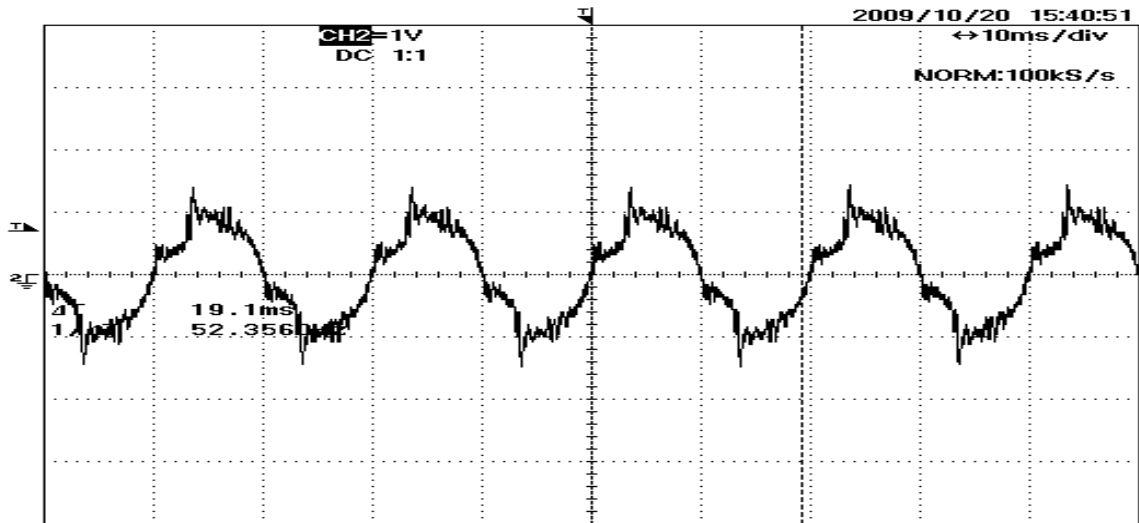
c. Output signal for 100 Hz

d. Input and output signals for 1 kHz

e. Input and output signals for 10 kHz

Figure 22: Input (Trace 1) and Output (Trace 2) for various frequencies

Based on the figures above, the input and output are waveforms with frequencies in the range of 10 Hz to 10 kHz. The output value is 0.2 Volt where it is added with the input's voltage. The calculated output is shown below by formula $0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right)$:

Calculated primary current:

V / R = 5 / 1.6

        = 3.125 Amperes

Therefore, the calculated output is:

$0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right) = 0.625 \cdot (3.125 / 12.5)$

                = 156 mV or 0.156 V $\approx$ 0.2 V

Thus, from the above experiments, the current transducer is operating as expected.

4.1.3 Communication between CME 2 and Accelnet Panel ADP

During the stage of communicating the Accelnet with the computer, CME 2 software was not able to connect with the amplifier at all where it detected the amplifier has no connectivity with the computer as shown in Figure 23 below. The problem may be caused by the wires or cables could have been shorted or opened unintentionally.
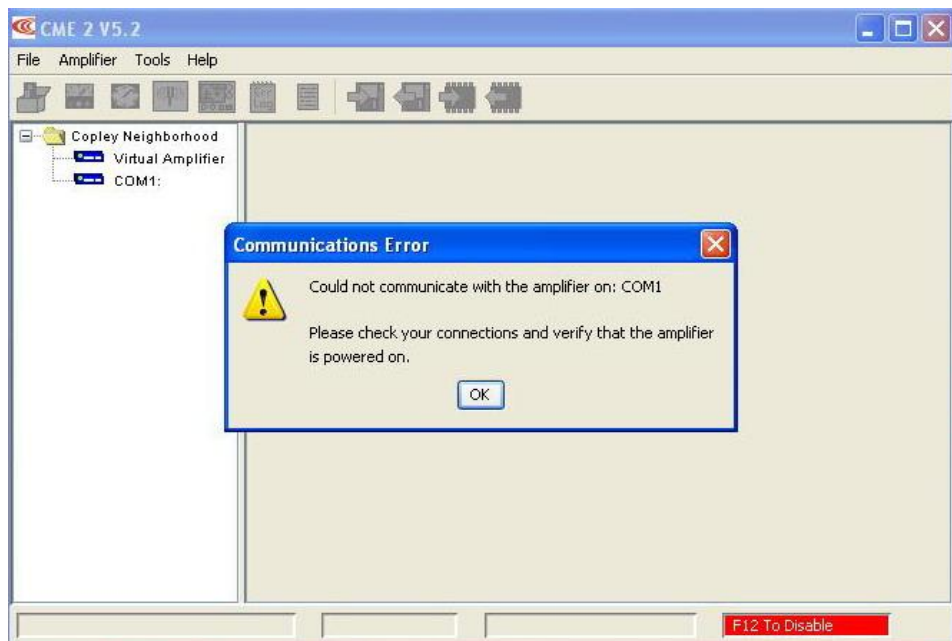
Figure 23: Communications error between computer and Accelnet

