Force Characterization of an Electromagnetic Linear Actuator

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A report submitted in partial fulfillment of the requirements for the degree of Mechatronic engineering

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MAY 2015

I hereby declare that I have read through this report entitled "Force Characterization of an Electromagnetic Linear Actuator" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Mechatronic engineering.

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I declare that this report entitle "Force Characterization of an Electromagnetic Linear Actuator" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Special to my beloved mother and father who always standby my side in giving supports morally and financially. Special thanks also to my special supervisor Dr. Mariam for her great efforts helping me toward success of this project.

ABSTRACT

Electromagnetic actuators are nowadays used in a vast variety of applications that require high thrust, high accuracy and different working ranges. The increasing advancements in the usage of electromagnetic actuators rises the need for more and more improvements in electromagnetic actuators especially in term of output force and working range. The thesis present an extensive characterizing study of two novel electromagnetic actuators each with different construction and characteristics aiming to analyze the behavior and output characteristics of the two designs and how these characteristics are effected by parameters and size variations. The two actuators are Tubular Linear Reluctance Actuator and Tubular Linear Permanent magnet with Halbach array Actuator. Each one of the designs has its own working principle, the Tubular Linear Reluctance Actuator employs induction motor principle where no permanent magnet is used and the other employs the synchronous motor principle where the mover is built of permanent magnets with one of the latest successful improvement of electromagnetic actuators. The study covers the variation of three parameter for each actuator air gap, number of turns and size. A comparative section is also presented for the purpose of comparison. The study concentrated extensively on the two characteristics of both actuators which are output thrust force and working range as they are considered two main concerns of any actuator design. The simulation is used to show the differences between the two design in many design aspects such as force, displacement and effects of parameters variations .The applied simulation is performed using 3D finite-element Ansoft software which is cabable of showing the magnetic field distribution in the whole actuator and predicting the strength and length of the output stroke.

ABSTRAK

Penggerak elektromagnet yang kini digunakan dalam pelbagai besar aplikasi yang memerlukan teras yang tinggi, ketepatan yang tinggi dan julat kerja yang berbeza. Kemajuan peningkatan dalam penggunaan penggerak elektromagnet meningkat keperluan untuk lebih banyak penambahbaikan dalam penggerak elektromagnet terutama dari segi daya pengeluaran dan pelbagai kerja. Tesis membentangkan kajian mencirikan banyak dua penggerak elektromagnet novel masing-masing dengan pembinaan dan ciri-ciri yang bertujuan untuk menganalisis tingkah laku dan output ciri-ciri kedua-dua reka bentuk dan bagaimana ciri-ciri ini dilaksanakan dengan parameter dan variasi saiz yang berbeza. Kedua-dua penggerak adalah tiub Linear Keengganan aktuator dan tiub Linear magnet Kekal Halbach pelbagai aktuator. Setiap satu daripada reka bentuk yang mempunyai prinsip sendiri kerja, yang tiub Linear Keengganan aktuator menggunakan prinsip motor induksi di mana tidak ada magnet kekal digunakan dan satu lagi menggunakan prinsip motor segerak mana penggerak itu dibina daripada magnet kekal dengan satu peningkatan berjaya terkini penggerak elektromagnet. Kajian ini meliputi perubahan tiga parameter bagi setiap ruang udara penggerak, bilangan lilitan dan saiz. Sebahagian perbandingan juga dikemukakan untuk tujuan perbandingan. Kajian tertumpu meluas di kedua-dua ciri-ciri kedua-dua penggerak yang output daya tujah dan pelbagai kerja kerana mereka dianggap dua kebimbangan utama mana-mana reka bentuk penggerak. Simulasi ini digunakan untuk menunjukkan perbezaan di antara kedua-dua reka bentuk dalam aspek reka bentuk banyak seperti kekerasan, anjakan dan kesan parameter variasi .The digunakan simulasi dilakukan menggunakan unsur terhingga perisian Ansoft 3D yang cabable menunjukkan taburan medan magnet dalam seluruh penggerak dan meramalkan kekuatan dan panjang output stroke.The FEM hasil analisis dan keputusan output strok dibentangkan.

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1 INTRODUCTION

1.1 Background

Constant technology advancements have made people's live convenient and comfortable, the effects of technologies that had arrived from little inventions and led to very major advances can be clearly noticed, transmission is a significant one of them. The evolution of transmission technology has a major contribution in current easy and convenient live .Transmission is seen almost in every sector of today's technologies ranging from primary and heavy industrial automation to advance electronics and aerospace actuation.

Electromagnetic actuators are of the most well-known types of linear transmissions work by converting electric and /or magnetic power to mechanical motion through magnetic field interactions. Electromagnetic actuators have lately became an area of interest to a huge number of researchers as they found it compact sector toward efficiency drive improvement ,energy saving and significant alternative for many other types of actuators such as piezoelectric and rotary to linear actuators. Electromagnetic actuators provide a various number of advantages over other types of actuators such as higher force, lower needed power and higher efficiency which are comprehensively detailed in chapter 2. In this thesis two linear electromagnetic actuators will be designed and characterized for the purpose of comparison between different novel topologies of designing linear electromagnetic actuators.

1.2 Motivation

The recent advancement of linear actuators and the increasing demand for energy and environment saving gave rise of intensive use of electromagnetic actuators especially the types of electromagnetic actuator which consist mostly from permanent magnets. Electromagnetic actuators are nowadays replacing many types of actuators and conventional actuation methods and its future potential is day to day increasing.

Linear electromagnetic actuators provide new actuation method used almost in all todays advanced technologies such as:

- ❖ Industrial automation.
- ❖ Automotive and aerospace actuation.
- ❖ Robots and medical tools.
- ❖ Transportation.

It's well known that two of the most critical problems facing the world today are global warming and high energy consumption. The usage of linear electromagnetic actuators could effectively contribute in reducing the large amount of emissions caused by transportation by implementing the new generations of automobile engines as it contributed in significant energy saving and mechanical wear in many applications. For example Levitated train, the usage of Levitated train introduced three to five times reduction of energy utilized by railroads trains and totally reduced the mechanical wear due to the employment of non-contact new technology.

The extensive use of electromagnetic actuators rises the need for the characteristics' optimization of the actuators. By optimizing the structure of the electromagnetic actuator, many characteristics of the electromagnetics actuator will be improved such as thrust force and working range. This led to a short conclusion that, more work is needed in order to improve the electromagnetic linear actuators. One such a work can contribute in the modern evolution of transmission technology.

1.3 Problem Statement

Throughout world's industries, it is been proven that electromagnetic actuator has overcome many disadvantages in other types of actuators such as weariness in Electro-mechanical actuators, high required voltage and short travel in Piezoelectric actuators and leakage, imprecise positioning in Hydraulic and Pneumatic actuators. However , electromagnetic actuator still suffer the problem of low to average force production and designing an actuator with high force, long stroke and more compact geometry is still challenging work in many applications which rises the need for more and more improvement efforts especially in term of output force and working range. Hence, a great deal of efforts in the last decade have been dedicated toward the improvement of this type of actuators. This thesis focuses on characterizing two Electromagnetic linear actuators each with different construction and arrangement of coils and magnets. The two designs are considered to improve the thrust and working range. The two designs are characterized and exclusively investigated in term of force and working range in which can be considered a contribution to the extensively increasing advancement of linear electromagnetic actuators.

1.4 Objectives

1. To characterize two novel designs of tubular electromagnetic actuator to produce highest possible thrust force and determine the possible ranges.
2. To analyze the two designs using Finite Element Method (FEM).
3. To compare and evaluate the two designs in term of output forces and working ranges.

1.5 Scopes

1. Design and characterize two types of tubular linear micro-electromagnetic actuator.
2. Analyze the thrust output force and the working range of the two designs using Finite Element Method (FEM).
3. Optimize the thrust output force and the working range of the two designs in term of geometric, size and coil-permanent magnet arrangement.

1.6 Project Limitations

Two design limitations of the project:

1. As the one of the best type of electromagnetic actuator used permanent magnet to generate its output thrust and with the high price of magnetic materials but the project is limited to use as less permanent magnet as possible. This limitation caused the project to choose only one of the actuators with permanent magnet while the other will use iron.
2. The project is limited to a working range of 100 mm as its maximum.

1.7 Outline of the Report

Chapter 1: Introduction-This chapter introduces an overview of the project including purpose, limitation, and motivation. A general information about the linear actuator and covered topics of the project are also presented.

Chapter 2: Literature review- This chapter summarize the most relevant concepts and evolution relating to linear actuators in general and electromagnetic linear actuators in particular. This includes magnetic interactions, optimization and output force calculations.

Chapter 3: Methodology- This chapter describes the methods and procedures employed to design the project represented in a flow chart, conceptual design, and structure of designs. This chapter include also working principles and simulation method of the two designs of the project. The proposed analysis set up is also presented.

Chapter 4: Results and Discussion - This chapter illustrates the two designs of the two actuator fully with their complete parameters and discusses obtained results of both designs. Also a short comparison between designs is presented.

Chapter 5: Conclusion and recommendation- This chapter describes the conclusion of the project provides some recommendations for future works.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Linear motion or what can be called rectilinear motion is a motion which takes place in a straight line. Linear motion is the basic of all kinds of motions. There are simple and complex products employing linear motion. These products are used in many kinds of machinery which are used exclusively to produce other technologies as its considered a main major part in manufacturing machines such as CNCs.

An actuator is an energy converting device which take one or more power source to create mechanical work or motion. The motion could be either linear (straight line) or rotary (rotation about a fixed point) in accordance with the requirements of the needed machine. The criteria of which an actuator is evaluated are output force, stroke speed and length, mover mass and power density and so on.

2.2 Overview of Actuators

2.2.1 Classification of Actuators

As actuators are energy converting devices, it convert an input from one or more sources to an output mechanical linear motion in a way which can be controlled using different methods. This energy conversion can be accomplished through different method depending on different operation principles and applications. According to different operation principles, linear actuators can be classified into four major and many minor types [1]. The four major types are presented in table (2.1) below.

Table 2-1 : Classes of actuators

Class of Actuator	Energy Transform	Application
Electromagnetic	Electrical-Magnetic-Mechanical	Solenoid, Voice Coil
Electromechanical	Electrical-Mechanical	Linear Drive, MEMS Comb Drives
Piezoelectric	Electrical-Mechanical	Ceramic, Polymer
Smart Materials	Thermal-Mechanical	Shape Memory Alloy, Bimetallic

These different classes of actuator employ different methods and principles to create the output motion. Electromagnetic actuators ; the actuation is created due to the interaction of the magnetic field created between coils, permanent magnets or coil and permanent actuator depending on the way they are arranged in a closed magnetic circuits. Piezoelectric actuators use Piezoelectricity which is represented in the electric charges that accumulates in a specific solid materials such as crystals, specific ceramics and so on in response to applied mechanical stress. The mechanism of actuation or motion in the shape memory alloys is change in the induced temperature which produces a significant shear strain when the material temperature is above the transformation.

2.2.2 Characterization of Actuators

Different Linear actuator exhibit different performance in term of output force [2], working range, needed voltage and robustness. A brief characterization of these actuators are presented in table (2.2) below.

Table 2-2 : Characterization of linear actuators

	Electrostatic	**Thermal**	**piezoelectric**	**Electromagnetic**
Force	Low	high	high	high
Working range	Short	long	moderate	long
voltage	High	low	moderate	low
Robustness	Moderate	moderate	high	high

Based on table (2.2), electromagnetic actuators provide high force and long working range with high robustness.

2.3 Electromagnetic Actuators

2.3.1 Magnetic Fields Interactions

Electromagnetic actuators in general employ magnetic field interactions to create magnetic forces and mechanical motions. The magnetic field is generated either by electric coil or the permanent magnet. Magnetic fields represent the fundamental mechanism by which the energy is converted from one form to another in the electromagnetic actuators.

Basic principles describe how magnetic fields employed in actuators [3]:

1. A current-carrying wire produces a magnetic field in the area around it.
2. A current-carrying wire in the presence of a magnetic field has a force induced on it (Motor principle).
3. A moving wire in the presence of a magnetic field has a voltage induced in it. (Generator principle).

2.3.2 Principles of Linear Electromagnetic Actuators

Electromagnetic actuators employ the principle of using coils and magnets to convert electrical and/or magnetic energy to mechanical energy. This conversion is accomplished through converting voltage and to motion (force and displacement). The force which create the mechanical motion over a specific range, is a result of the interaction of the magnetic field generated either by current currying conductor or permanent magnets [4].

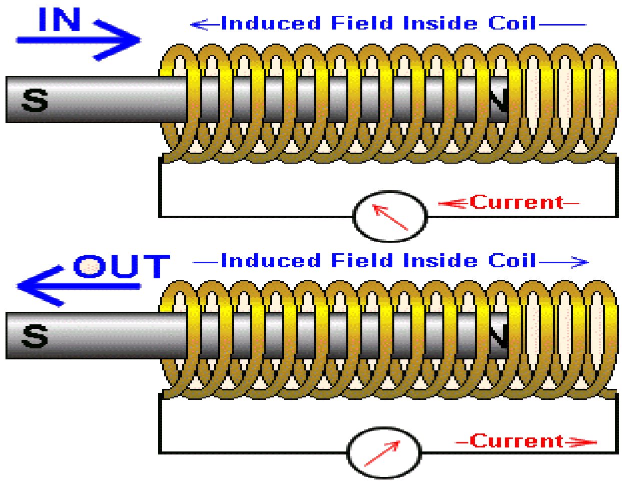

Figure 2.1: Basic principle of linear electromagnetic actuator [5]

As illustrated in figure 2.1 as the magnetic field of magnet traveling from north to south pole interact with the fields of the current currying conductor, force perpendicular to the fields is generated. The magnitude of the force depends in the density of the flux generated in the air gab.

$$F = ILB \qquad (2.0)$$

Where F is the thrust output force, I is the current flowing in the conductor, L is the length of the coil and B is the flux density.

In order to determine the direction of the magnetic fields in a rounded set of coil (solenoid), the right hand rule is employed. The right hand figures are pointing with the direction of the current while the thumb is pointing to the North Pole where the field travels from S to N [6].An illustrative figure 2.2 is presented for clarity.

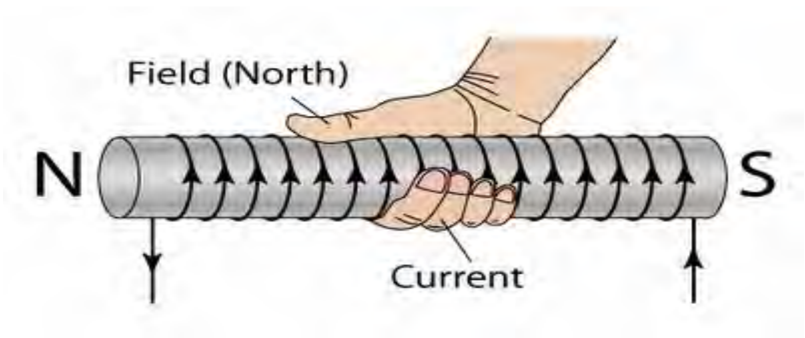

Figure 2.2: Right hand rule for determining the direction of the field [6]

2.4 Electromagnetic Linear Actuators

2.4.1 Classification of Electromagnetic Linear Actuators

There are two main components of any Electromagnetic linear actuator which are stator (Stationary part of the actuator) and mover (Moving part of the actuator). According to different arrangement and fabrication of these two component, electromagnetic linear actuator can be classified to two main categories which are flat and tubular geometry, each with its own performance characteristics .The configurations of the two categories is shown in figure 2.3 below.

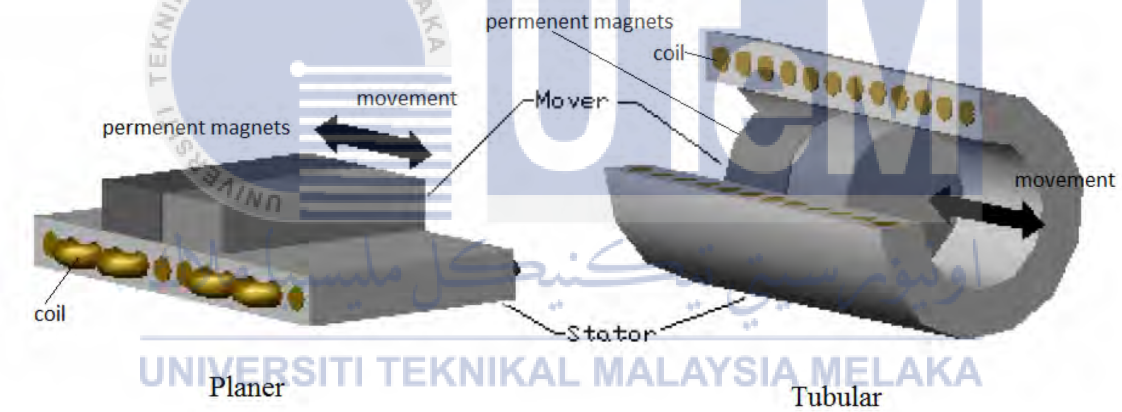

Figure 2.3: Two main categories of electromagnetic actuator [6]

A simple comparison of these two categories resulted in three conclusions:

- Tubular type mechanically is more rugged, which is a result of having all components inside piston like structure.
- Tubular type minimize if not eliminate stray magnetic field in the direction of travel.
- For the same sizes and weights of the actuators, the force density delivered by tubular actuator is greater than that by planer actuator [6].

2.4.2 Classification of Tubular Electromagnetic Linear Actuators

Tubular Electromagnetic linear actuators can be classified according to coil and magnet utilization and arrangement to three different topologies as depicted in figure (2.4) bellow moving coil [7] , moving iron[8] and moving magnet [9].

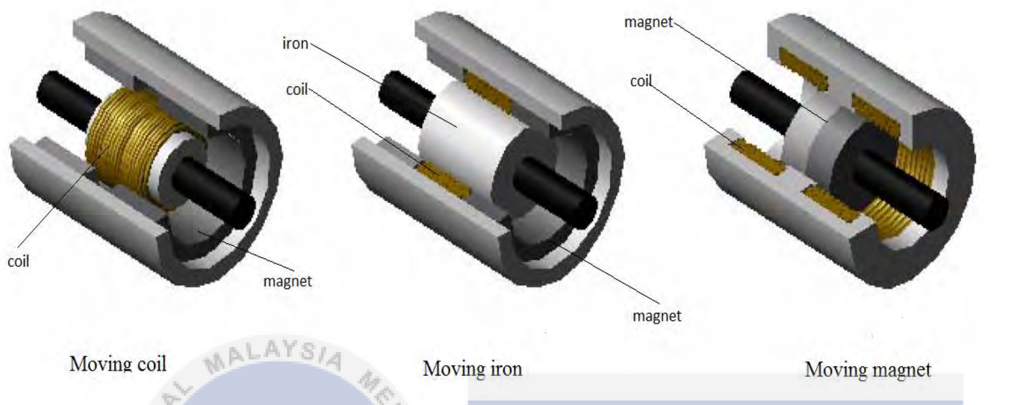

Figure 2.4 : Three topologies of linear actuators [9]

The performance characteristics of the three topologies of linear actuators can be summarized as:

Moving coil type which uses coil in the mover and PM (permanent magnet) in the stator. This type has small mover mass and high dynamics, but relative poor thermal dissipation, low reliability and large size. Moving iron exhibit high thrust force. But its large inertia can cause low dynamic performance resulting in less stability in the actuator. Moving magnet type have low mass mover and with the new improvements such as Halbach PM array, teeth optimization and so on, moving magnet can achieve higher thrust force and higher stability and accuracy.

Of the three different configuration of linear topologies, tubular permanent-magnet actuators provide the highest possible efficiency and high thrust force with excellent servo characteristics [10]. This led to the increment of the use tubular permanent-magnet actuators in many applications such as manufacturing [11], medical tools [12], transportation [13], advance electronic devices [14], and robotics [15]. On the other hand moving iron provide some weighted advantages over the other two types such as their very simple structure, ruggedness, and the fact that they are relatively inexpensive to manufacture [16].

2.5 Advantages of Electromagnetic Linear Actuators

With the advancement of transmission technology, electromagnetic actuators in particular have been an area of interest among all other kinds of actuators. This is due to the numerous advantages that electromagnetic actuators provide over other actuators. Of these many advantages:

1. Electromagnetic linear direct drives (linear actuators) have the ability to provide high forces, large strokes, high reliability, and fast response [17].
2. Electromagnetic actuators which directly generate linear motion offer numerous advantages over rotary-to-linear counterparts, the absence of mechanical gears and transmission systems significantly results in a much higher efficiency, higher dynamic, and the reliability of the actuator is significantly improved [18].
3. Permanent magnet linear motors are widely applied in modern industrial applications, particularly for the tasks requiring high speed and high positioning accuracy, such as semiconductor process, numerical control machine tools and micro-electromechanical systems [19].
4. Electromagnetic linear actuator has characteristics such as high responsibility, high controllability, and simple structural configuration [20].
5. Electromagnetic linear actuator provides design flexibility and bidirectional motion.