After discussions with Mr Saiful and Mr Imran, the connections between of RS-232 and RJ-11 are checked on the connectivity in order to verify the connections. The communication problem between Accelnet and CME 2 may be caused by the connections between RS-232 and RJ-11 since there are few modifications done on the connectors because some limitations.

At the end of the connectivity checking, the connection from RS-232 which is Rx was wrongly connected with the Rx of RJ-11. The Rx from RS-232 actually supposes to be connected with the Tx of RJ-11. The mistake was done previously during the configuration of the connections. The following Figure 24 shows the mistake done on the connections as stated above.
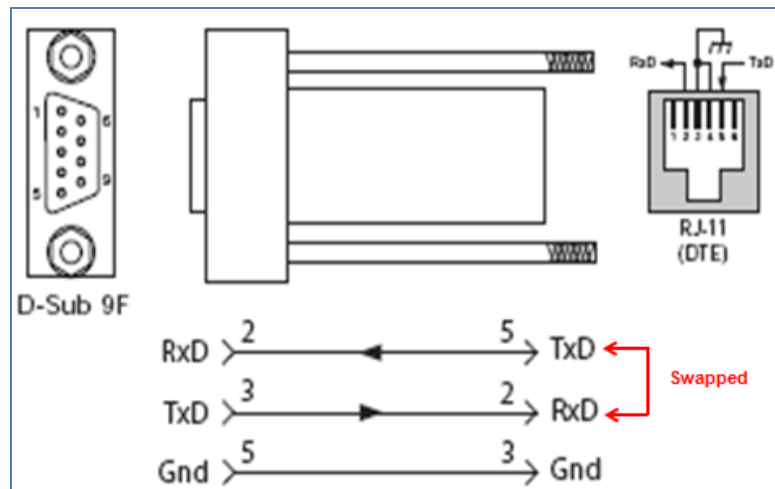
Figure 24: Wrong connections detected

4.1.4 Configuration on the CME 2

After the connections between the RS-232 and RJ-11 were corrected, the software detected the Accelnet and the configurations of the CME 2 are started before operating the servotube actuator. The procedures in configuring the CME 2 software are shown in the Appendices.