2.6 Improvement of Tubular Electromagnetic Linear Actuators

With the modern evolution of PM actuators towards high efficiency and high power density and as moving magnet tubular electromagnetic linear actuators appeared to be advantageous over other kinds of actuators. A great deal of improvements have been made in order to increase their reliabilities, efficiency and improve their output performance such as thrust and working range. Most of the efforts by researchers were made on making the magnetic circuit configuration more efficient. One of the best known improvement was proposed in [21]. By applying the introduced Halbach array magnets on PM linear actuator, the performance of the actuators can be notably improver .compared with the normal PM structure, the Halbach array actuator exhibits the following advantages [21]:

- It introduced a larger air gap flux which increase the power density of the actuator.
- The inherently sinusoidal air gap field distribution can be obtained without recourse to skewing of the stator.
- Due to good self-shielding effect, rotor back-iron is not important, which result in reducing the mass and inertia and the dynamic performance can be improved.

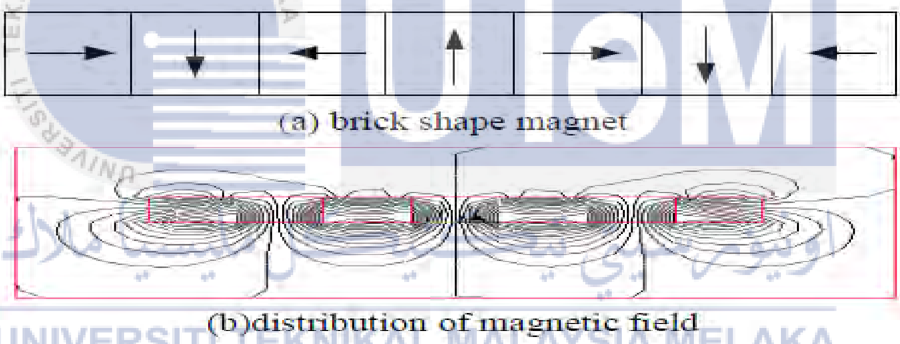

Figure 2.5: Halbach array [21]

The Halbach array is shown in figure 2.5, its basic principle of the Halbach arrangement is that it strengthen the magnetic field in one side while reducing if not eliminating the field in other side of the magnet.

2.7 Thrust Calculation of the Tubular Inductance and PM Actuators

2.7.1 Inductance Linear Actuator

The thrust calculation of the linear inductance stepping actuator have been derived in [16] and here are the collective set of formulas:

The magnetic force of this actuator is derived from the equation:

$$f_m = 0.5i^2 \frac{dl}{dx} \tag{2.1}$$

Where Fm is the force, I is the input current, x is displacement and l is the conductor length.

As the magnetic force is dependent on the derivative of the inductance, the inductance has to be calculated.

The step windings consist of three parts so

$$N_T = N_1 + N_2 + N_3 \tag{2.2}$$

$$L_{\min(T)} = L_{\min(1)} + L_{\min(2)} + L_{\min(3)} \tag{2.3}$$

$$L_{\max(T)} = L_{\max(1)} + L_{\max(2)} + L_{\max(3)} \tag{2.4}$$

In the equations the $L_{\min(T)}$ represents the minimum inductance of the step winding motor , $L_{\max(T)}$ represents the minimum inductance of the step winding motor, $L_{\min(i)}$ represents the minimum inductance of the ith part of the step winding motor and N is the winding turns.

As the winding inductance is defined in its relevant region, hence, the inductance has to be calculated for each region.

2.7.1.1 First region:

$$L_1 = L_{m1}\left[1+\cos\left(\frac{3\pi}{l}\left(\frac{2l}{3}-x\right)\right)\right] + L_{\min(T1)} \quad , -1 > x < \frac{-2l}{3} \tag{2.5}$$

$$L_{m1} = \frac{L_{\max(1)} - L_{\min(1)}}{2} \tag{2.6}$$

$$L_{\min(1)} = L_{\min(T)} \tag{2.7}$$

Equation 2.5 calculates the inductance from the beginning of the motor until the end of the first step winding .The inductance is $L_{\min(1)}$ and when it reached the end of the first winding the inductance is $L_{\max(1)}$.

2.7.1.2 Second region:

$$L_2 = L_{m2}\left[1+\cos\left(\frac{3\pi}{l}\left(\frac{2l}{3}-x\right)\right)\right] + L_{\min(T2)} \quad , \frac{-2l}{3} > x < \frac{-1}{3} \tag{2.8}$$

$$L_{m2} = \frac{L_{\max(2)} - L_{\min(2)}}{2} \tag{2.9}$$

$$L_{\min(2)} = L_{\max(1)} + L_{\min(2)} + L_{\min(3)} \tag{2.10}$$

Equation 2.8 calculates the inductance from the beginning of the step winding 2 until the end of the second step winding .The inductance at the beginning of step winding 2 is calculated in equation 2.9 and when it reached the end of the first winding the inductance is the sum of the maximum of the first and second regions and the minimum inductance of the third winding.

2.7.1.3 Third region:

$$L_3 = L_{m3}\left[1 + \cos\left(\frac{3\pi}{l}\left(\frac{2l}{3} - x\right)\right)\right] + L_{\min(T3)} \quad , \frac{-1}{3} > x < 0 \tag{2.11}$$

$$L_{m3} = \frac{L_{\max(3)} - L_{\min(3)}}{2} \tag{2.12}$$

$$L_{\min(2)} = L_{\max(1)} + L_{\max(2)} + L_{\min(3)} \tag{2.13}$$

Equation 2.11 calculates the inductance from the beginning of the step winding 3 until the end of the third step winding .The inductance at the beginning of step winding 2 is calculated in equation 2.12 and when it reached the end of the first winding the inductance is the sum of the maximum of the first, second and third region.

2.7.2 Tubular Linear Actuator with Halbach Array

The thrust calculation of the Tubular linear actuator with Halbach array actuator have been derived in [21] as follows:

In this design the two assumptions are made: the current flowing through the sheet in the inner surface of the stator and both iron permeability and actuator length are infinite.

Since the free current in the stator is zero $\nabla \times H = 0$, so $\nabla \times B = \mu_o \nabla \times M$ .The magnetic vector potential A is defined by $\nabla \times A = B$ and as the actuator is tubular ,hence , the vector potential has only θ component . As a result, The Poisson's equation, in terms of the Coulomb gauge, $\nabla \times A = 0$ is defined by:

$$\frac{\partial^2}{\partial_r^2} A_\theta + \frac{1}{r}\frac{\partial}{\partial_r} A_\theta - \left(k_n^2 + \frac{1}{r^2}\right) A_\theta = -\mu_o \times k_n \left(\frac{c_1}{r} + c_2 r\right) M_{rn} \tag{2.14}$$

Here μ_o represents the permeability of free space, $k_n = \frac{n\mu}{\tau}$ is the spatial wave number of the nth harmonic, τ is the actuator's pole pitch, M_{rn} is the Fourier coefficient of the nth order radial magnetization components, the coefficients c_1 and c_2 are selected in order to reduce the radial component M_r. At this point, axial and radial components of the flux density resulted $B_{zn} and\ B_{rn}$ can be defined by:

$$B_{zn}^{I} = k_n[A_n^I I_0(k_{nr}) - B_n^I k_0(k_{nr})] \cos(k_n z) \tag{2.15}$$

$$B_{zn}^{II} = k_n[[A_n^{II} I_0(k_{nr}) - B_n^{II} k_0(k_{nr})] + \frac{2c_2\mu_o M_{rn}}{k_n^2}] \cos(k_n z) \tag{2.16}$$

$$B_{rn}^{I} = k_n[A_n^I I_1(k_{nr}) - B_n^I k_1(k_{nr})] \sin(k_n z) \tag{2.17}$$

$$B_{rn}^{II} = k_n[[A_n^{II} I_1(k_{nr}) - B_n^{II} k_1(k_{nr})] + \frac{\mu_o M_{rn}\,(\frac{c_1}{r} + c_2 r)}{k_n}] \sin(k_n z) \tag{2.18}$$

The apex I, II reference to regions one, two, k_1, k_2 represents modified Bessel functions of first and second kind of order 1 and k_0, k_0 of order zero.

The linear current density J may be expanded into Fourier series according to the following equation:

$$J_\theta(z) = \sum_{n=1,odd}^{\infty} J_n \sin(k_n z) \tag{2.19}$$

Where J_n is a function of the distribution and value of the current, and since the current is assumed to be distributed in an infinitesimal then sheet, the governing equation will be the Laplace equation 2.19 with $M_{rn} = 0$.

The final axial thrust exerted on the stator winding caused by the interaction between the permanent magnet field and the current flux density in the infinitesimal tubular actuator length dz is defined by [23]:

$$dF_z(z) = -2\pi r_s J_\theta(z) B_r^I(r_s, z) dz \qquad (2.20)$$

2.8 Previous Work Done on Tubular Linear Electromagnetic Actuators

In [22] the Design Optimization of Radially Magnetized, Iron-Cored, Tubular Permanent-Magnet Machines and Drive Systems was presented. The paper showed that the design optimization of such a device must account for the losses and Volt/Ampere rating of the converter as well as the different design parameters of the tubular actuator. They derived formulas that are capable of providing an effective means of optimizing the design of machines and drive systems in general and linear actuators in particular. Those formulas will aid the design process when addressing a given particular performance specification.

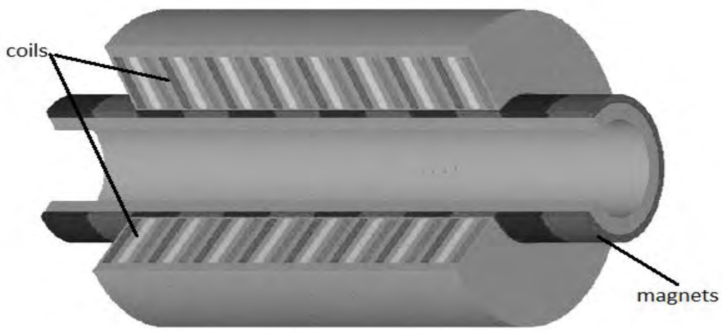

Figure 2.6: Radially Magnetized Iron-Cored tubular permanent-magnet actuator [22]

In [23], studied the 3D analytical and numerical methods to model the distribution of the magnetic field in a tubular actuator with skewed permanent magnets (PMs).The paper tried to reduce the large force ripple by skewing the permanent magnet in the mover of the actuator which is caused by the finite length of the stator and /or mover, the winding distribution with the form of excitation (DC or AC) and the stator's slot openings. They used skewed PMs to optimize the finite length instead of the conventional methods which are choosing the proper number of slots/poles, using soft-magnetic wedges and changing the magnet to pole pitch ratio. However, Skewing of the mover requires a unique permanent magnet shapes, complex ferromagnetic tooth shapes and coil shapes which is more expensive. The paper used 3-D finite element analysis to analyze the actuator.

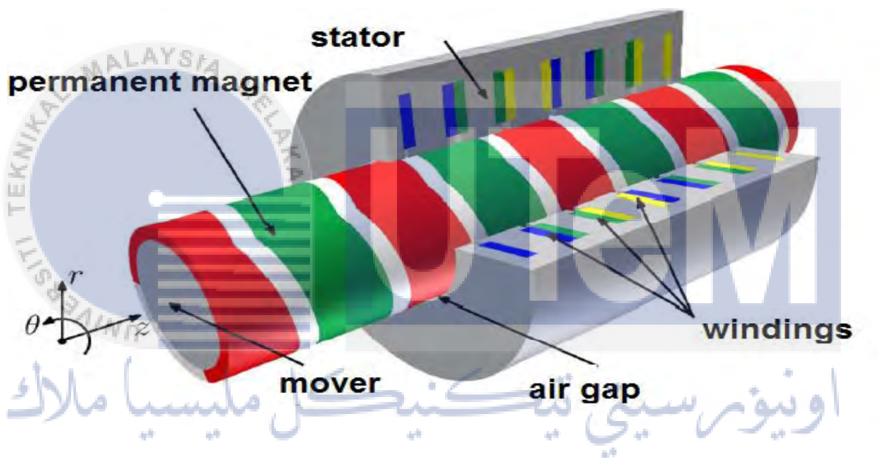

Figure 2.7: Tubular actuator with skewed permanent magnets [23]

Another work done in [24], In this paper a novel Magnetically Levitated Linear Actuator (MLLA), which mainly consist of a moving-magnet armature with Halbach magnetized PMs, a cylindrical frame, a rod and electromagnetic (EM) poles. The designed actuator in this paper is employed for linear compressors applications. The paper presented applying the Halbach array to enhance the force of the actuator. The designed actuator provide high reliability, dynamic performance stability, high servo characteristics and less power loss. However this design was limited to a very short stroke.

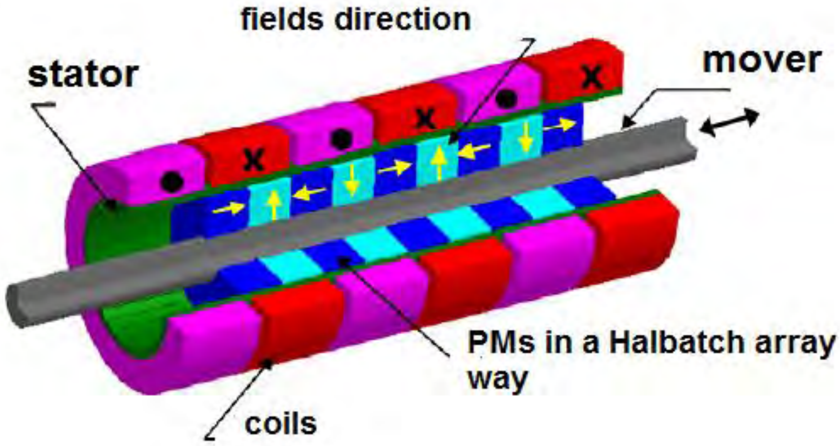

Figure 2.8: Novel magnetically levitated linear actuator [24]

Another work done in [25].This paper presented the design a linear tubular switched reluctance motor for heart assistance circulatory by applying both analytical and finite element modeling. This design is of the moving iron type of electromagnetic actuator. The actuator is designed to be used in a left ventricular assist device (LVAD). The proposed LVAD concept of pulsatile blood pump to be employed in the aorta descending. In this actuator a mechanical valve is inserted inside the mover (plunger) in order to create a pulsatile flow. However, the designed actuator does not focused on the force enhancement and, hence, the force provided by the actuator is small. The actuator configuration is presented in figure 2.9 and the real design is presented in figure 2.10.

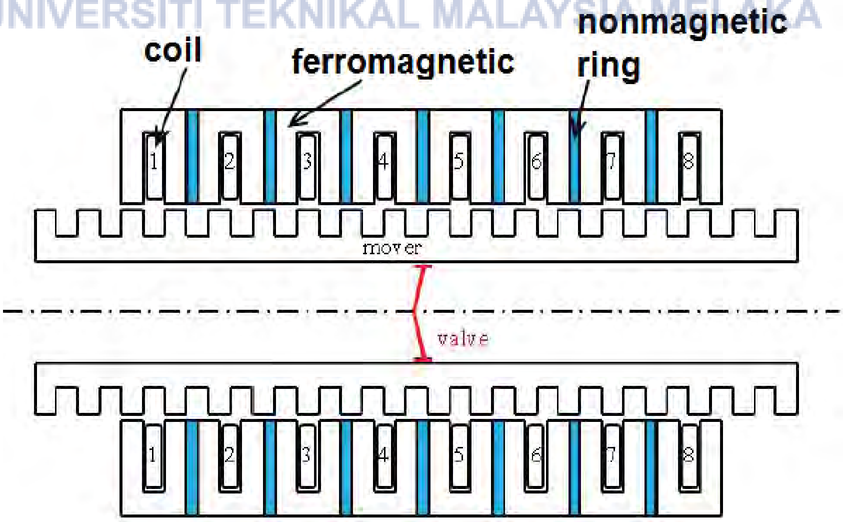

Figure 2.9: Internal construction of linear tubular switched reluctance motor [25]

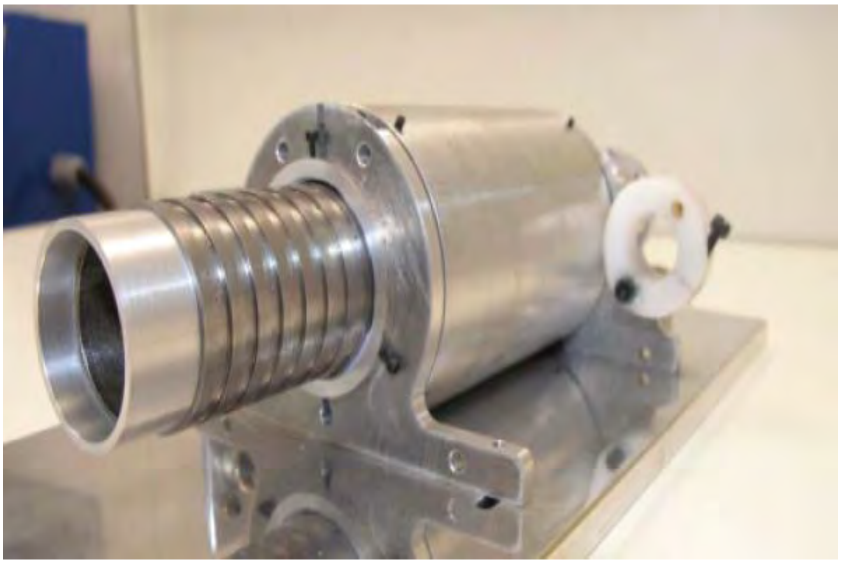

Figure 2.10: Linear tubular switched reluctance motor [25]

2.9 Literature review summary

The flow of the literature review has covered many steps starting from general to specific from all types of actuators to best type of actuators from many types of linear electromagnetic actuator to best and most improved types of electromagnetic linear actuators. Based on the comparisons in this chapter the tubular type of electromagnetic actuator shows the best characteristics especially in term of output force and displacement. This was followed by four previous designs of tubular electromagnetic linear actuators that show lagging force characteristics solved by Halbach array in tubular PMs Actuators and by step windings in tubular reluctance actuators. Hence the chosen designs for this project employ the Halbach array to the PMs tubular actuator in favor of maximizing the output thrust and displacement and employed step winding to the tubular reluctance in order to maximize and equalize the force in the whole stroke of the actuator.

CHAPTER 3

3 METHODOLOGY

In an electromagnetic actuators' designs, a real challenges are extensively present due to truth that every different design has its own different characteristics according to the material used and the arrangement of the component of the actuator. Some topologies provide high force but show a little robustness and accuracy and vice versa, hence, a significant challenge is the choice of actuator type. The flow of designing the actuators are explained in the design strategy section. With the designs are completely configured a force characterization is undertaken. The setup of the force characterization is presented in the force characterization section.

3.1 Design Strategy

The selection of each actuator in the project has undergone few steps in order to make right choice to efficiently satisfy the design objectives which is in our case high force ,long working range and an acceptable cost.

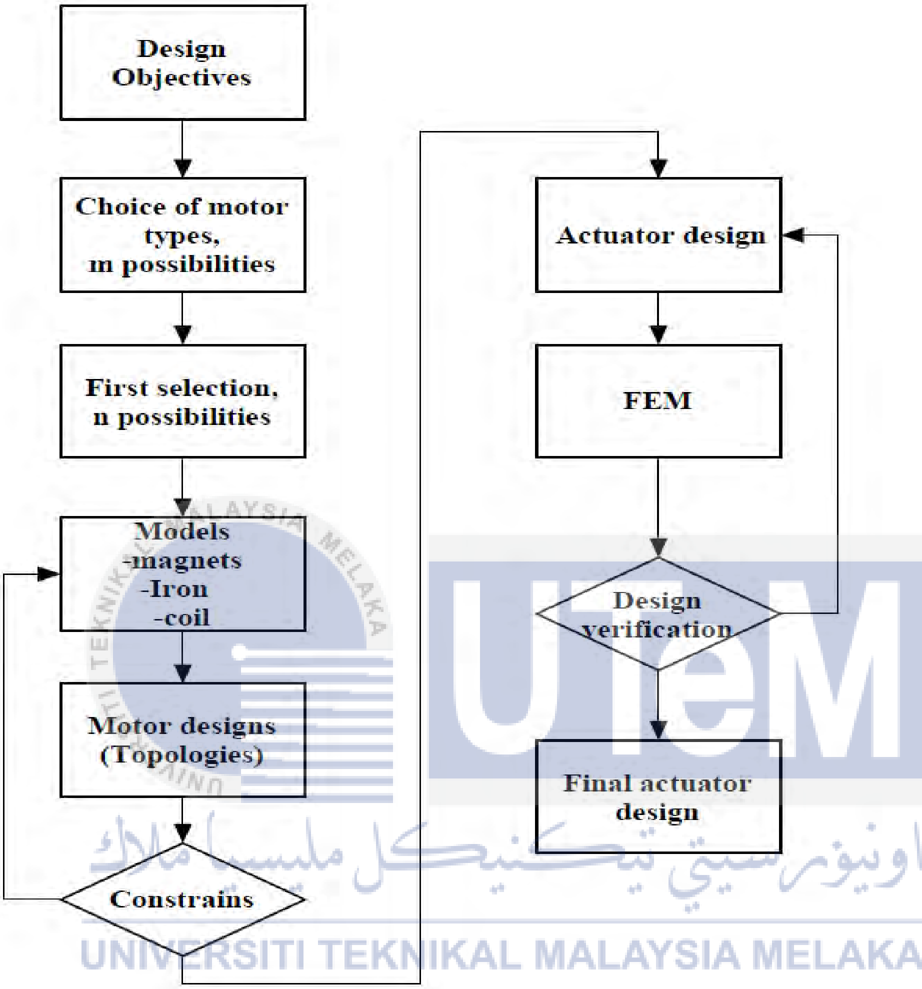

Figure 3.1 Flow chart of the design process

The process flow of selecting the actuators designs is shown in the flow chart figure 3.1 and can be described briefly as follow:

After specifying the required objectives, four types of actuators are tested to meet the required specifications which are Smart Materials, Electromechanical, Piezoelectric and Electromagnetic. The comparison of the four types in the literature review chapter has shown that the electromagnetic type show the best characteristics in term of high force, long working range, low voltage and robustness.

At this point, Electromagnetic actuator is chosen, but here a choice has to be made whether to use planer type or tubular type of the electromagnetic actuator. As shown in chapter 2 tubular type provides higher force and greater stability. Under tubular electromagnetic actuators, there are many possible topologies could be employed such as moving coil which is excluded from the project's options due to its high cost. Two other choices are left moving magnet (tubular linear permanent magnet actuator) and moving iron (tubular linear reluctance actuator). These two actuators have been chosen to be designed and characterized in this project.

Three parameter will be varied in each of the two design in order to study the effect of varying each of them. The three parameter are:

1. Air gap.
2. Number of turns.
3. Size.

3.2 Conceptual Design

3.2.1 First Design (Tubular Linear Reluctance Actuator)

The presented structure is considered to strengthen and enhance the thrust force and working range in tubular linear reluctance actuator. The new structure in this actuator is used to strengthen force and working range by applying some changes to the typical actuator .The significant change applied is making a novel step winding structure in a way that the coils are rearranged without effecting the total number of the coils. The coils rearrangement effects the slop of inductance curve, which straighten the slop of the inductance curve no matter where the mover is positioned along the bore. Figure 3.2 shows the conventional coil arrangement around the mover. A disadvantage of this arrangement is that as the mover is displaced from its center position, the inductance decrease causing the force to decrease and a proposed solution to this problem is shown in figure 3.3 with different coil arrangements which make an equal inductance even if the mover is not in its center position. The improvement is done by increasing the coil at the outer edges of the stator and decreasing it in the center position.

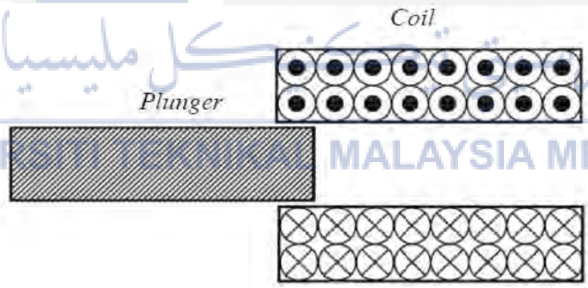

Figure 3.2 : Conventional coil arrangement.

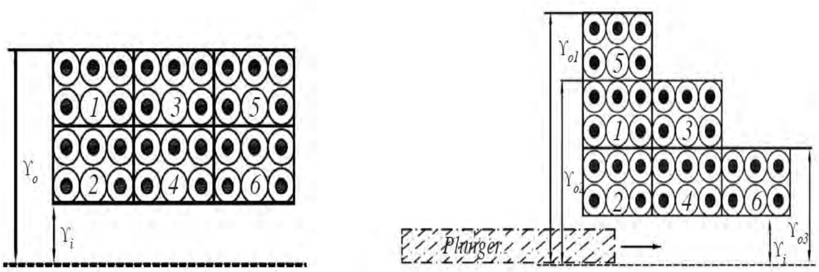

Figure 3.3 : Proposed coil arrangement.

3.2.2 Second Design

The presented design is improved from normal tubular electromagnetic actuators in a way that the output thrust force is enhanced by inserting the cylindrical Halbach array into the mover. The schematic structure of permanent magnet with Halbach array is illustrated in figure 3.4 which shows the different arrangements of permanent magnets. The mover is planned to be consisting of cylindrical PMs located at the internal side of the coils. The PMs are arranged in Halbach array way in favor of maximizing the field generated outside the surface of bore in the moving part. The cylindrical Halbach array arrangement is shown in figure 3.5.

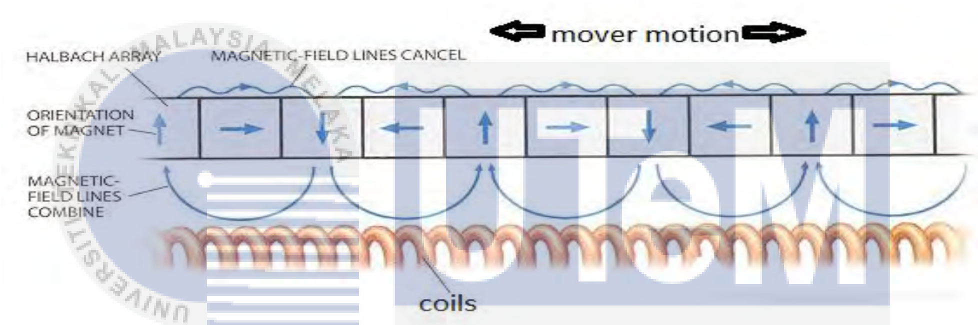

Figure 3.4 : Halbach array field distribution.

As can be seen the magnetic field is greatly enhanced in one side which is the desired side and weakened at the other side where no need for the field.

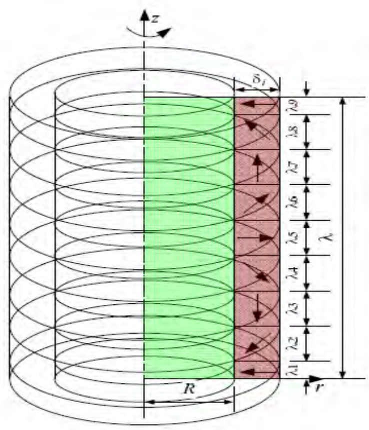

Figure 3.5 : Cylindrical Halbach array [22]

3.3 Designs structure and initial parameters

3.3.1 First Design (Tubular Linear Reluctance Actuator with step windings)

The designed Tubular Linear Reluctance Actuator with step windings consist of two main parts which are stator and mover. In this design the stator contains set of coil turns while the mover consist only of iron. Table 3.1 indicates all the initial parameters of the designed actuator. Table 3.2 shows the parameters of the three windings steps.

Table 3.1 : Parameters of the Tubular Linear Reluctance Actuator with step windings

Symbol	Quantity	Value
N	Number of turns	Table 3.2
D_{ci}	Coil inner diameter (mm)	Table 3.2
D_{co}	Coil outer diameter (mm)	Table 3.2
D_{mo}	Mover outer diameter (mm)	20
L_c	Length of the mover (mm)	90
L_w	Length of the winding (mm)	90
d_c	Conductor diameter (mm)	0.3
d_g	Air gap (mm)	1

Table 3-2 : Parameters of the winding's steps

Symbol	First winding	Second winding	Third winding
N	17	33	66
D_{ci}	20	20	20
D_{co}	25	30	40

Figures 3.6, 3.7 and 3.8 shows the design of the Tubular Linear Reluctance Actuator with step windings actuator indicating the mover and stator of the actuator design.

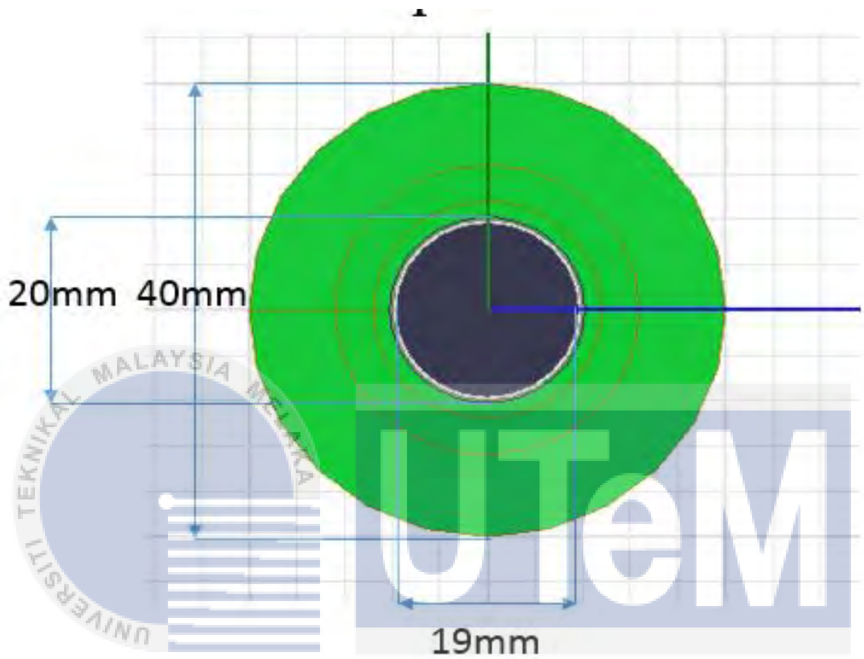

Figure 3.6 : Top view of the reluctance actuator

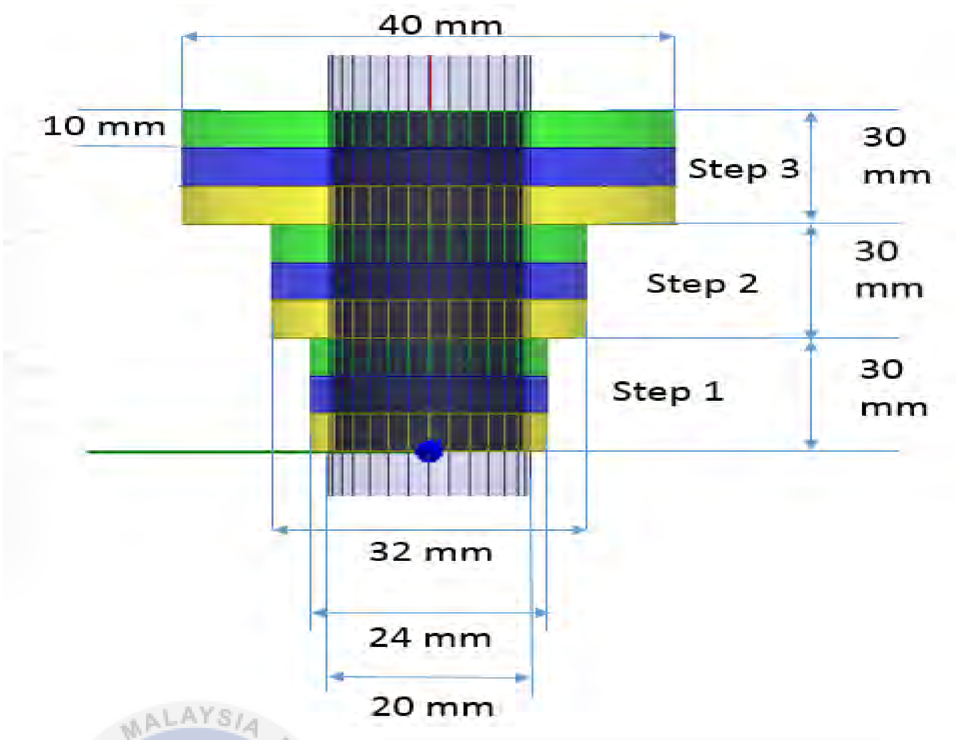

Figure 3.7 : Dimensions of step windings of the reluctance actuator represented in side view

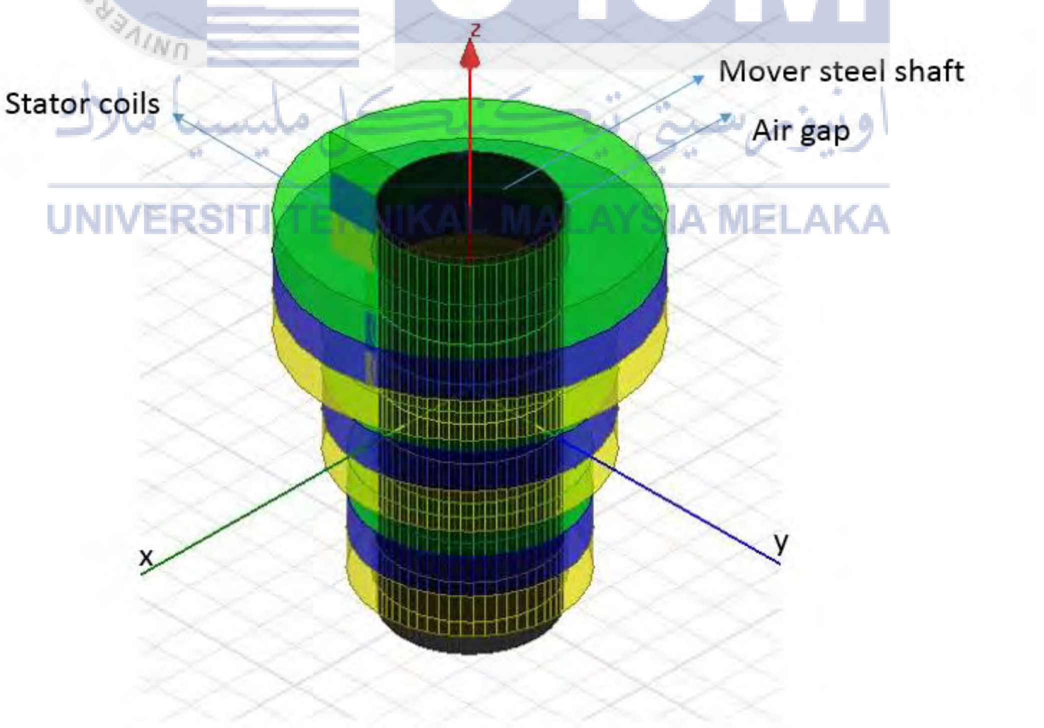

Figure 3.8 : 3D view of the Tubular Linear Reluctance Actuator with step windings

3.3.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

The designed Tubular Linear Permanent Magnet with Halbach Array Actuator consist of two main parts which are stator and mover. In this design the stator contains set of coil turns while the mover consist of iron shaft rounded by permanent magnets inserted in Halbach way. Table 3.3 indicates all the parameters of the designed actuator.

Table 3-3 : Parameters of the Tubular Linear Permanent Magnet with Halbach Array Actuator

Symbol	Quantity	Value
N	Number of turns	66
D_{ci}	Coil inner diameter (mm)	21
D_{co}	Coil outer diameter (mm)	40
D_{shaft}	Shaft outer diameter (mm)	12
D_{mo}	Magnets outer diameter (mm)	20
D_{mi}	Magnets inner diameter (mm)	12
L_c	Length of the mover (mm)	90
L_w	Length of the winding (mm)	90
h	Magnet height (mm)	10
d_g	Air gap	2

Figures 3.9, 3.10 and 3.11 are the views of the Tubular Linear Permanent Magnet with Halbach Array Actuator.

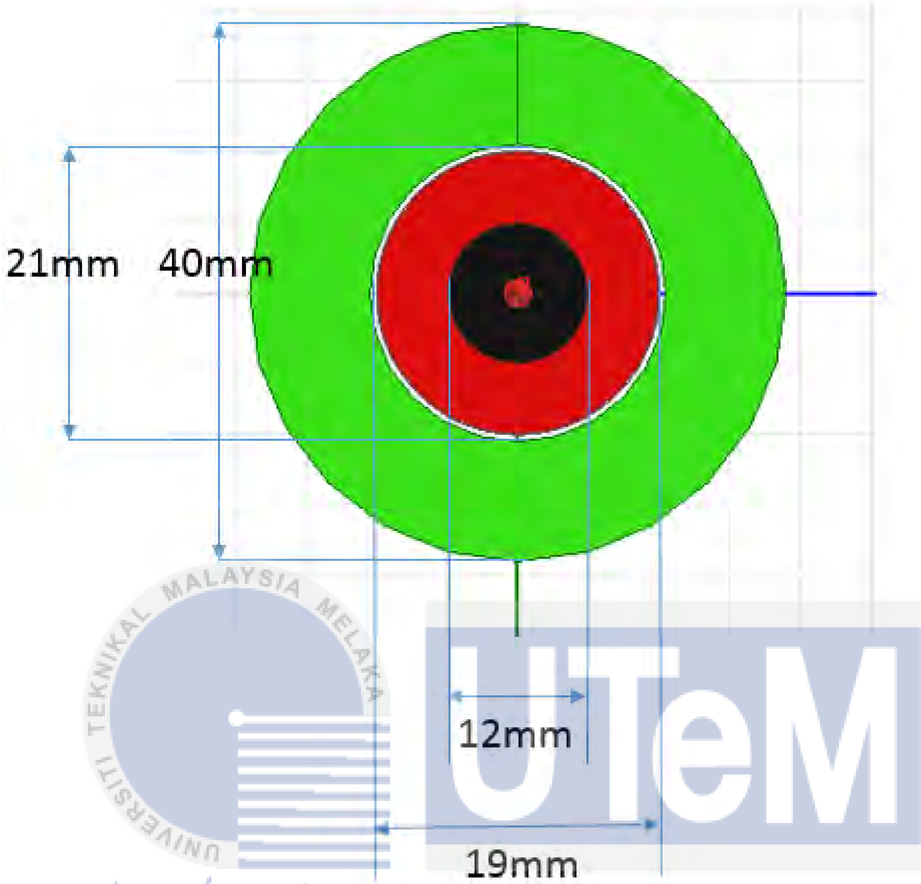

Figure 3.9 : Top view of the permanent magnet actuator

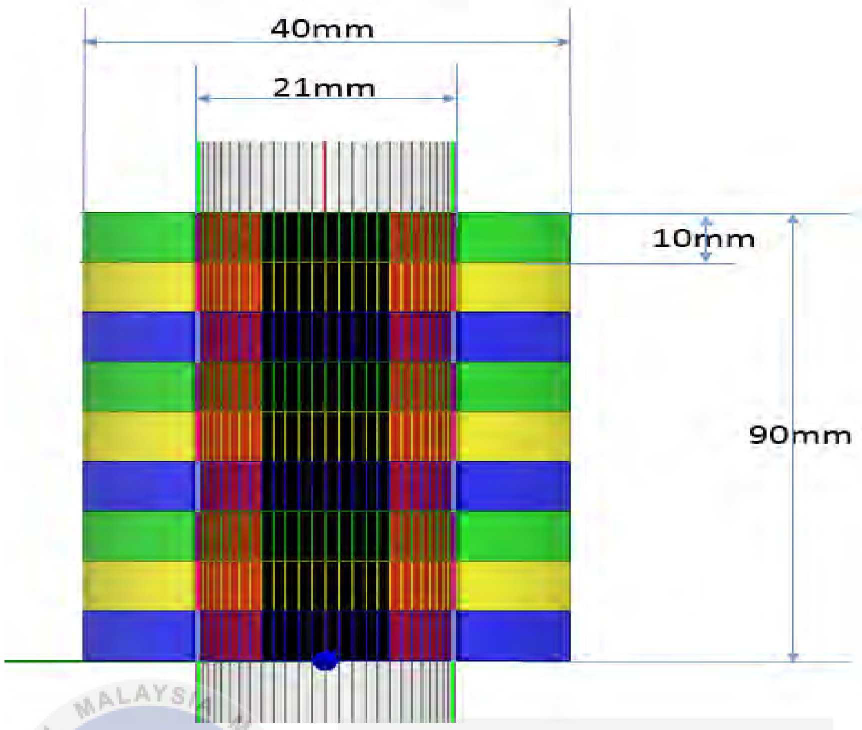

Figure 3.10 : Side view of the permanent magnet actuator

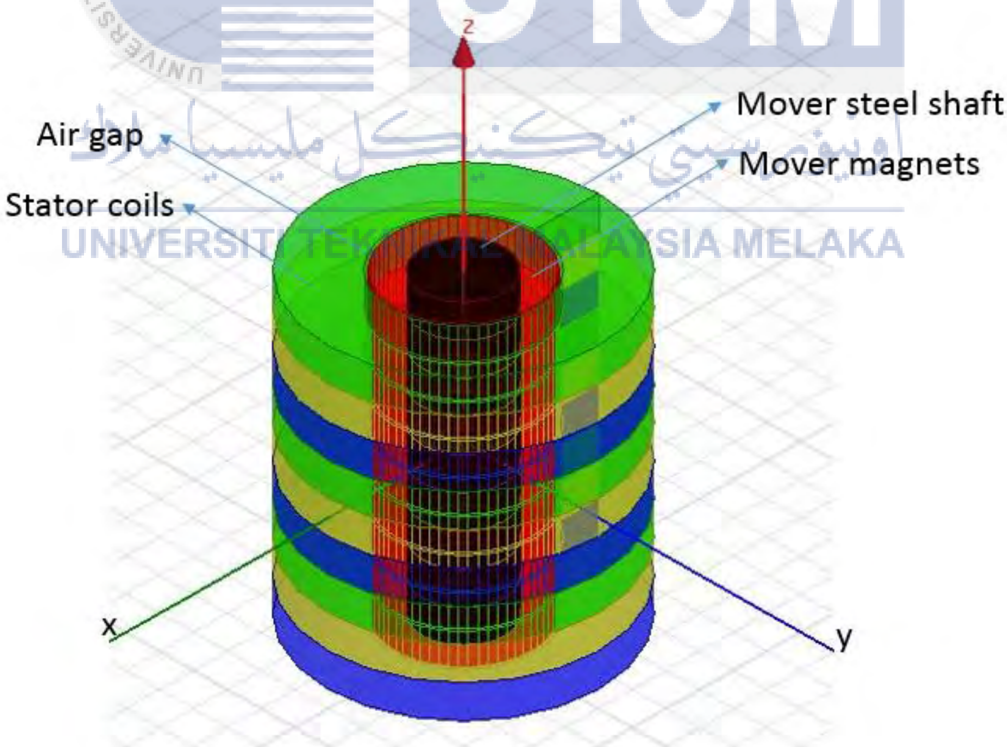

Figure 3.11 : 3D view Tubular Linear Permanent Magnet with Halbach Array Actuator

3.4 Working Principle

3.4.1 First Design (Tubular Linear Reluctance Actuator)

A tubular linear reluctance actuator mainly consists of two main parts: a stationary part (stator) and moving part (mover). The stationary part consist of exiting windings which is responsible of producing magnetic field and moving part which consists of a ferromagnetic material or what can be called a plunger.