4.1.5 Commutation for 3-phase brushless linear motor (Servotube Actuator)

The following figure is the result for the first running for servotube actuator. The current injections is basically set to 10 A during the configuration on the CME 2 software. However, the CPU used could not be turned on after this first running and the new CPU was installed to run the actuator again but there are two errors came out as shown below.
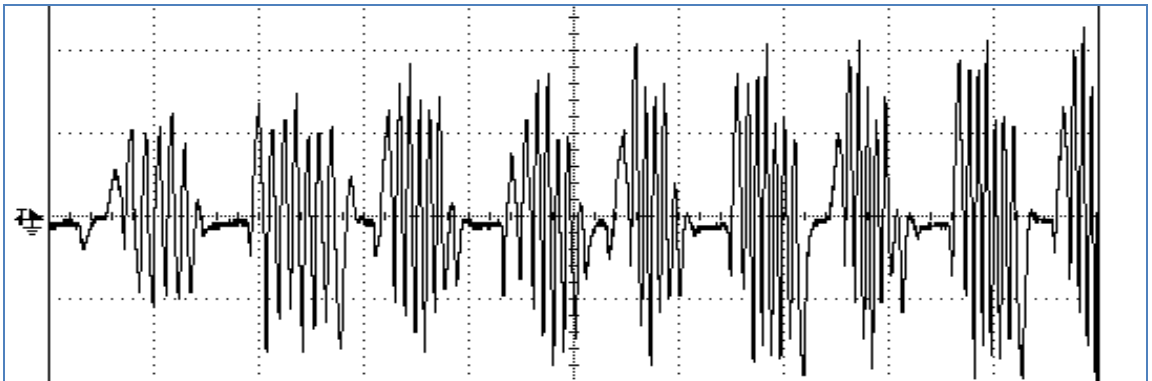
Figure 25: Observation on servotube actuator's commutation waveform
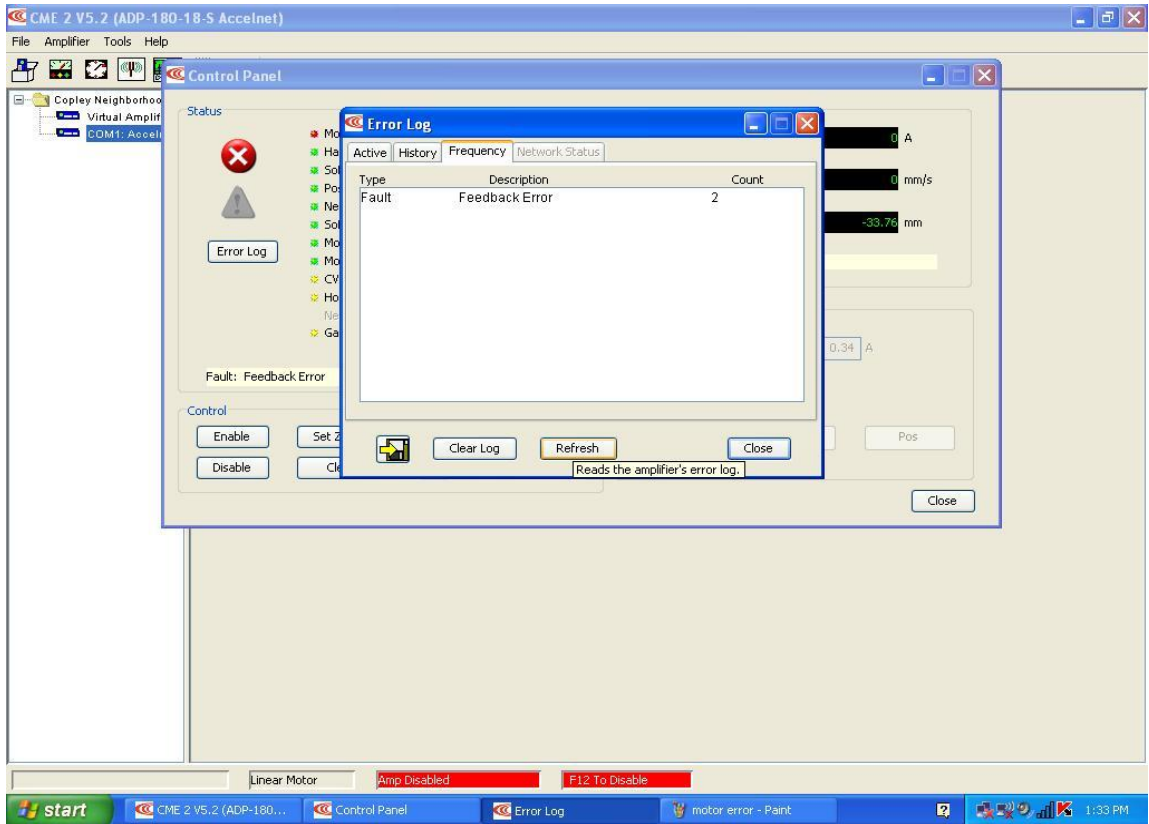
Figure 26: Feedback errors detected

4.1.6 Configuration on data collection of commutations

Basically, the Accelnet is powered by two batteries car (24 V) and there are three-phase of currents from Accelnet to the servotube actuator. The current transducer is placed in between both of Accelnet and servotube actuator to measure the current. However, in this project only one current transducer is used and the measurement of current injections can be done only for single phase. The configuration for this testing is shown in Figure 27 below.
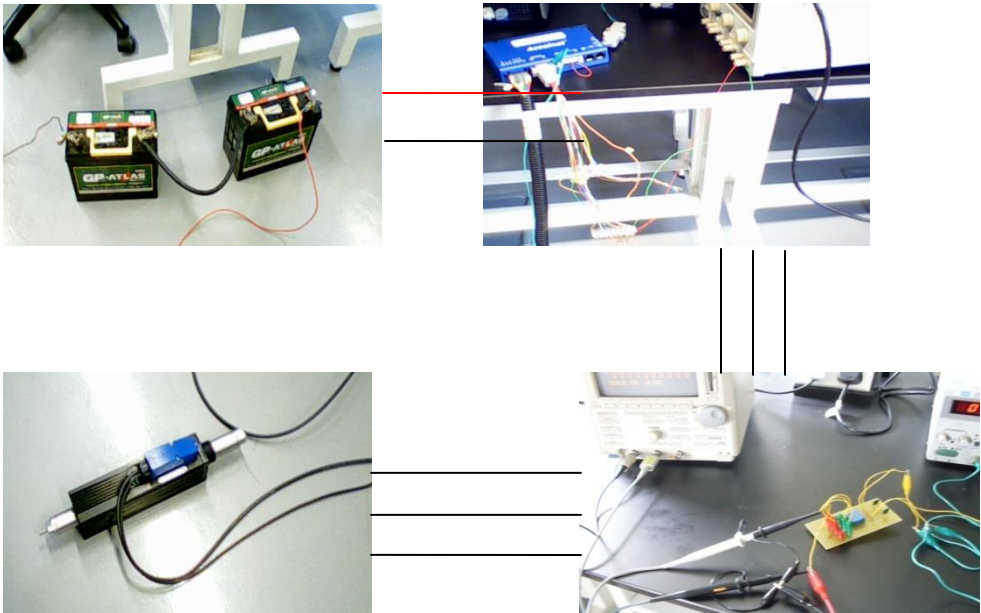
Figure 27: Configuration of connections

4.2 Discussion

4.2.1 Current Transducer

From the results obtained and calculation, the result seems to be different from the desired value for both testing: 2.3 Volts and 5 Volts sinusoidal waveforms. The difference may be caused by the additional resistance which exists in the wires or jumpers used on the circuit construction since the pins are needed to be connected externally, not on the PCB board.

When the resistance increases, the primary current I_p will be decreased. Therefore, the value output which based on formula $0.625 \cdot \left(\dfrac{I_p}{I_{pn}} \right)$ will also decrease. Testing's result also seems not to follow the theory when additional resistance is applied since it is higher than the calculated one. This problem may be caused by some errors happened in the circuit connections (loss connection, short or open circuit) or power supply inconsistency.

Therefore, after the PCB board as shown in Figure 28 is fabricated and current transducer is installed on the PCB, another testing on transducer is conducted. By installing transducer on a proper board, the problems or errors is reduced as shown in previous chapter.
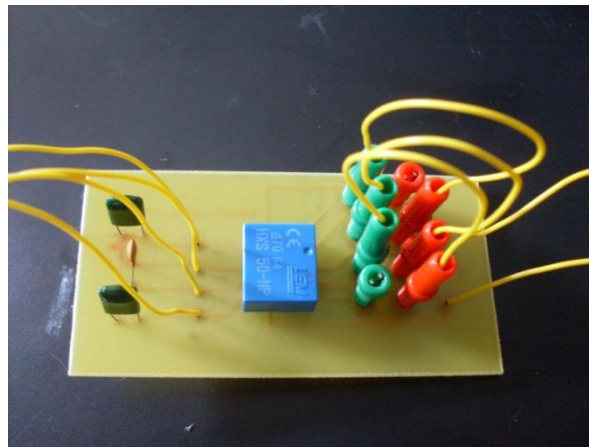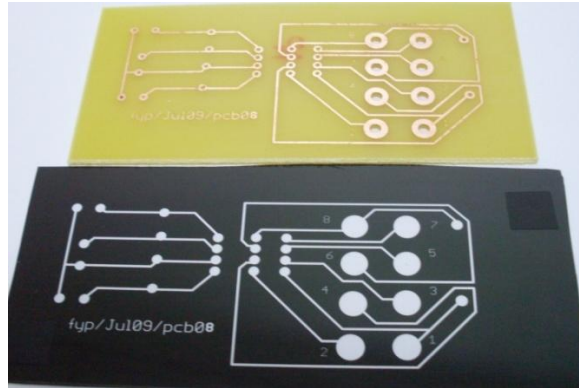
Figure 28: PCB and installed current transducer

4.2.2 Commutation for servotube actuator

When the servotube actuator was run, it was operated based on sinusoidal commutation where it was set earlier during the CME 2 software configurations. The frequency measured at that time was 2.381 Hz and the maximum voltage was 13.4 V. Current injected into the respective phases are set to 10 A and the maximum speed of the servotube actuator is set to 100 mm per second.