As the tubular inductance actuator is viewed as an electric actuator in which attractive energy is created by tendency of its mover (plunger) to align with a position where the inductance brought about by the energized coils down at its most extreme or the position where the reluctance to attractive flux is at its minimum value. The ferromagnetic material located in the mover causes the reluctance to be lessened and, thus, attractive power is created because of the change in the inductance of the material encompassing the windings as the mover transform its position. The ferromagnetic mover has a much more permeability than the air gap. As an after-effect of that, the attractive flux is created easier at the point where the mover is focused inside the coils, which implies the reluctance is least for a given flux level and it is likewise the position or the point with the slightest energy in the actuator. At the point when the mover is displaced from its focused position, the attractive strengths will dependably attempt to restore the mover to its focused position. As the tubular inductance actuator is various arrangement of coils initiated successively to draw the mover along the bore of the actuator, subsequently, the mover is just pulled; it will never be pushed. Figure (3.12) shows that the magnet flux is strong at the displacement region where the plunger is pulled to this area.

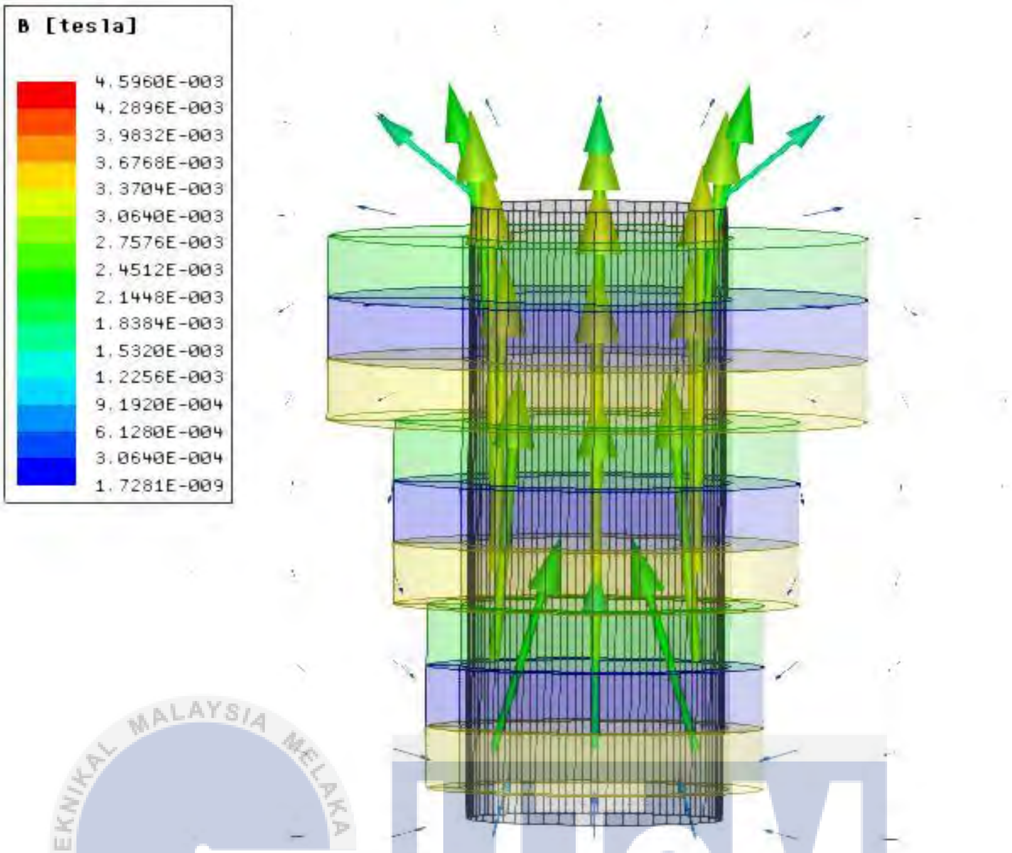

Figure 3.12 Magnetic field in the step winding actuator

3.4.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

A tubular linear permanent magnet actuator mainly consists of two parts: a stationary part (stator) and moving part (mover). The stationary part is composed of the exciting coil which produces the magnetic field and the moving part consist of permanent magnets. The movement of the mover is achieved by the interaction between the field of the exiting stator coil and the permanent magnets in the mover. In contrast to the normal parallel permanent magnets, the field distribution of a Halbach array is strengthen in the outer side of the magnet which is the needed side ,while canceled in the inner side. This results in an improvement of the usage of the magnetic materials and increases the strength of magnetic field and power density. A sample of the distribution of magnetic field in a Halbach array could be more illustrated in figure 3.13 .Figure 3.14 shows how the magnetic field is formed to cause the mover to displace to whether direction negative or positive.

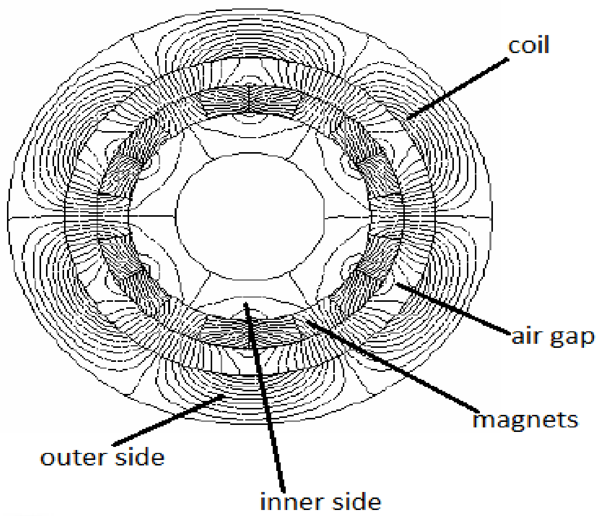

Figure 3.13 : A sample of the distribution of magnetic field in a Halbach array

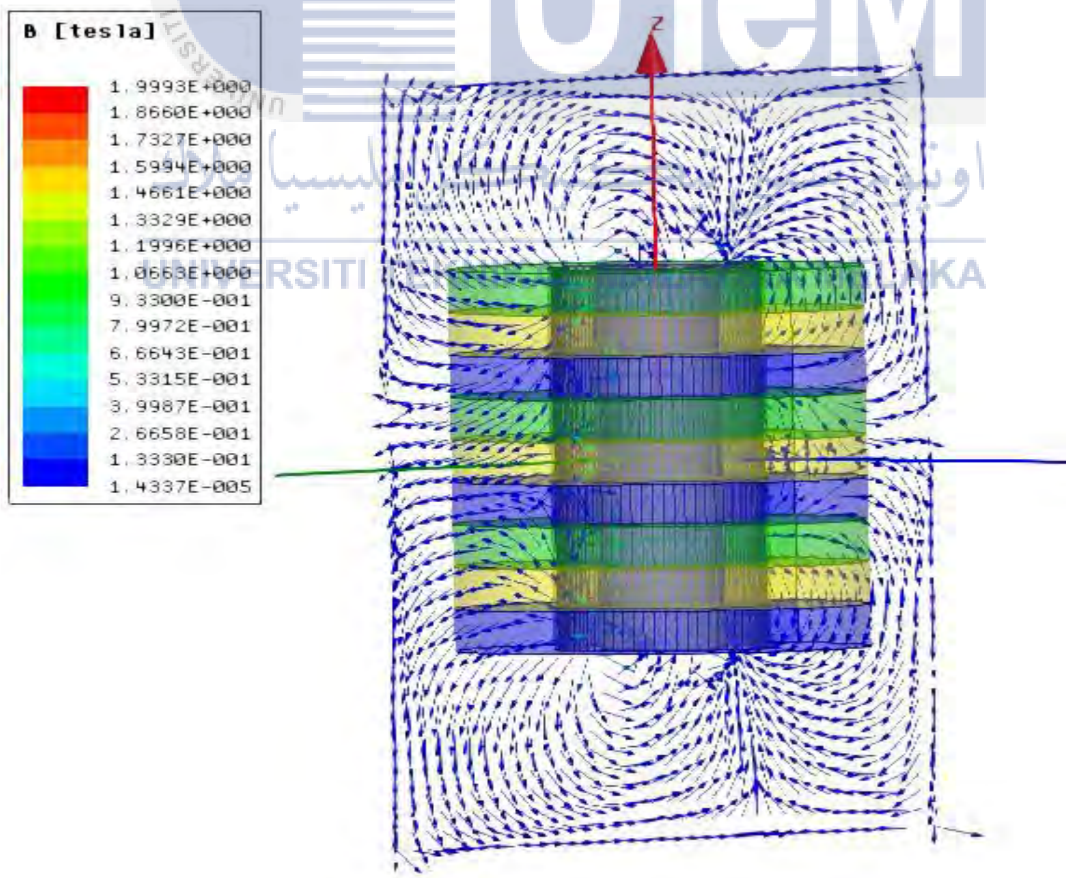

Figure 3.14 Magnetic field in the Permanent magnet actuator

3.5 Simulation Method

In this project, the finite-element Ansoft software will be employed to calculate the distribution of the magnetic field in both tubular linear permanent magnet actuator with cylindrical linear Halbach arrays and tubular linear reluctance actuator with different parameters. The program uses maxwell's equations as the fundamental for magnetic field distribution analysis. It is used to show the magnetic field distribtion in the whole actuator. The 3D finite-element solution has been chosed to analyse both designs by applying a periodical boundary condition. The permanent material is sintered NdFeB35, for which Brem=1.4T and Hc=1100KA/m. using the FEM analysis many parameters can determined such as the magnetic field "B", the magnetic flux "Ø" , force and displacement. The analysis can be done by means of the 2D and 3D designs, this software presents a powerful tool which is able to predict the magnetic field before starting the real mechanical design of the device. The ansoft simulation is used to show the differences between the two design in many design aspects such as force, displacement and effects of parameters variations.

The flow chart in figure 3.15 explains the flow or process done by the Maxwell when a design is simulated.

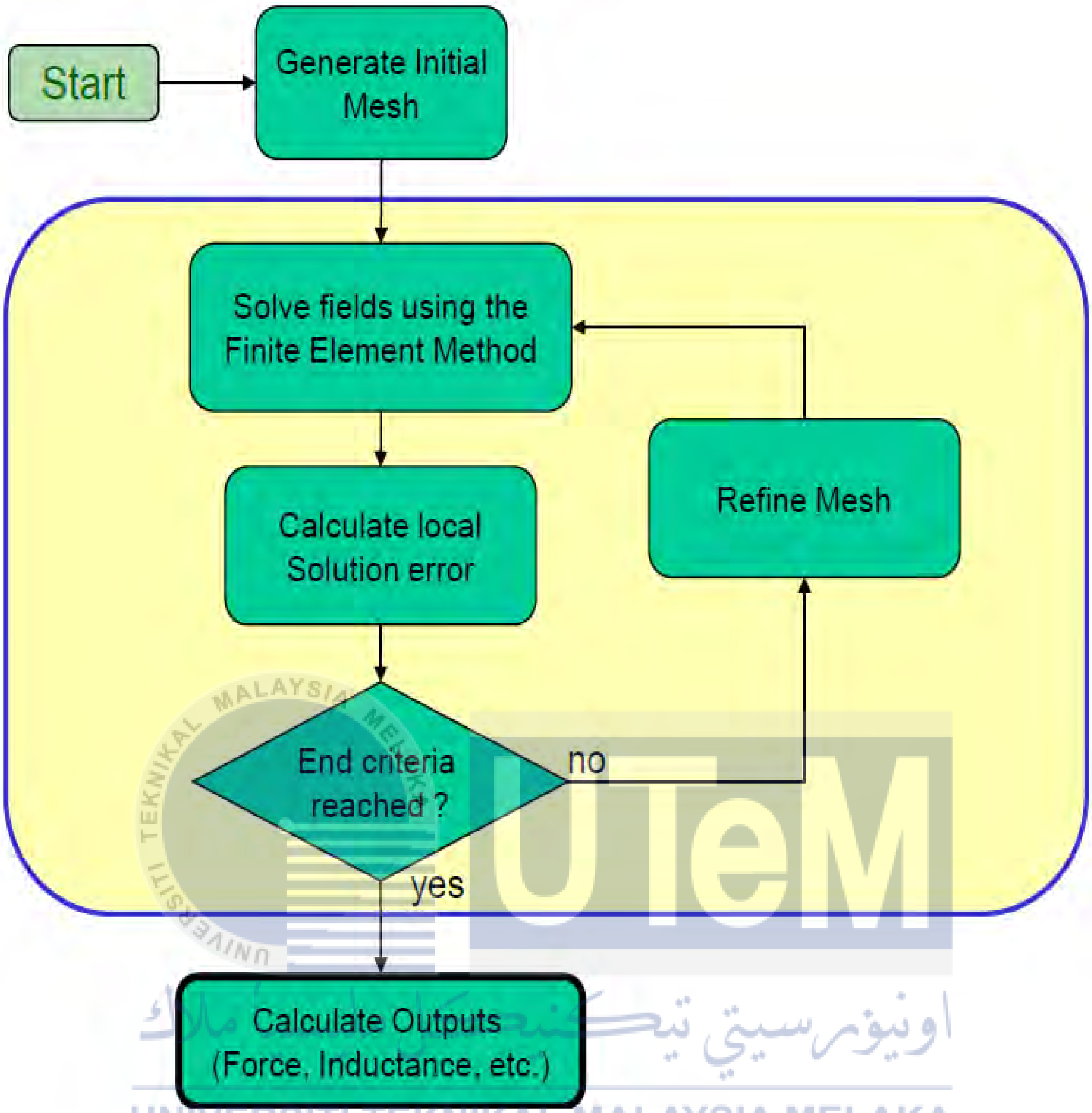

Figure 3.15 Process of simulation in the Maxwell software

The software starts generating meshes of the design and solve the distribution of magnetic field in the simulation region taking error into consideration and correcting it every pass then, dicides wheather the end criteria is reached which is number of passes in our case. Finally the software calculate the derived variables such as force and displacement.

Designs set up

3.5.1 First Design (Tubular Linear Reluctance Actuator with Step Windings)

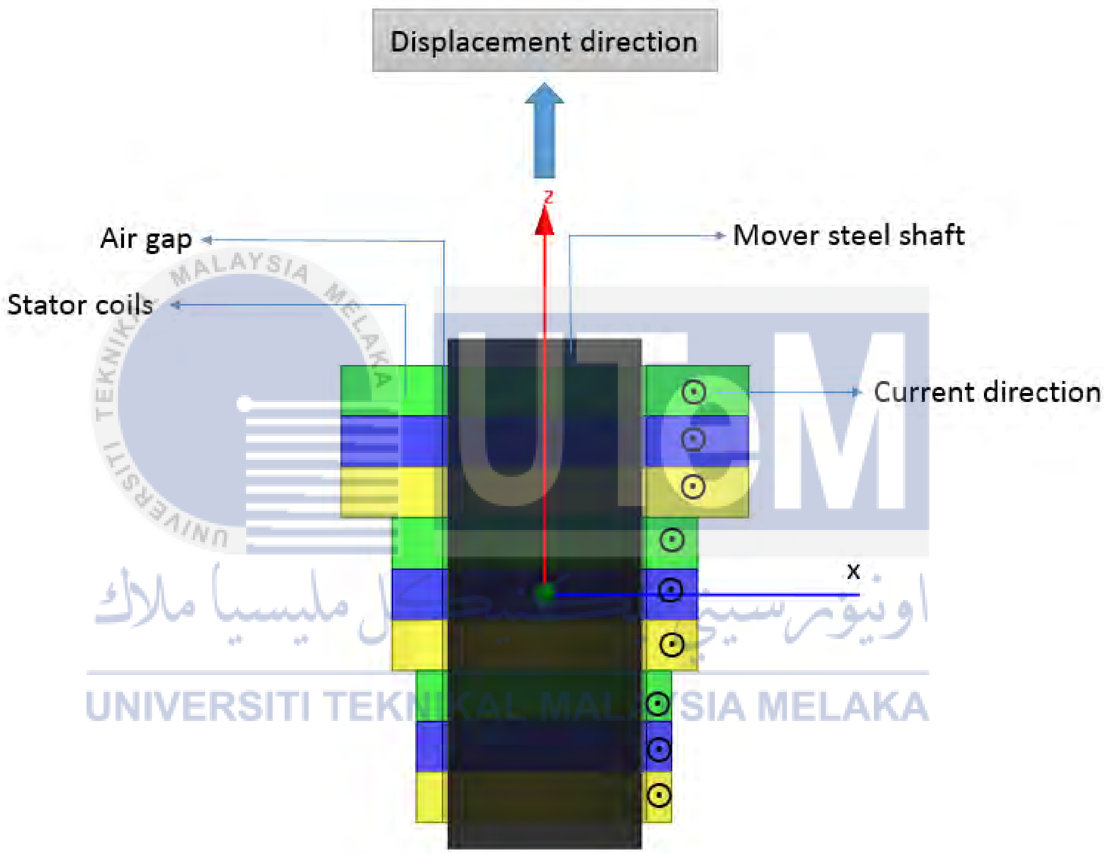

Figure 3.16 Section of reluctance actuator indicating the current direction

The current is set counter clockwise as indicated in figure 3.16 and confirmed by software in figure 3.17.

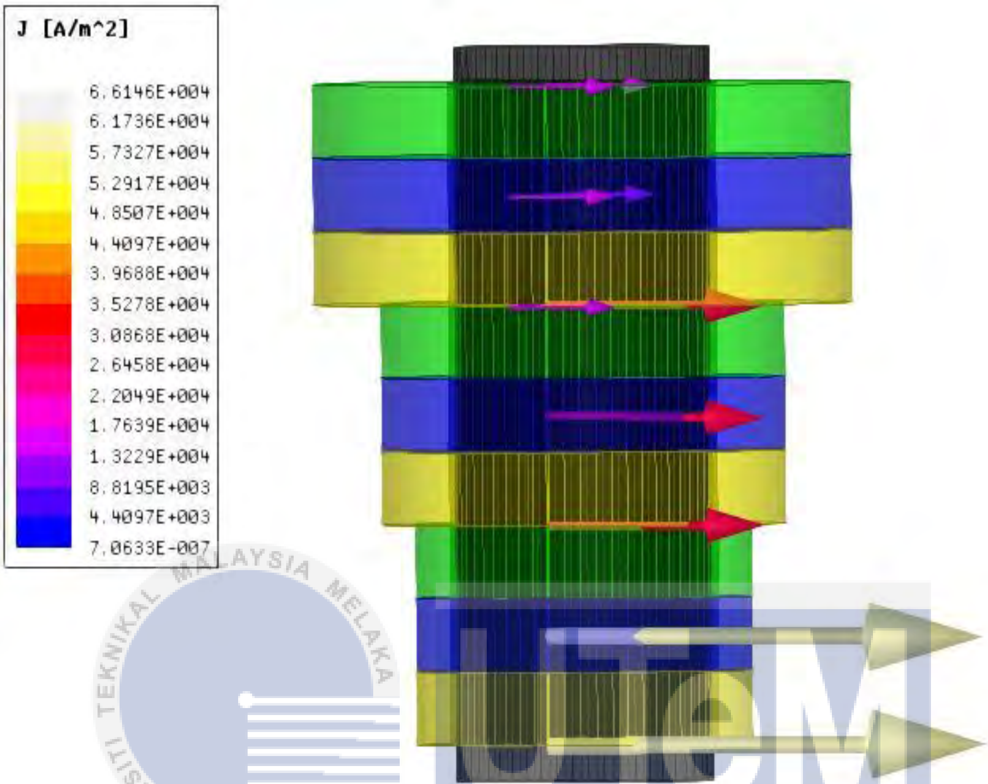

Figure 3.17 Current direction in step windings actuator in the Maxwell software

3.5.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

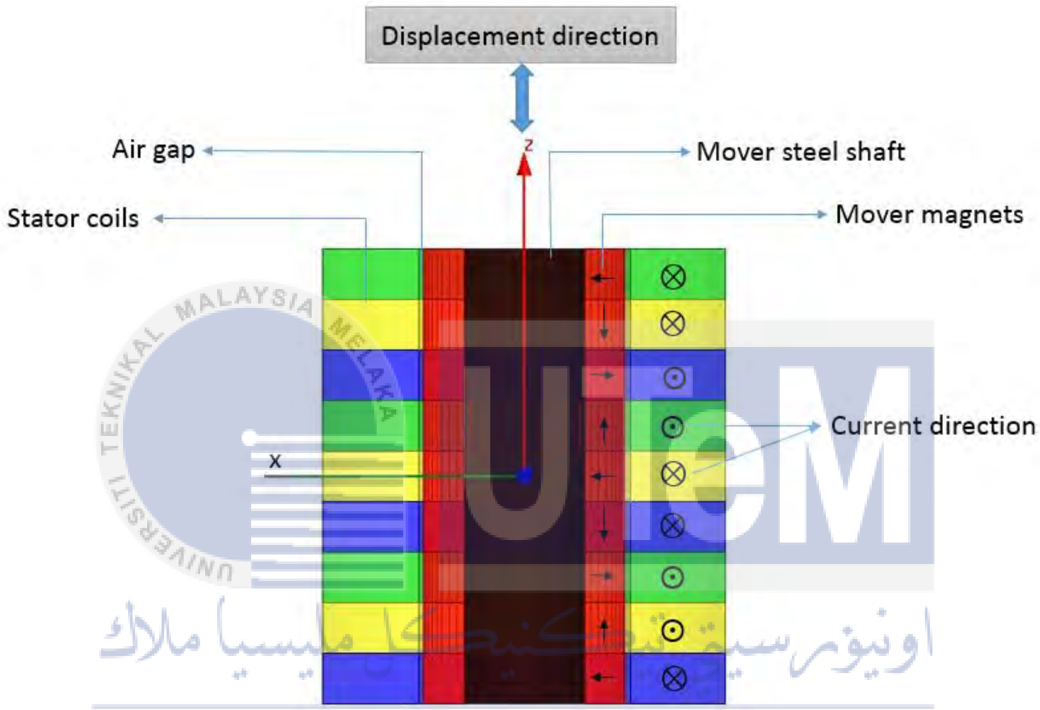

Figure 3.18 Section of permanent magnet actuator indicating the current direction

The current is set as indicated in figure 3.18 to maximize the strength of the magnetic field in the displacement region and to be arranged with the Halbach array magnets. The directions are confirmed in the Maxwell software in figure 3.19. The setting of the magnetization directions of the Halbach array magnets is applied to the design and shown in figure 3.20.