Based on the waveform obtained as in Figure 25, it is a sinusoidal shape even though there some noises appear in the waveform. This noise might be produced by the servotube actuator when the translator moves to the right and left sides. The body of the servotube actuator moves together with the translator where it is supposedly be placed in fixed position.

The waveform shows that the changing of the current's polarity is very fast in order to commutate the actuator. The changing of current polarity is controlled by the activating inputs to switches of the inverter bridge. For a single-phase, the sequence of switches activating are S1, S4, S2 and S3. By following this sequence the DC power supply will be inverted to AC and at the same time will commutate the servotube actuator.
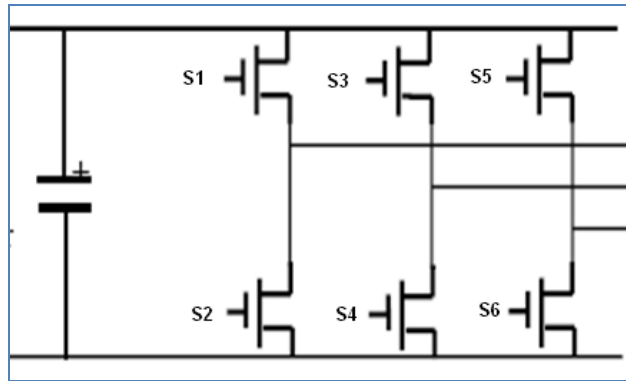
Figure 29: Inverter Bridge

There are also no current injected to the phase as shown in Figure 30, where at this moment the translator stops whether it stops on the left or on the right. This condition will happen to all three-phase and the period taken depends on the required velocity.
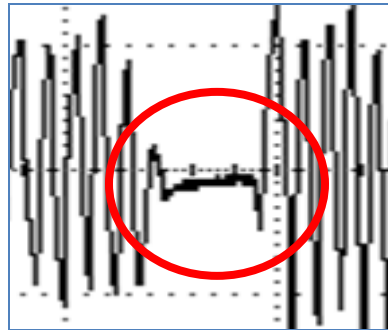
Figure 30: No current injection

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Hardware and software configurations of all components are completed at the end of the project. The servotube actuator is connected with the Accelnet and the controlling parts are configured using CME 2 software. However, the computer used for the project was down before more testing are done on the servotube actuator.

Current injection or commutation strategies to the servotube actuator's phases (three-phase brushless linear motor) are observed on the sinusoidal commutation used in the settings. The waveform of commutations is observed by passing the current injections to a single-phase through current transducer HXS-50-NP which will capture the current injected.

The changing of currents' polarities at the phases proved that the current switching is very important in commutating a three-phase brushless linear motor and this is known as electronic commutation using an inverter bridge. The magnetic fields produced from this switching process will interact with the permanent magnets and forces are produced. Without this proper commutation, the three-phase brushless linear motor cannot be operated.

5.2 Recommendations

5.2.1 Connections of the system

Errors may happen during the current injections measurement from the Accelnet to servotube actuator since some of the connectors seems not in good condition. There are connectors' inductors already broken and this may cause short circuit problem. This will lead to unsafe operation to the system and may cause damage to the devices.

The connections of the motor's feedback also need to be improved such they should be tagging in order to avoid misconnection from the feedback encoder to the Accelnet. Since currently CME 2 software showed two feedback errors, it is better to check these connections.

Apart from that, in order to improve the communication between CME 2 software and Accelnet, RS-232 and RJ-11 connectors should be replaced with new ones. The connector of RS-232 and RJ-11 should be directly connected to each other without any additional connectors.

5.2.2 Current transducer

In this project, there is one transducer which was installed on the Printed Circuit Board (PCB). During the measurement of the currents, only single-phase current was measured at a time when the servotube actuator is running. Therefore, two more current transducers are needed in measuring the currents. These new current transducers should be tested first to ensure their functionality same as the first current transducer.

There are two Printed Circuit Board that already been fabricated in the lab. Same configurations will be used for the connections but the wires used should be thicker since the currents which will be measured may be very high in the range of 6 Amperes to 18 Amperes. This high current may burn the current transducer if the wires used are not able stand the rate of the current.

5.2.3 Data collection on the commutation

As stated before, the waveform obtained in this project is for sinusoidal commutation. In future, the other commutation types should be observed and compared to each other: Sinusoidal, trapezoidal and six step. This comparison will verify the most effective and practical commutation for servotube actuator.

Besides that, the noises appeared in the waveform as discussed before this should be reduced by designing a casing for the servotube actuator to hold the actuator's body in a fixed position. It will eliminate the vibrating parts on the system. This casing is also necessary to be designed for safety purpose in case the translator moves away from the body part if the power supply to the Accelnet suddenly is turned off.

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[6] Linear Motors, Application Guide, Aerotech

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[10] Technical description, Copley Controls Corp., Accelnet Panel ADP for brushless/brush motors

APPENDICES
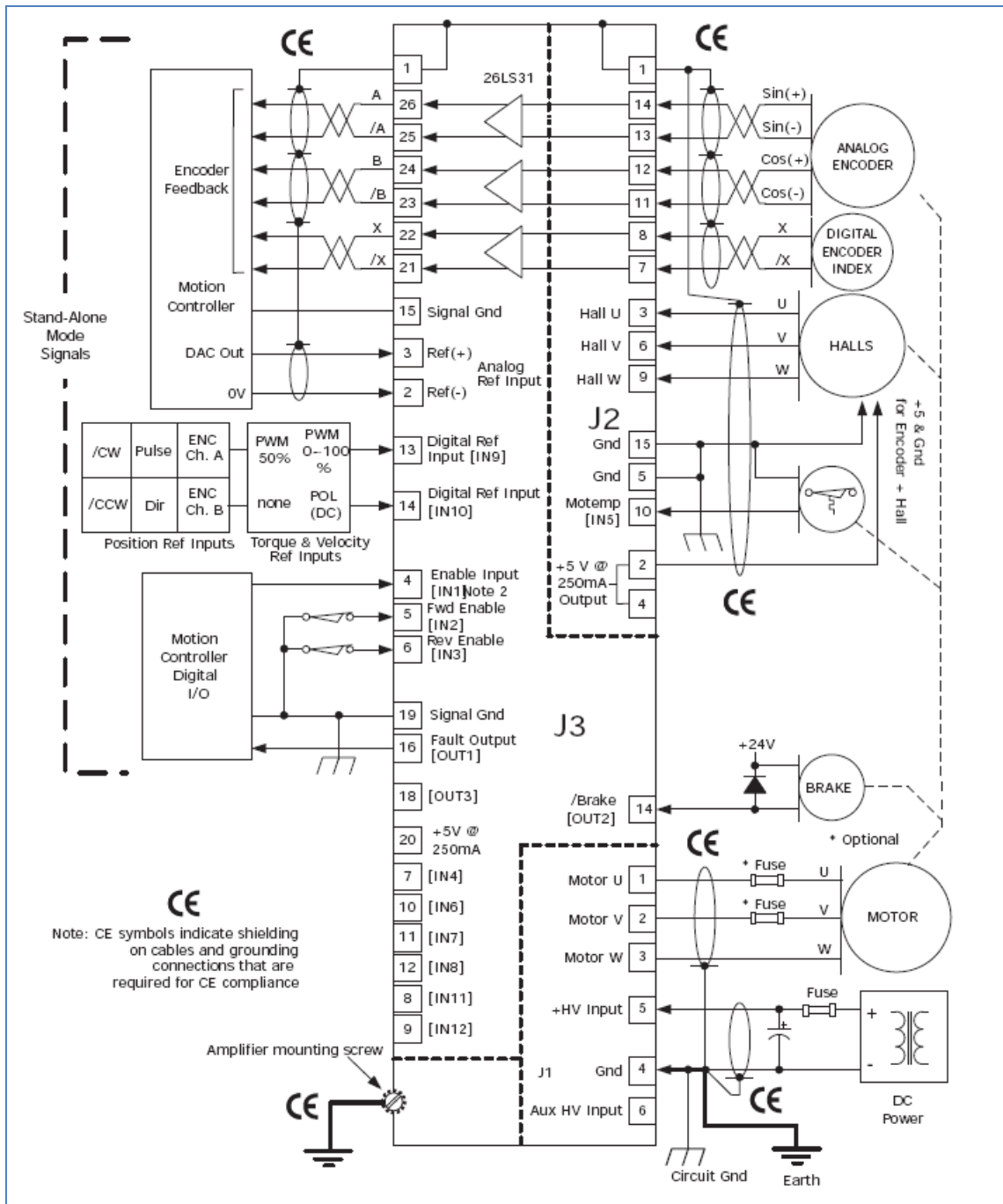
Connections of Accelnet Panel ADP