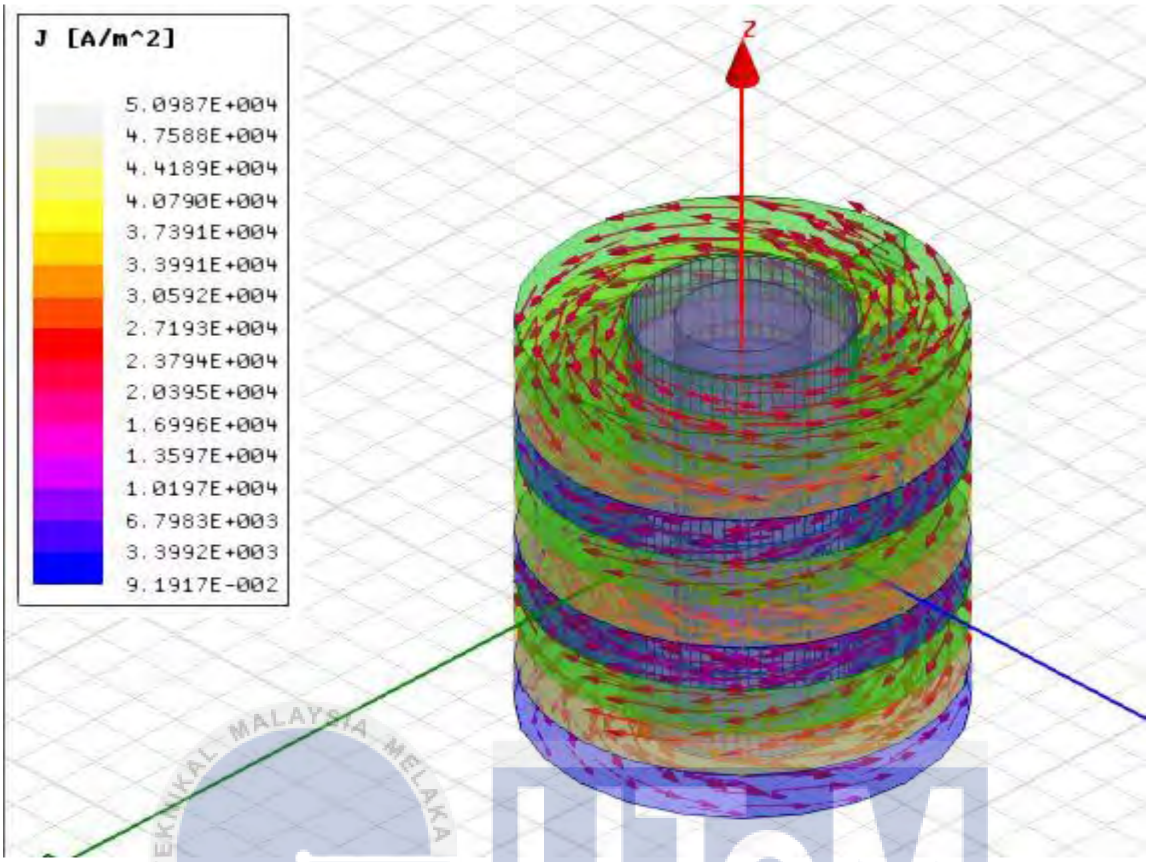

Figure 3.19 Current directions in permanent magnet actuator in the Maxwell software

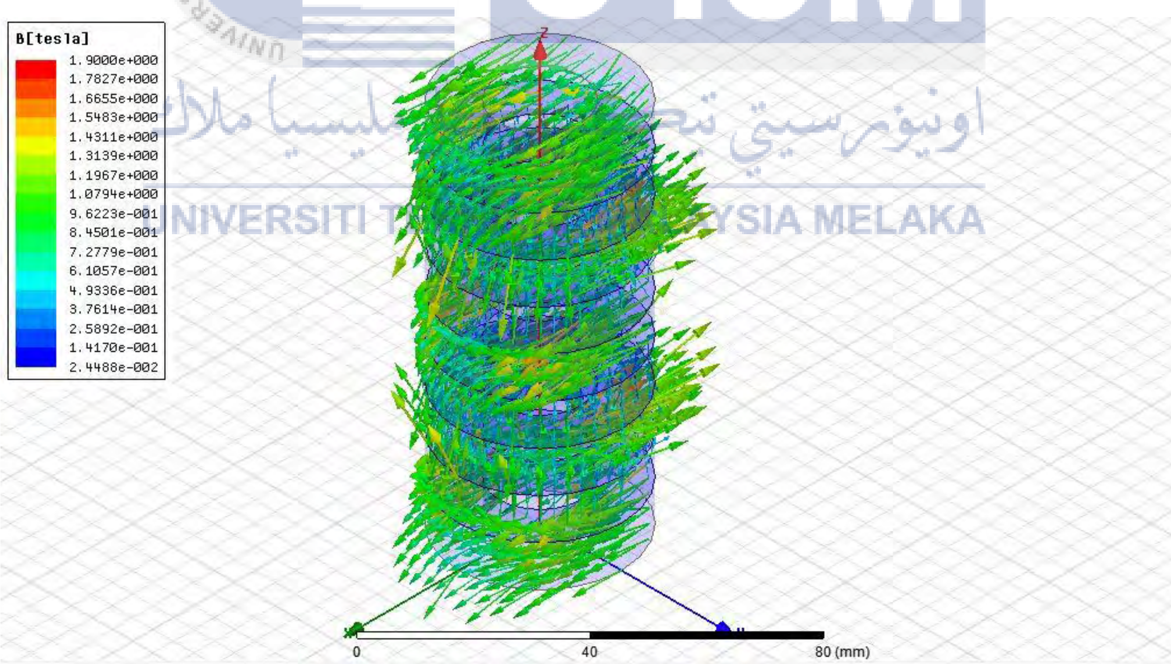

Figure 3.20 Magnetization setting for the Halbach array magnets

3.6 Force Characterization Set Up

The two actuators are completely configured and all the parameters are selected, the designs are in the stage of simulation which is FEM analysis and then comparison will be made between the two designs.

3.6.1 First phase: analyzing the distribution of the magnetic fields:

The fields' distribution will be analyzed along the stator and then along the mover to see the behavior of the fields and the finding points where the field is strong and weak. This analysis will be done through applying different values of current to each actuator in the Maxwell's software.

3.6.2 Second phase: analyzing the thrust in both designs:

The thrust will be analyzed with both designs' original size and parameters by applying different values of current.

3.6.3 Third phase: analyzing the displacements of both designs:

The displacement will be analyzed with both designs' original size and parameters by applying different values of current.

3.6.4 Fourth phase: parameters variation:

Three parameters are varied for each design to study the effects of each parameter while keeping the other two parameters fixed. The parameter variation is arranged as follows:

3.6.5 Varying the air gap for both designs:

This phase applies number of different values of air gap for both designs to analyze the effects of the air gap on the density of the fields between the stators and movers.

3.6.6 Varying the number of turns for both designs:

In this phase the number of turns is varied three times in each design to record the effect on the behavior of the actuators in term of force and displacement.

3.6.7 Varying the number of turns for both designs:

In this phase the analysis is applied to six different sizes of every design to study how the force is effected as size both mover and stator are increased.

3.6.8 Final phase: comparing the characteristics of both designs:

Lastly in this phase thrust, displacement and parameters variations of the actuator as compared.

CHAPTER 4

4 RESULTS AND DISSCUSTION

The Tubular Linear Reluctance Actuator with step windings and Tubular Linear Permanent Magnet with Halbach Array Actuator have been selected and designed. All designs' specifications have been obtained and also the parameters to be varied are chosen. In this section the obtained results are presented for all analyze aspects starting with magnetic field distribution, force and displacement analysis, and parameters variations results then concluded with short comparison between the two designs.

4.1 Magnetic field distribution

4.1.1 First Design (Tubular Linear Reluctance Actuator with Step Windings)

The distribution of the magnetic field in the actuator is shown in figure 4.1 .As can be seen from the figure the strongest field produced at the center of the actuator with the maximum reluctance difference followed by lesser value of the field at the top then minimum at the bottom where the minimum number of turns exists. The strength of the field in the displacement region identify the strength of the force which is produced by the magnetic field. The maximum value of magnetic field produce the highest force which is shown in the thrust analysis section. In the top view of the field distribution in the actuator in figure 4.2 the maximum magnetic field is around the edges of the mover and getting lesser toward the center of the mover where this point is the farthest from the air gap where the field is generated.

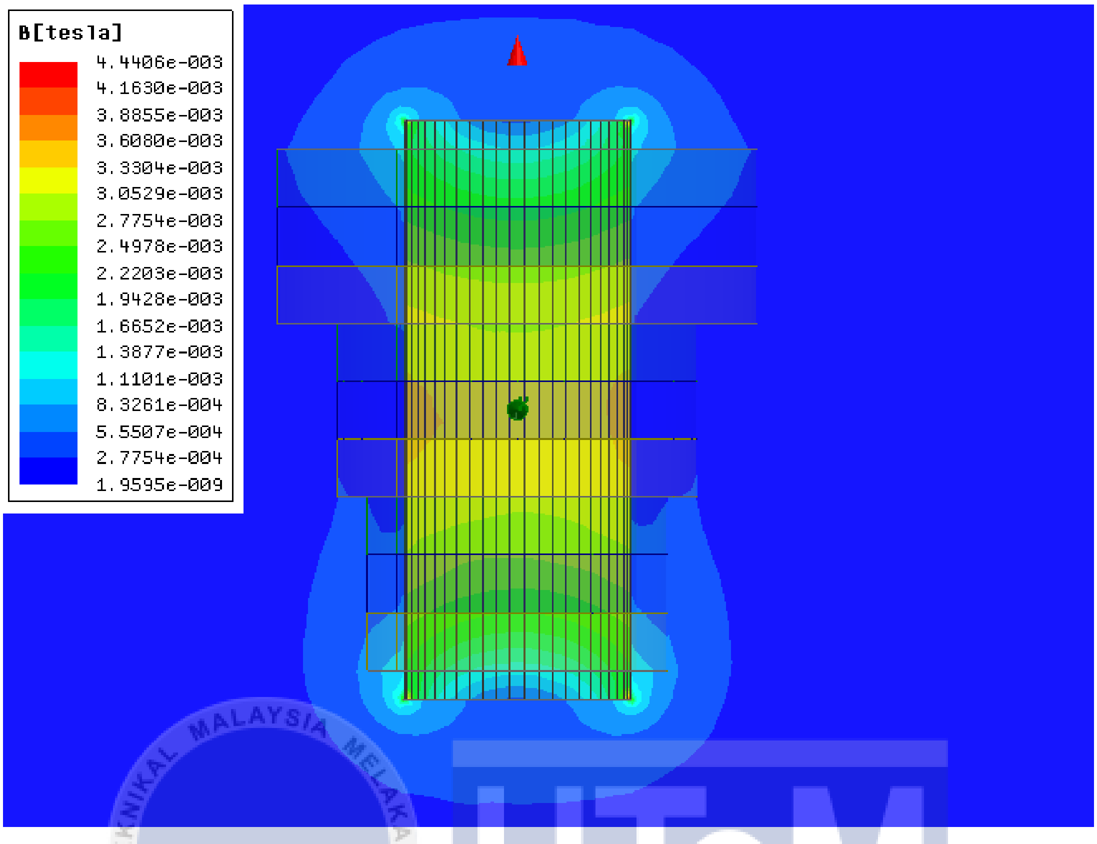

Figure 4.1 Magnetic field distribution in reluctance step windings actuator (side view)

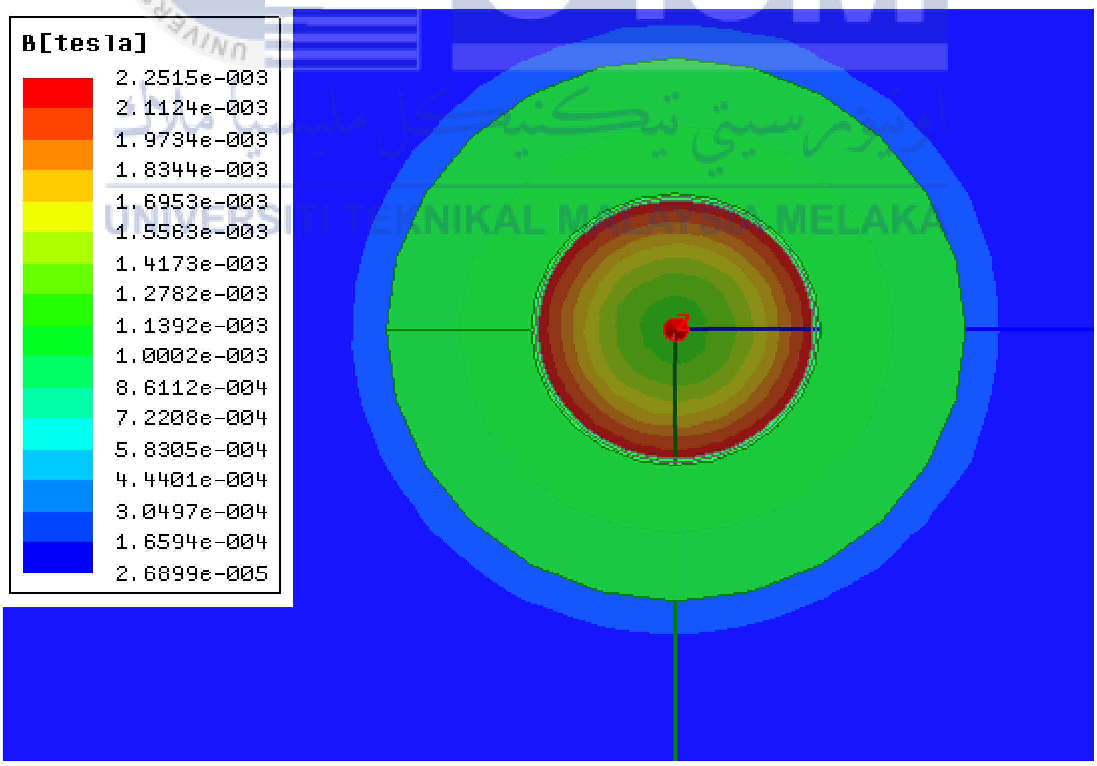

Figure 4.2 Magnetic field distribution in reluctance step windings actuator (top view)

4.1.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

In this design the distribution depends mainly how the magnetic field produced by coils aligned with the magnetic field produced by the magnets. As shown in figure 4.3 the strongest field produced in magnets number 1, 3, 5 ,7 and 9 where the magnetization direction of the magnets is in the x direction aligning with the field produced by coils. The magnetic field produced in the air gap region which cause the force on the mover is divided into four regions each with a height of 2h where h is the height one magnet. This distribution indicates that the stroke will be short and will be repeated every 2h which is 20 mm in this design. Figure (4.4) shows the top view of field distribution in the actuator where the magnetization direction of the magnet is in the x direction. The field is maximum at two edges of the mover where the field of magnet and coils aligned. On the another hand the field in the position where the magnetization direction is in the z direction the magnetic field is equally distributed around the mover diameter as the field of the coils does not align with the magnetization direction of the magnet shown in figure 4.5.

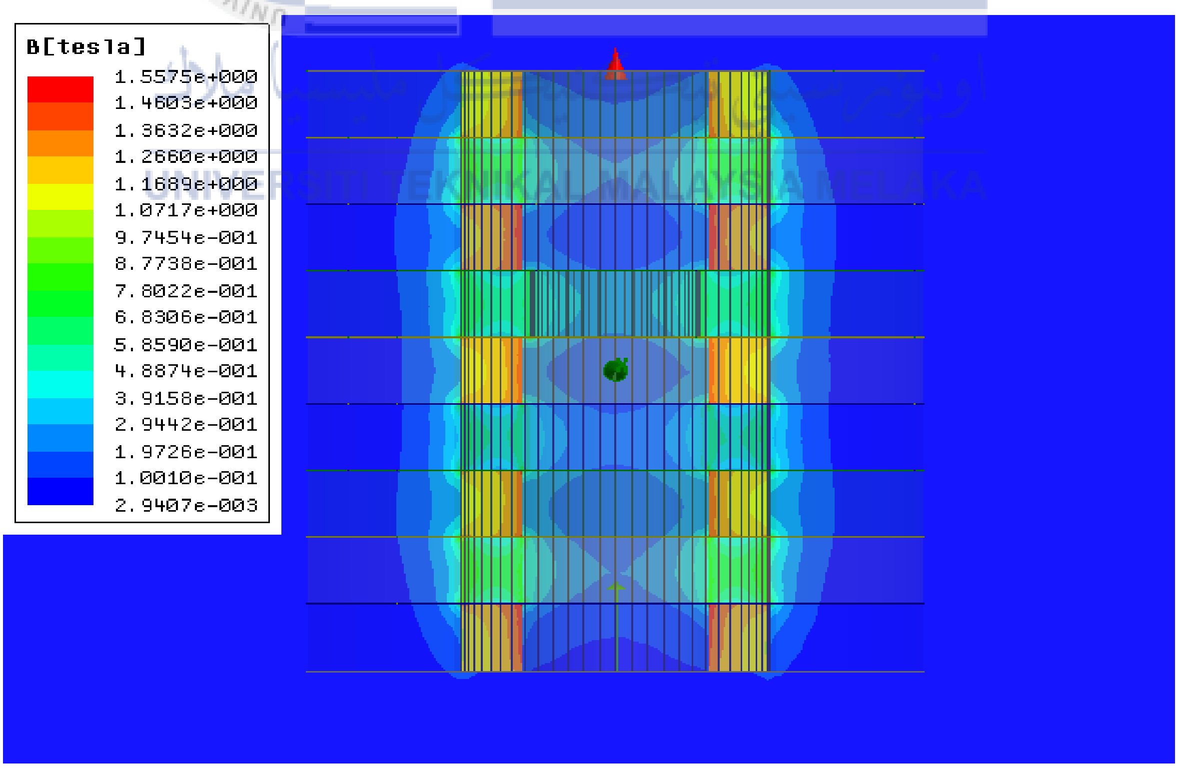

Figure 4.3 Magnetic field distribution in the permanent magnet actuator (side view)

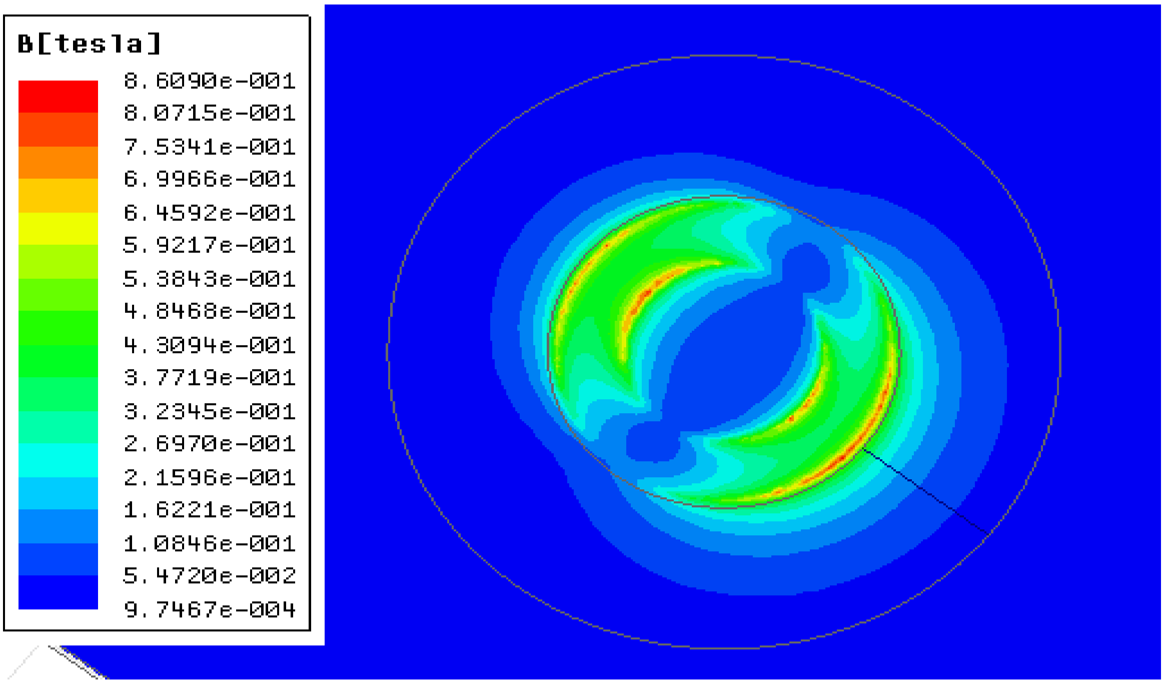

Figure 4.4 Magnetic field distribution in the permanent magnet actuator where the magnetization direction of the magnet is in the x direction (top view)