J6 RS-232

PIN	SIGNAL
1	No Connection
2	RxD
3	Signal Ground
4	Signal Ground
5	TxD
6	No Connection

J6 CABLE CONNECTOR
RJ-11 style, male, 6 position
Cable: 6-conductor modular type

J4-J4 CAN BUS

PIN	SIGNAL
1	CAN_H
2	CAN_L
3	CAN_GND
4	No Connection
5	Reserved
6	(CAN_SHLD) [1]
7	CAN_GND
8	(CAN_V+) [1]

J4, J5 CABLE CONNECTOR:
RJ-45 style, male, 8 position
Cable: 8-conductor, modular type

J3 CONTROL SIGNALS

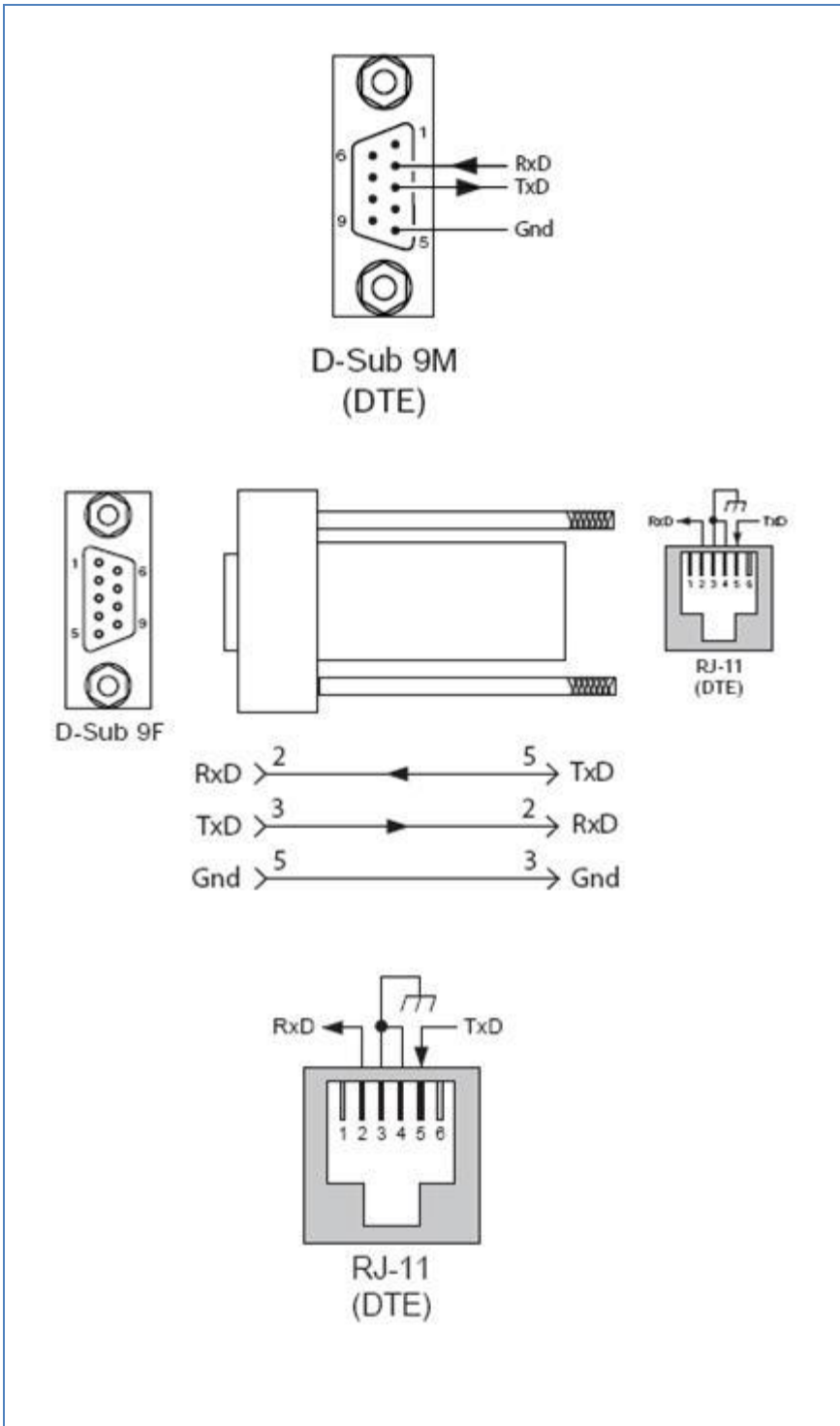| PIN	SIGNAL	PIN	SIGNAL	PIN	SIGNAL
1	Frame Gnd	10	[IN6] HS	19	Signal Gnd
2	Ref(-)	11	[IN7] HS	20	+5 Vdc (Note 1)
3	Ref(+)	12	[IN8] HS	21	Multi Encoder /X
4	[IN1] Enable	13	[IN9] HS	22	Multi Encoder X
5	[IN2] GP	14	[IN10] HS	23	Multi Encoder /B
6	[IN3] GP	15	Signal Gnd	24	Multi Encoder B
7	[IN4] GP	16	[OUT1]	25	Multi Encoder /A
8	[IN11] GP	17	[OUT2]	26	Multi Encoder A
9	[IN12] GP	18	[OUT3]		