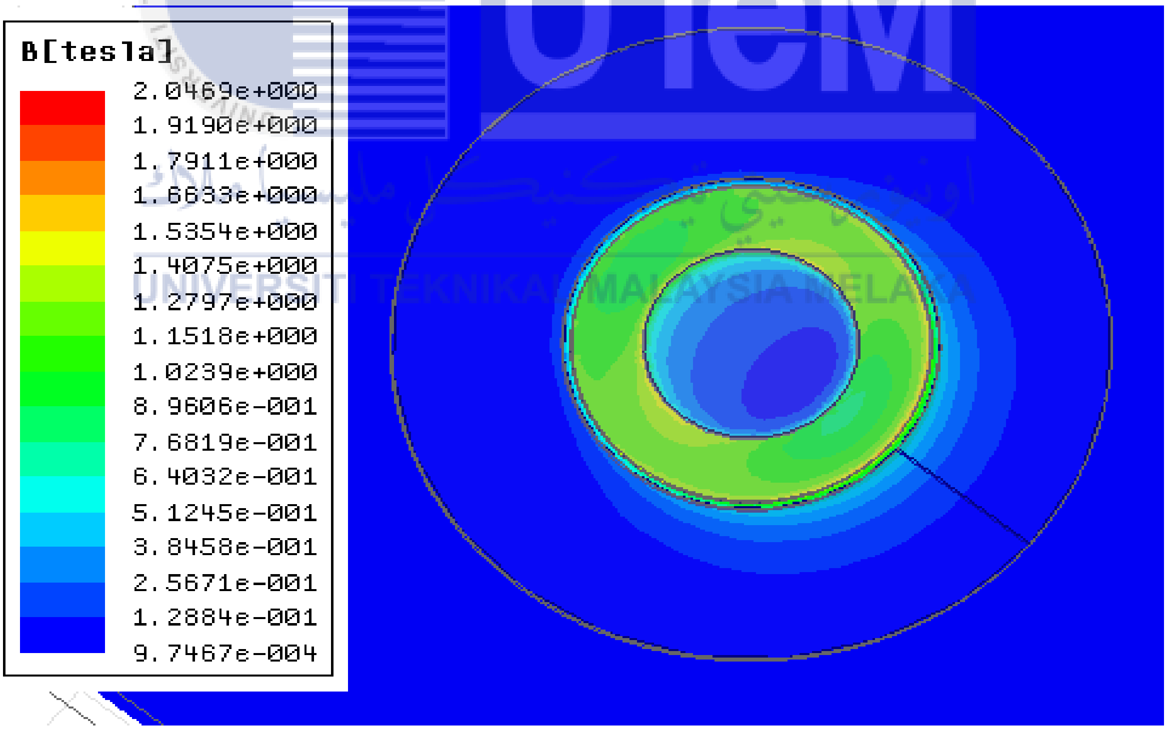

Figure 4.5 Magnetic field distribution in the permanent magnet actuator where the magnetization direction of the magnet is in the z direction (top view)

4.2 Thrust Analysis

4.2.1 First Design (Tubular Linear Reluctance Actuator with Step Windings)

In this section the thrust force for Tubular Linear Reluctance Actuator with step windings is analyzed in both positive and negative directions.

4.2.1.1 Positive direction

The movement is in the positive direction ranging from 0 to 90 mm as shown in figure 4.6. The mover or plunger is moving into the center position where the thrust ends.

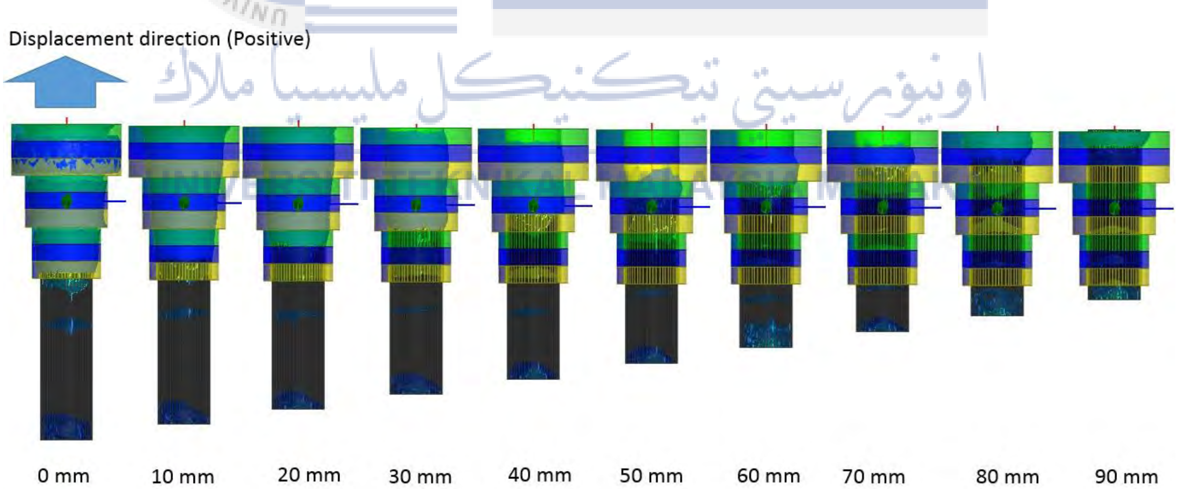

Figure 4.6 0 to 90 mm displacement of step windings actuator

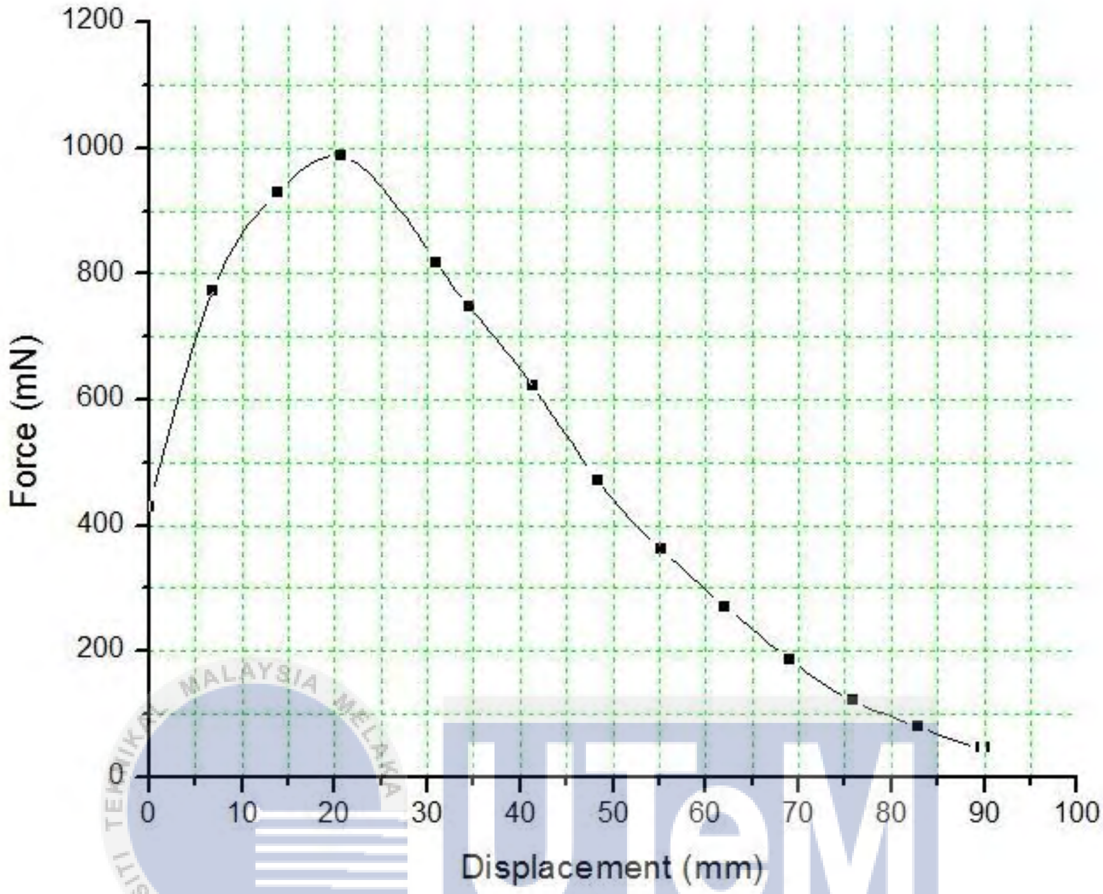

Figure 4.7: Force vs 0-90 mm displacement of step windings actuator (positive direction)

Figure 4.7 shows the displacement of the plunger along 90 mm (the length of the actuator). It is clearly noticeable that as the plunger get closer to the center position of the coil the force acting on it increases due to the change of the reluctance inside the actuator. At the end of the stroke which is 90 mm there is nearly zero force acting on the plunger. The highest force generated in the actuator is at 5-30 mm displacement where the difference in inductance is at its maximum as the inductance at the beginning of the stroke is the combination of the three steps' difference and the lowest force is at 90 mm where the difference in inductance is almost zero. The longest stroke with considerable force obtained by this actuator is 70 mm. This proves the function of the steps which is to get the maximum stroke with the highest possible force.

4.2.1.2 Negative direction

On the other hand, when reversing the direction of displacement to negative direction the mover does not displace as there is no enough force to move it and the reluctance is maximum at the center which hold the mover. This proves the theory stated in literature review which claim that the actuator only pulls but never pushes. Figure 4.8 shows the force vs the displacement in the negative direction, no displacement occurs.

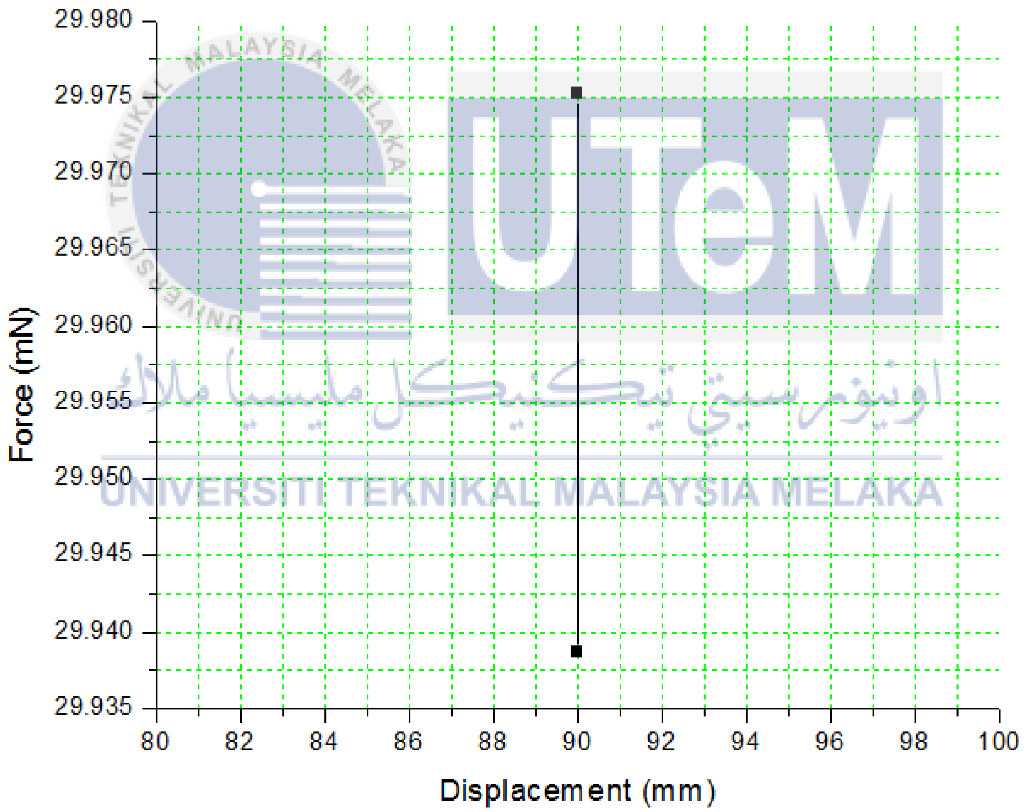

Figure 4.8 Displacement of step windings actuator (negative direction)

4.2.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

In this section the thrust force for Tubular Linear Permanent Magnet with Halbach Array Actuator is analyzed in both positive and negative directions.

4.2.2.1 Positive direction

The movement is in the positive direction ranging from zero to 90 mm as shown in figure 4.9. As indicated in the figure the mover or plunger is moving out from center position up until reaches the full thrust at 90 mm.

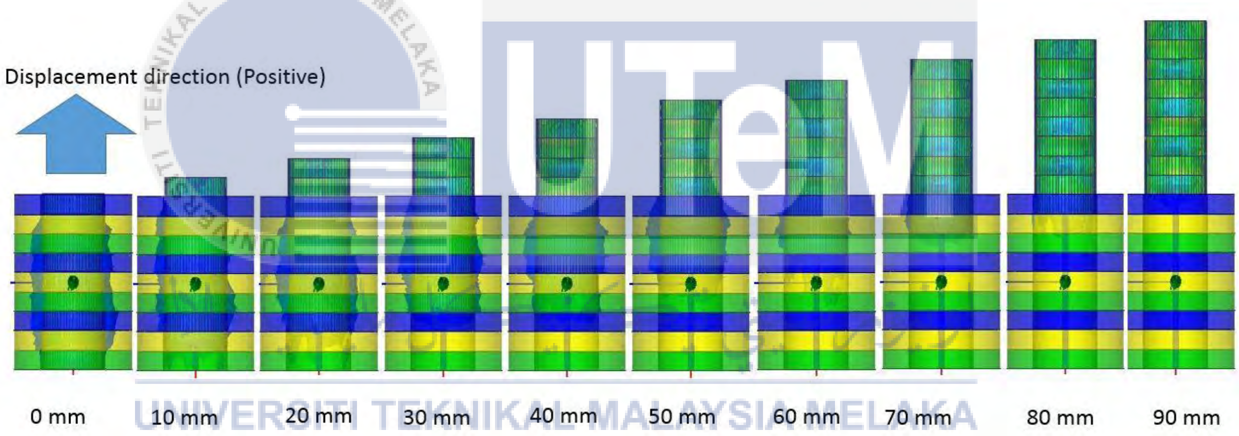

Figure 4.9: Displacement from 0 to 90 mm of permanent magnet actuator (positive direction)

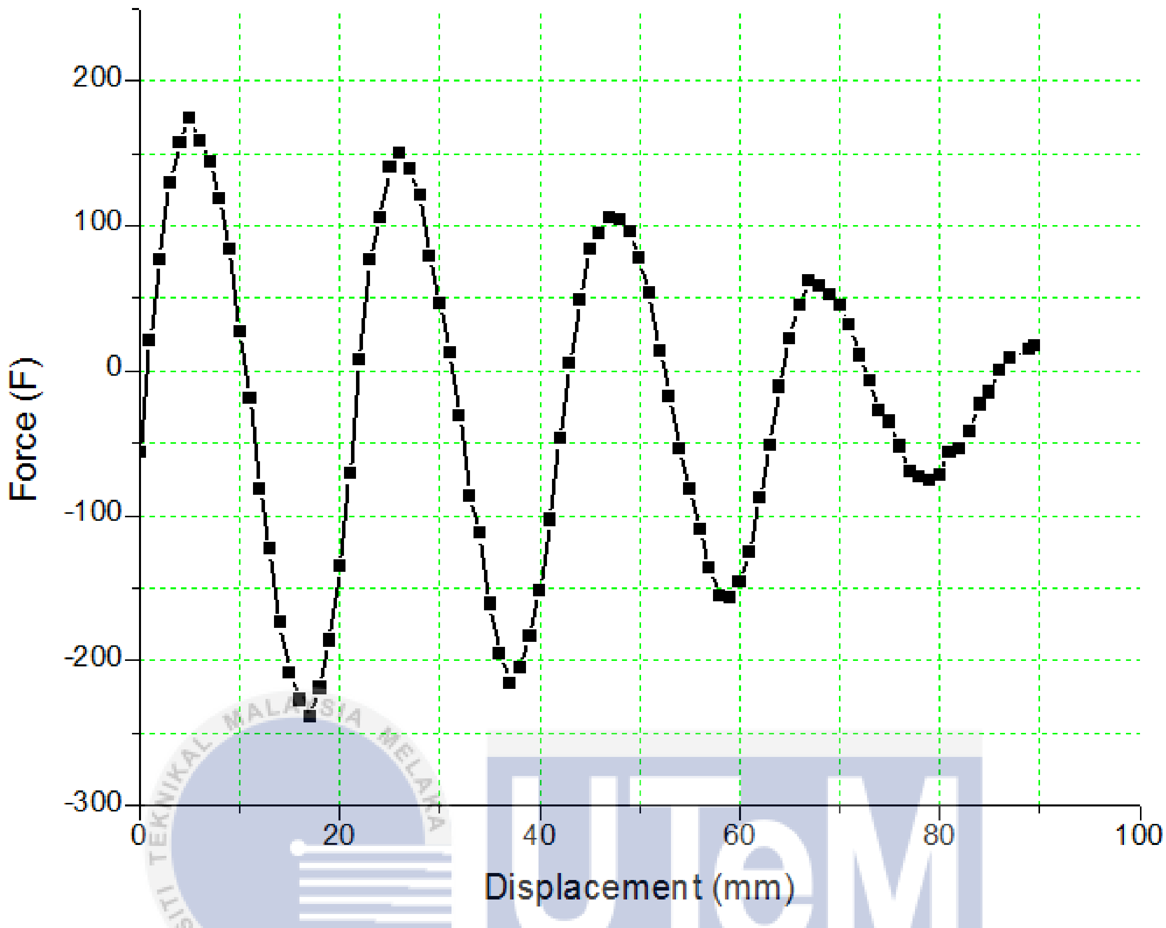

Figure 4.10 Force (N) vs displacement 0-90 mm for permanent magnet actuator

As can be seen from figure 4.10 the force of this design is a sinusoidal like which means it's a short stroke high force actuator. The actuator perform complete sinusoidal wave at 20 mm which is equal to the height of two magnet and keep repeating the same pattern with the thrust force decreasing as the mover is displaced from the center of the actuator. The force is maximum in the positive direction at 0.5h, 2.5h, and 4.5h where h is the height of one magnet. On the other hand, the force is maximum in the negative direction at 1.5h, 3.5h, and 5.5h. The design exhibit controllable high force servo characteristics needed by vast variety of applications where precision, high force and short stroke is required.

Negative direction

The movement is in the positive direction ranging from negative 90 mm to 0.0 mm shown in figure 4.11. As indicated in the figure the mover or plunger is moving in toward the center position until reaches the full thrust at 0.0 mm.

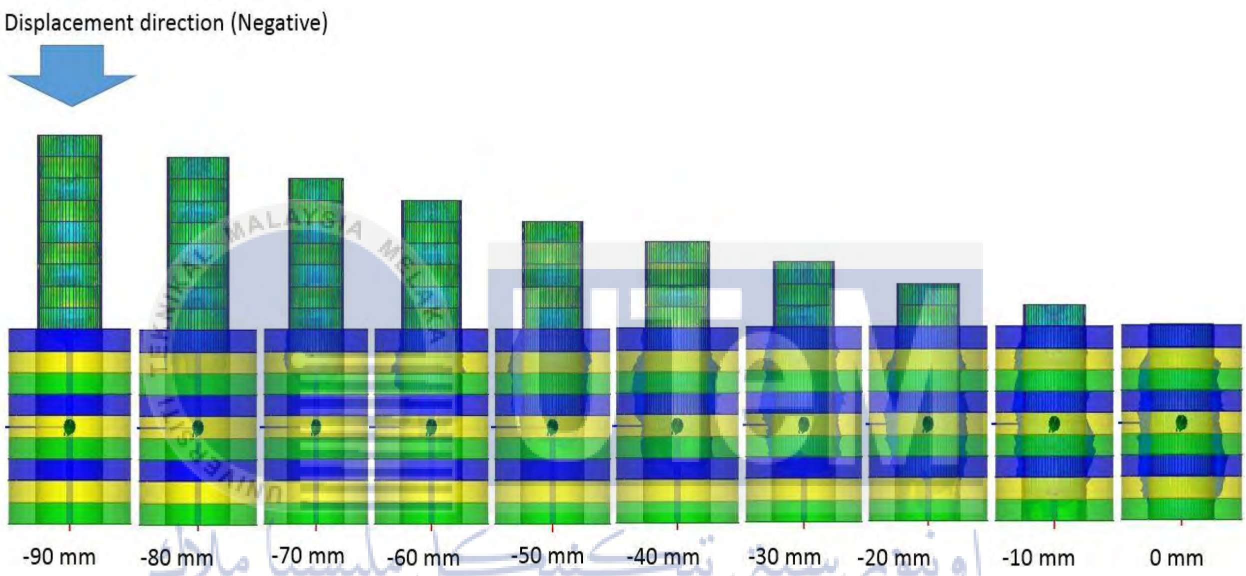

Figure 4.11 Displacement from 90 to 0 mm of permanent magnet actuator (negative direction)

As indicated in figure 4.12 when changing the stroke direction where the mover starts from -90 mm the length of the actuator the force characteristics are the same as positive direction except that the force wave is increasing as the mover displaces to the center of the actuator.

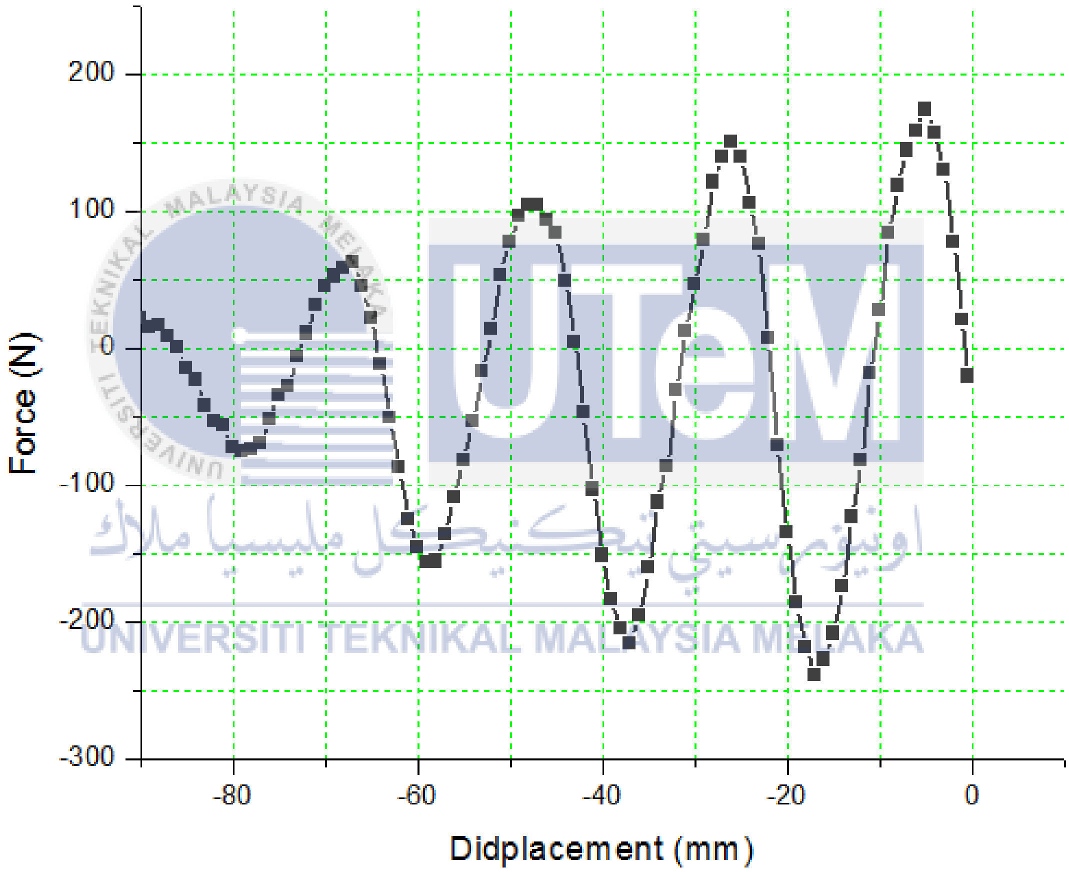

Figure 4.12 : Force vs displacement -90-0 mm for permanent magnet actuator

4.3 Parameters Variations

Three parameters are varied in both designs air gap, number of turns and size scale. One parameter is varied at a time while keeping the other two constant.

4.3.1 Air Gap Variation

4.3.2 First Design (Tubular Linear Reluctance Actuator with Step Windings)

The air gap is varied from 0.5 mm to 1.5 mm with 0.2 interval. Figure 4.13 show the air gap varied in the real design.

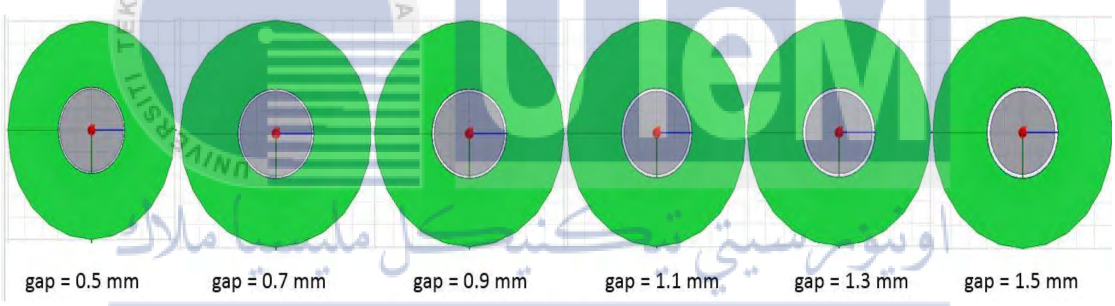

Figure 4.13 : Air gap variation in real design

Figure 4.14 shows the force for six different air gaps between the stator and mover as the current increase from zero to 20 A. The thrust reaches 55 N in the design with 0.5 mm while it reaches only 45 N in the design where the air gap is 1.5 mm. This is due to the magnetic field gets weak as distance between the coil and the steel mover gets higher. The force steps down great number in the first three designs where the air gap is still small, but after that only slight decrement in the induced force. According to the results of the six variation it can be concluded that the force decreases as the air gap between the stator and mover gets larger. However the air gap cannot be less than 1 mm due to mechanical limitations.

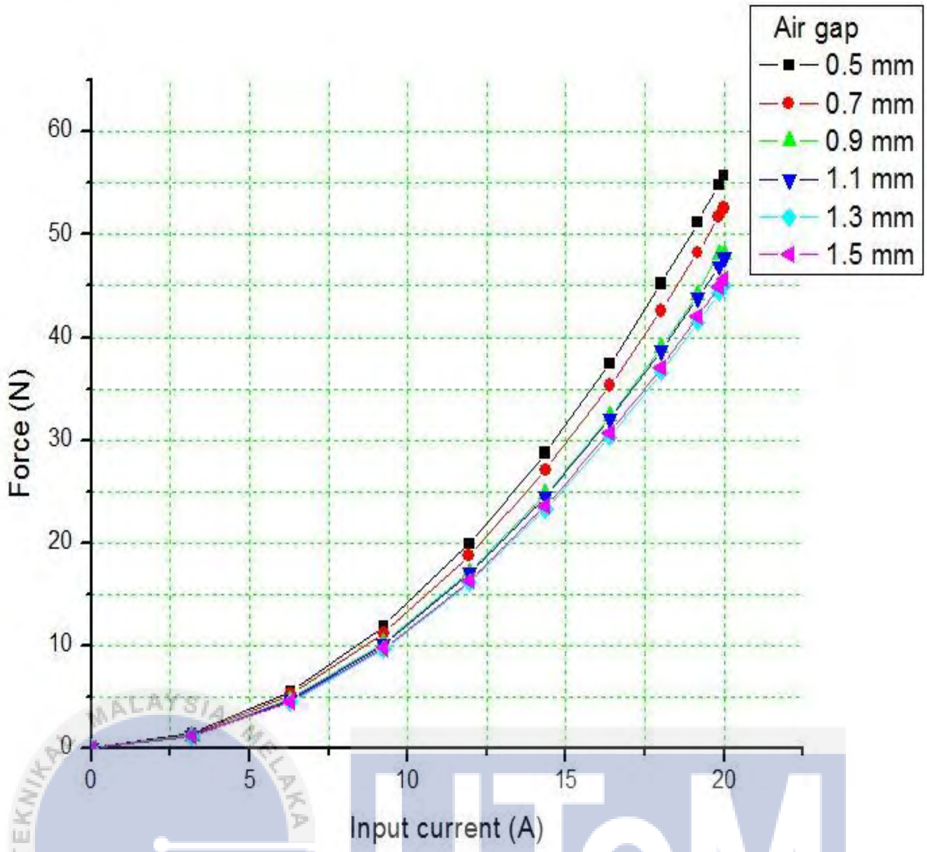

Figure 4.14 : Force vs input current for six different air gaps

4.3.3 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

In this design the air gap is varied two times one time for small gap from 0.5 mm to 1.5 mm shown in figure 4.15 and the other time comparing the original 0.5 mm with two high values 2 and 2.5 mm shown in figure 4.16.

4.3.3.1 Small Air Gap

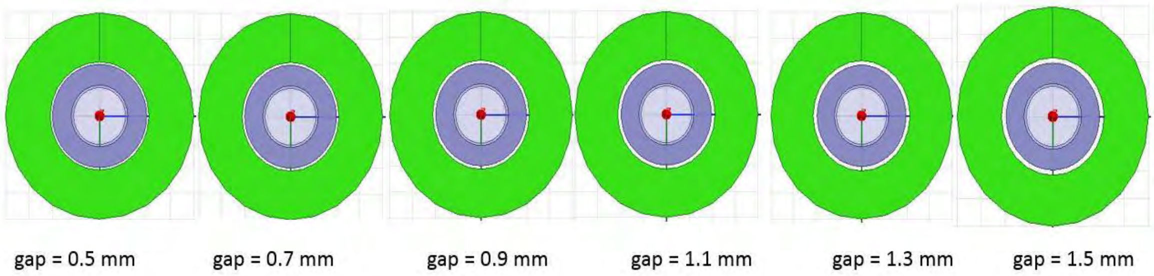

Figure 4.15 Air gap variation in real design 0.5 to 1.5 mm

The resulting force for six different air gap in Tubular Linear Permanent Magnet with Halbach Array Actuator are showed in figure 4.16. The graph shows almost the same produced force in response to the applied current from 0 to 20 A but with different starting force caused by magnets for example the resulting force for 0.5 mm is 24 N starting from -1 N at 0 A and ends with 23 N at 20 A and for 1.5 mm it is 23 N started with 62 N at 0 A and ends with 85 N at 20 A.

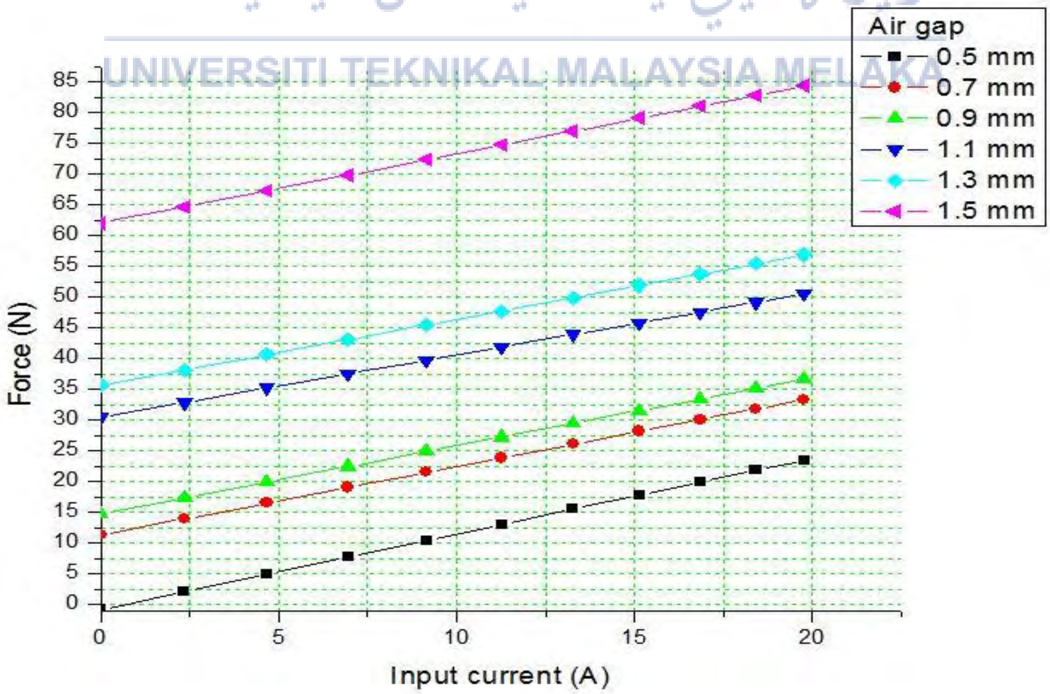

Figure 4.16 : Force vs input current for six different air gaps

4.3.3.2 Large Air Gap

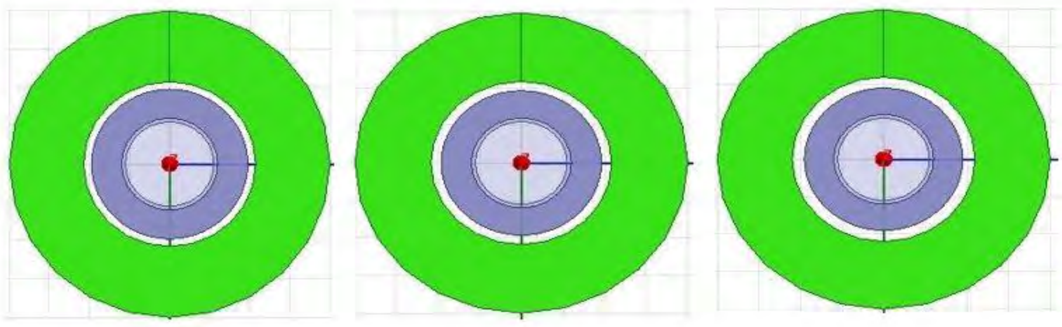

Figure 4.17 Air gap variation in real design 0.5, 2 and 2.5 mm

The graph in figure 4.18 shows the resulting force VS applied current for three different air gaps. The original gap for the design is 0.5 mm and two large values for air gap 2 mm and 2.5 mm. The result indicates that when the gap reaches 2 mm and get higher the produced force in response to applied current starts to decrease greatly. The force produced with 0.5 mm is 24 N but its only around 6 N and also when the gap gets 2 mm and higher the starting force caused by magnets starts to decrease in the positive direction and increase in the negative direction .

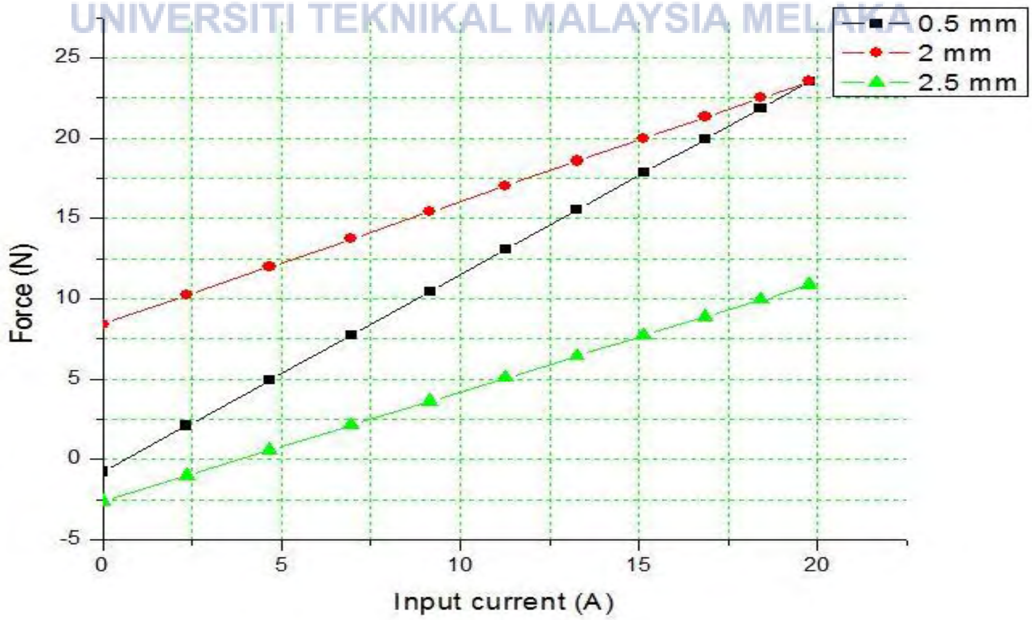

Figure 4.18 : Force vs input current for three different air gaps

4.4 Number of Turn's Variation

4.4.1 First Design (Tubular Linear Reluctance Actuator with Step Windings)

Each of the three steps of the Tubular Linear Reluctance Actuator with step windings has different number of turns and when varying the number of turns all three steps are changed for every variation. At every variation a set of three different number of turns are applied. The sets values and the design with the applied variation are shown in figure 4.19.

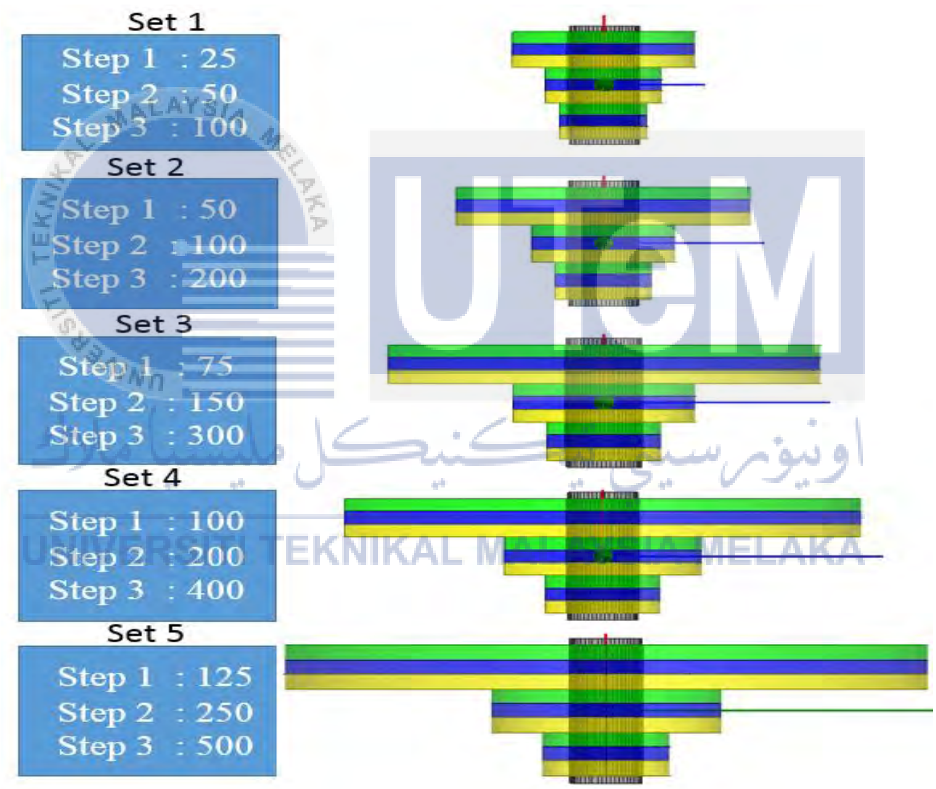

Figure 4.19 : Five different sets of turns applied to the design

As the number of turns increases the force increase, this is what can be concluded from the graph in figure 4.20 where the five sets of number of turns are applied to the design. The graph shows the force by the five sets as the current is varied from 0 to 20 A .In the first design with the set number one which is the smallest is applied, the force produced is 75 N at its maximum when the input current is 20 A .The increment of force between the first three sets is small 50 to 100 N but when applying set 4 and 5 the increment starts to get high reaching 175 N between set three and set four and 325 N between set 4 and 5.

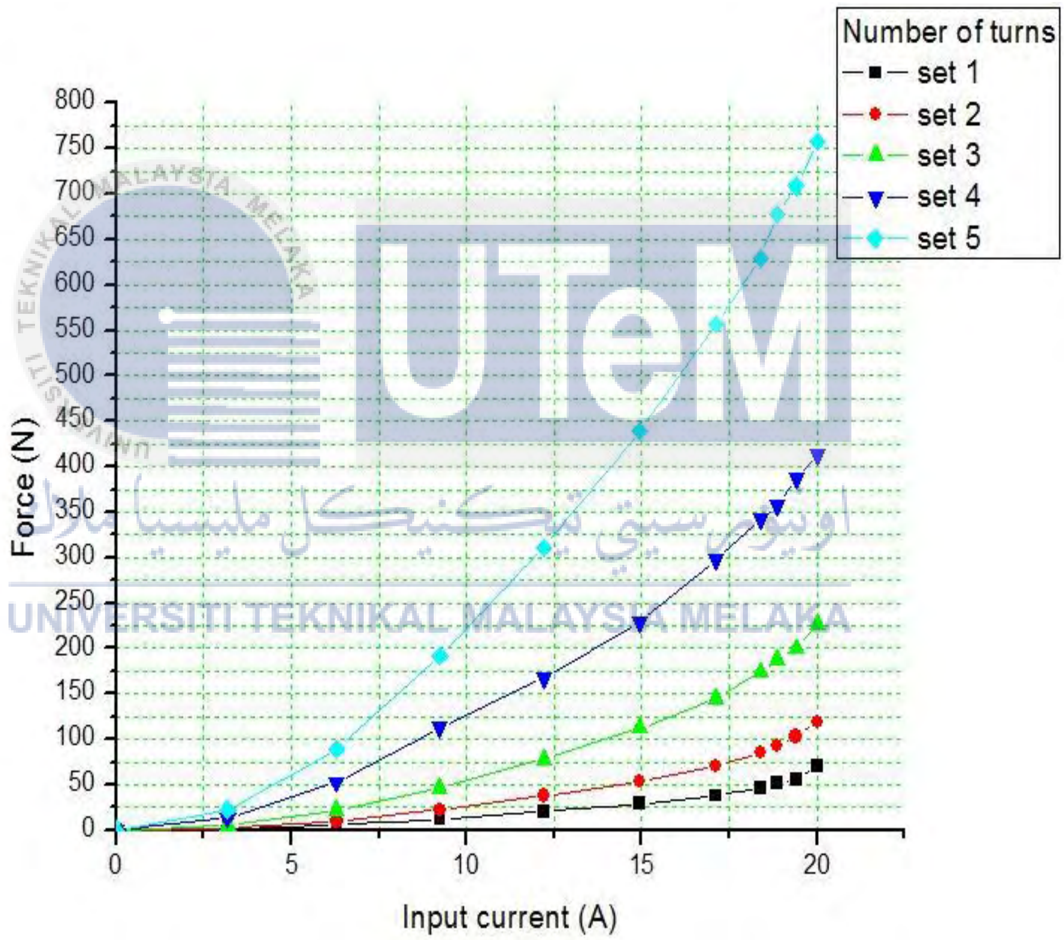

Figure 4.20 : Force vs input current for five different sets of number of turns

4.4.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

The number of turns of coil is varied in this section to show how the produced force response to the variation. Figure 4.21 shows Tubular Linear Permanent Magnet with Halbach Array Actuator design with 5 different number of turns from 100 to 500 turns with 100 turn's interval.