J3 CABLE CONNECTOR:
High-Density D-Sub
26 Position, Male

J2 MOTOR FEEDBACK

PIN	SIGNAL	PIN	SIGNAL	PIN	SIGNAL
1	Frame Gnd	6	Hall V	11	Encoder Cos(-)
2	+5 Vdc (Note 1)	7	Encoder /X	12	Encoder Cos(+)
3	Hall U	8	Encoder X	13	Encoder Sin(-)
4	+5 Vdc (Note 1)	9	Hall W	14	Encoder Sin(+)
5	Signal Gnd	10	[IN5] Motemp	15	Signal Gnd

J2 CABLE CONNECTOR:
High-Density D-Sub
15 Position, Male

J1: MOTOR & POWER

PIN	SIGNAL
1	Motor U Output
2	Motor V Output
3	Motor W Output
4	Ground (HV, Signal)
5	+HV Input
6	Aux HV Input

J1 CABLE CONNECTOR:
Terminal block, 6 position, 5.08 mm, black
  Beau: 860506
  RIA: 31249106
  Weidmuller: 1526810000
  PCD: ELFP06210
  Weco: 121-A-111/06
  Tyco: 796635-6

Specifications of Accelnet Panel ADP Connectors

Configuration of RS 232 and RJ-11

CONFIGURATION ON THE CME 2 SOFTWARE

1) All the connections from Accelnet to Servotube Actuator are rechecked.

2) Two car batteries (24 V) are connected to the Accelnet as power supply.

3) Accelnet and computer are connected via RS-232 before CME 2 is opened.

4) When the CME 2 window is opened, basic setup settings are changed (*Change Setup*) under **Basic Setup** icon.

5) *Motor options* are set to Linear, Brushless selection.

6) *Feedback options* are set to (Hall type: Digital), (Motor Encoder: Primary Incremental), (Position Encoder: Secondary Incremental) and (Position Encoder Type: Linear).

7) *Operating mode options* are set to (Operating mode: Position, velocity or current) and (Command source: Analog).

8) *Misc options* are set to (Commutation mode: Sinusoidal, trapezoidal and estimated sinusoidal). Then, the setups are changed.

9) After that, the setup for **ServoTube Motor Setup** is changed under **Basic Setup** icon.

10) Motor options are set to (Series: XTA, Model: 3806S).

11) Operating mode options are set to (Operating mode: Position, velocity or current) and (Command source: Analog).

12) Digital **Input/ Output** settings are set up to (Digital Inputs 1-5: Pull up +5V), (IN1: Amp Enable-LO Enables with Clear Faults, de-bounce time 0 ms) and (IN5: Motor Temp HI Disables).

13) *Auto Phase* settings are set up to (Motor Actual Position: 578 counts), (Auto phase current: 2.36 A), (Increment rate: 180 degree) and then auto phasing is started.

14) When the auto phasing is completed, motor phase initialization is started. The settings are saved to the disk.

15) *Auto Tune* is opened and choose current loop tune to start the tuning for linear motor. All configurations are saved to the disk.

16) The ServoTube Actuator is ready to be run.

GANTT CHART FYP II