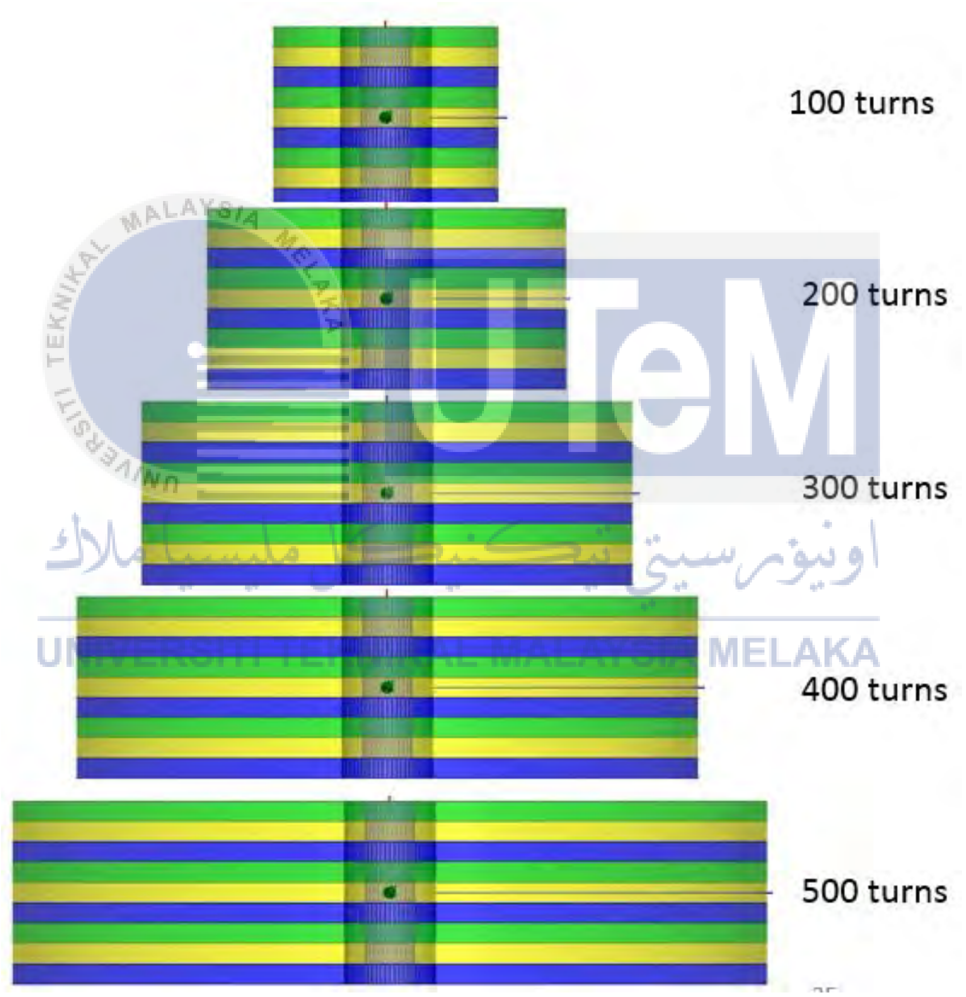

Figure 4.21 : Five different number of turns applied to the design

Figure 4.22 shows clearly that as the number of turns increases the produced force increases. The force produced by the 100 turns is 43 N and starts to increase regularly as the number of turns increase until it reaches 134 N for 500 turns. The starting force caused by magnets is the same as the size of the magnets is not changed.

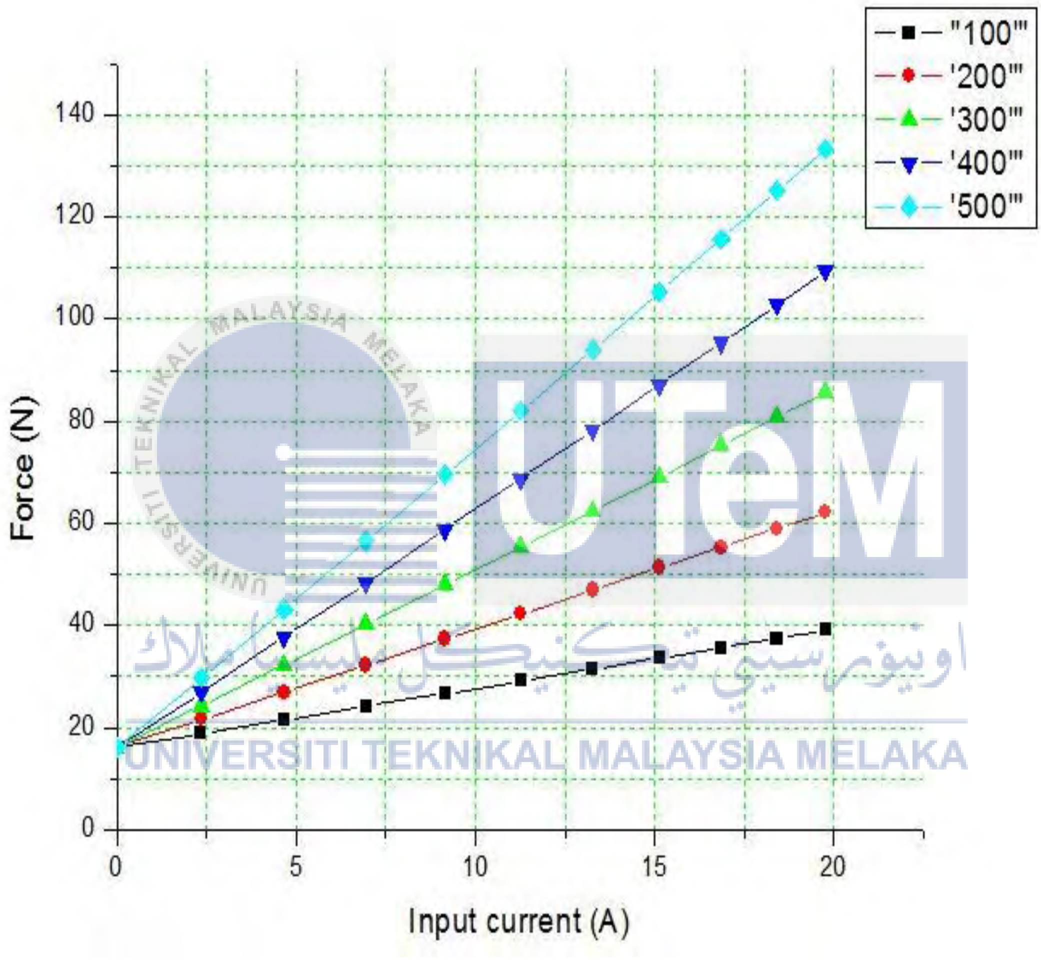

Figure 4.22: Force vs input current for five different number of turns

4.5 Size Scale Variation

4.5.1 First Design (Tubular Linear Reluctance Actuator with Step Windings)

Six different sizes are analyzed, the original size and 20, 40, 60, 80 and 100% larger than the original. Figure 4.23 shows the six different sizes. When scaling the actuator the whole size is scaled which means that both stator and rotor are scaled.

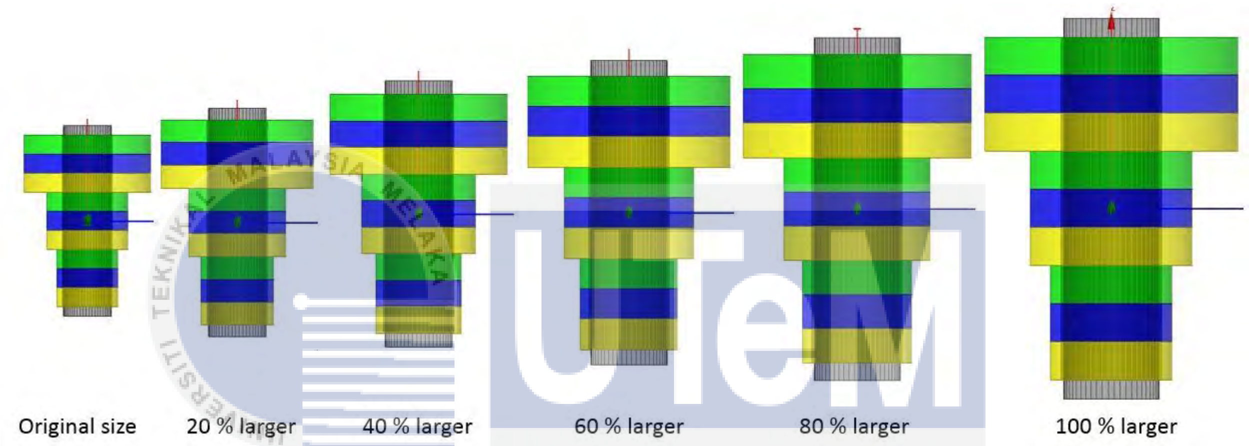

Figure 4.23 : Six different sizes of the design

Scaling the size design in order to explore the difference in the induced force when varying the plunger and the stator at the same time. The graph in figure 4.24 shows the induced force acting on the plunger for the six different sizes vs different values for the input current ranging from zero to 20 A. The graph shows that the forces for original and 20 % larger are almost the same and small change between 40% and 60% .Smaller change between the same and 80% and 100%. As a conclusion, as the size increased the force induced but a significant note is that original , 40 % and 80% are far better choices that can save cost and produce high forces because of the small difference between the output force of 40 % and 60 %. The same goes for 80 % and 100% .

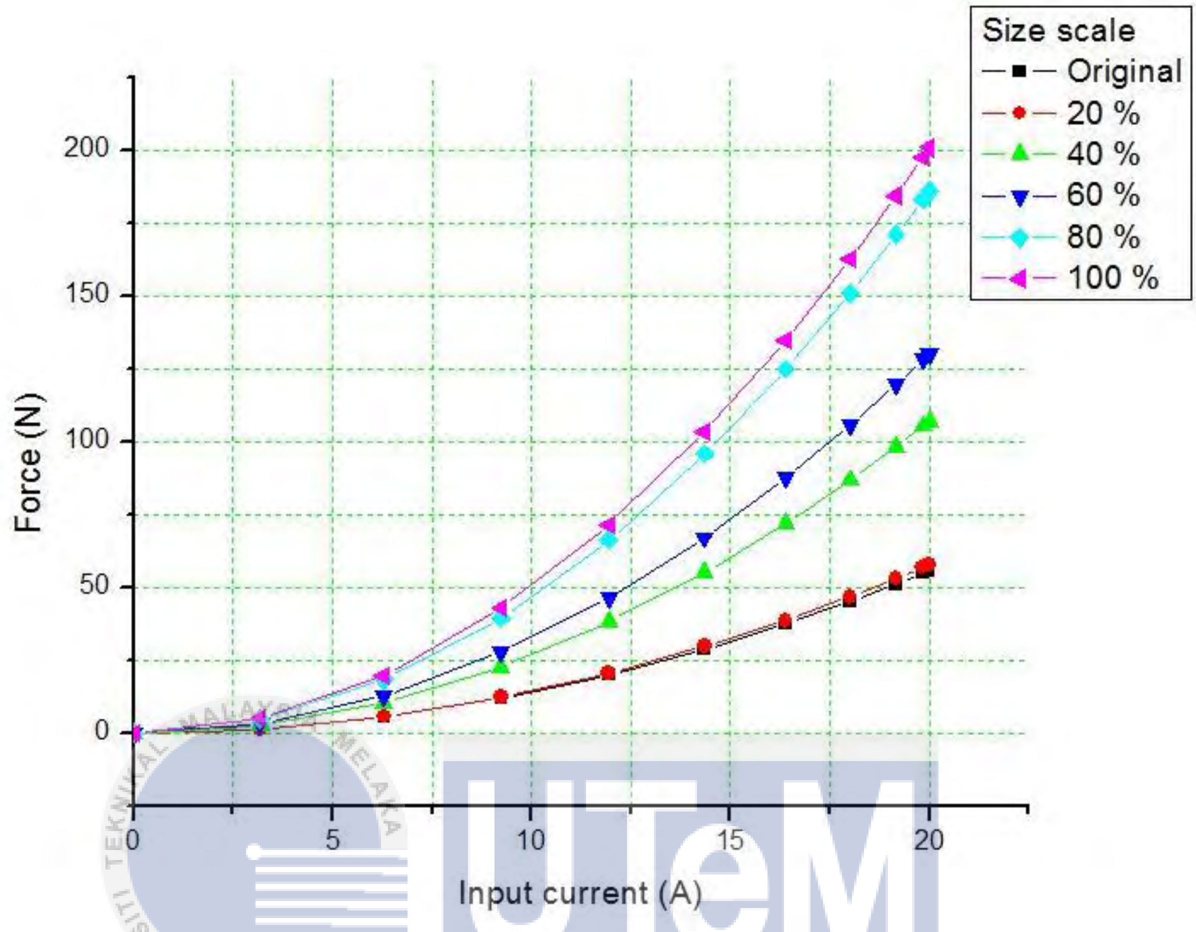

Figure 4.24 Force vs displacement for six different sizes of the design

4.5.2 Second design (Tubular Linear Permanent Magnet with Halbach Array Actuator)

In this section the force of different sizes of Tubular Linear Permanent Magnet with Halbach Array Actuator are analyzed and the produced forces are obtained. Figure 4.25 shows the design in different sizes starting from the original size and increasing the size by 20 % at a time until the size is doubled at 100 % increment.

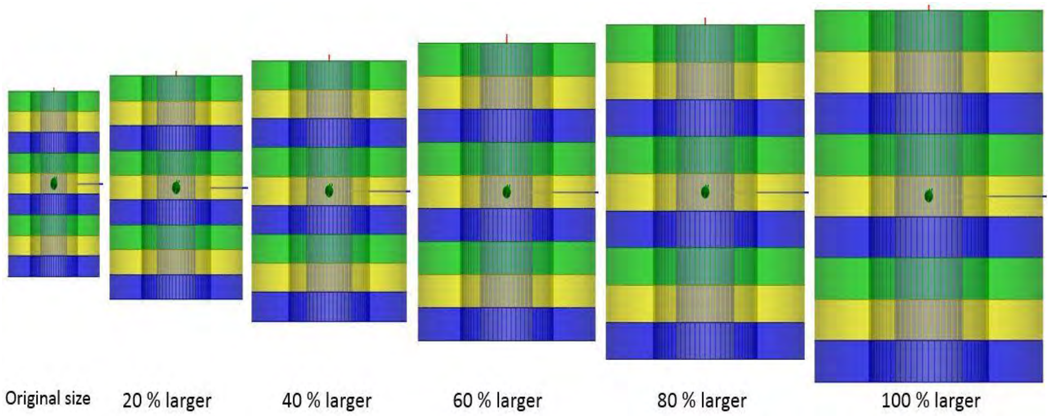

Figure 4.25 Six different sizes of the design

The results of produced force vs input current for six different sizes of the actuator are presented in figure 4.26.The results indicates great difference in resulting force as the size varied. The force increases as the size increase but the best size would be 100 % larger than the original as it shows large output force difference than the 80 %.

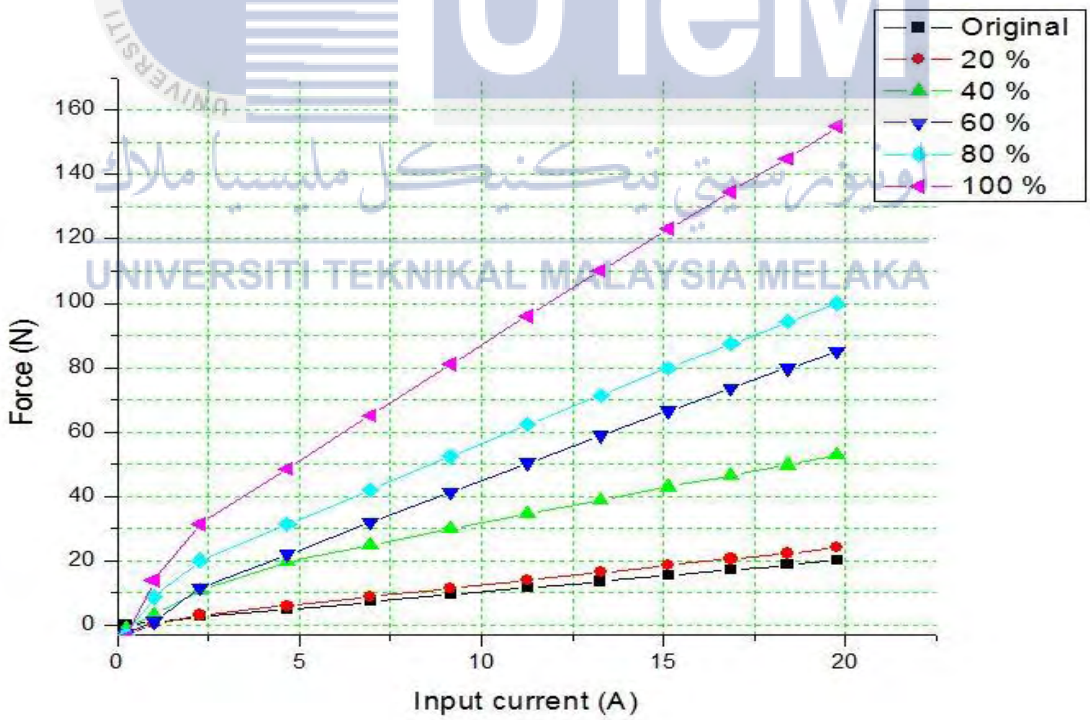

Figure 4.26 : Force vs displacement for six different sizes of the design

4.6 Comparison between the Two Designs

4.6.1 Thrust

Table 4-1 Charactristics comparision between the two designs

Characteristic	**First design (Reluctance Actuator)**	**Second design (Permanent Magnet Actuator)**
Maximum Force (N)	1	185
Stroke (mm)	70	20
Displacement Direction	Positive	Positive and negative
Starting Force (N)	0.4	-50

4.6.2 Parameters Variation

Table 4-2 Comparison of parameters variations between the two designs

Parameter	**First design (Reluctance Actuator)**	**Second design (Permanent Magnet Actuator)**
Air gap	The larger the air gap the smaller the force	Small gap difference does not affect the produced force but effects the starting force. Larger air gap (2 mm and higher) the produced force decreases as well as the starting force.
Number of turns	The higher number of turns the higher the force	The higher number of turns the higher the force
Size scale	The larger the size the higher the force	The larger the size the higher the force

CHAPTER 5

5 CONCLUSION & RECOMMINDATION FOR FUTURE WORK

5.1 CONCLUSION

In this report Tubular Linear Reluctance Actuator with step windings and Tubular Linear Permanent Magnet with Halbach Array Actuator were designed and the Maxwell FEM analysis is used to confirm the validity of the designs. The magnetic field distribution, thrust, displacement and effects of the air gap, number of turns and size scaling were analyzed and the data for all results were successfully obtained. The step winding structure for the reluctance actuator significantly improves the reluctance actuator performance and generates more force and longer stroke. Nevertheless this design still suffer two disadvantages; high current is needed in order to generate high force and also high air gap value is needed due to the mechanical limitations of air gap which would results in slight decrement in the force. The permanent magnet actuator exhibit high force due to the use of magnet and the Halbach array arrangement of magnets but still produce short stroke. However, the Maxwell FEM analysis proves that the Permanent magnet actuator produces more force than reluctance actuator but with much smaller stroke, and hence Permanent magnet actuator is preferred in applications where high force ,low voltage and short stroke is required whereas reluctance actuator is preferred where high voltage is available and long stroke is required.

5.2 RECOMMINDATION FOR FUTURE WORK

More studies for both designs are recommended to overcome the low force for reluctance actuator and short stroke for permanent magnet actuator as overcoming these disadvantages can lead to an evolution in transmission technology especially industrial section.

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APPENDIX

Gantt chart