DESIGN AND MODELING OF A SHORT-STROKE LINEAR PERMANENT MAGNET MOTOR

By

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FINAL PROJECT REPORT

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CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

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

(NOR HAZIANA BINTI ISAHAK)

ABSTRACT

The thesis concentrates on design and modeling a short-stroke linear permanent magnet motor using finite element analysis. Various types of linear machines technologies have been review such as, linear induction motor, linear synchronous motor, linear switched reluctance motor, linear DC motor and linear permanent magnet brushless motor. The advantages of linear permanent magnet motor which are, there is no field winding required for the motor since the permanent magnet will produce the excitation flux for the motor. Even though it has higher cogging torque but it also has higher output power. In other aspect, the permanent magnet motor believe would give better dynamic performance due to the higher magnetic flux density in the air-gap. Four proposed design have been developed for further analysis; the single slot linear permanent magnet motor with air-cored and iron-cored also the double slot linear permanent magnet motor with air-cored and iron-cored. The design is relatively to improve efficiency of the compressor system for refrigerator pump, which basically have very low efficiency. The proposed design undergoes the optimization process with optimizing the dimension of the motor that give influences to the motor performance.

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First and foremost, highest thanks to The Almighty, the source of my life, wisdom and hope for giving me the strength and patience to pursue and complete this final year project.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The research is to design and modeling of a short-stroke linear permanent magnet motor for air-vapor compressor system. These linear motors are increasingly popular solutions for today automation applications.

The studies show, our energy consumption nowadays very high and its rates become greater. Electrical power consumption of refrigeration load is most related to the higher energy consumption based on their efficiency of the compressor system. This compressor system has a very low efficiency due to the single phase rotary motor used inside the compressor. Design and modeling a short-stroke linear motor using permanent magnet material, believed could improve the efficiency of the compressor, thus reducing the power consumption.

Figure 1 highlights the compressor in the refrigeration cycle, as compressing the refrigerant gas, the compressor raises its temperature. The condenser dissipates the heat and the gas condenses before flowing through an expansion valve. This reduces the pressure and the refrigerant expands and evaporates. Finally, the evaporating refrigerant absorbs the heat from inside the refrigerator.

Figure 2 denotes the conventional refrigerator compressor comprises a rotary electric motor; single phase induction motor which drives a reciprocating pump through crank.

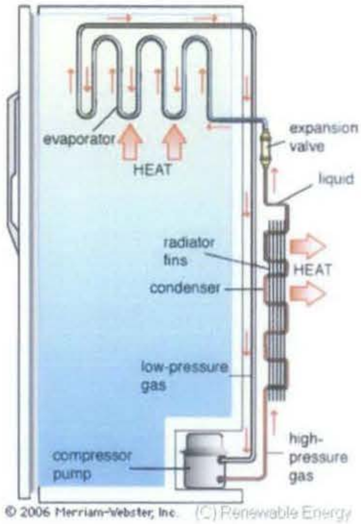

Figure 1 Refrigerator system.

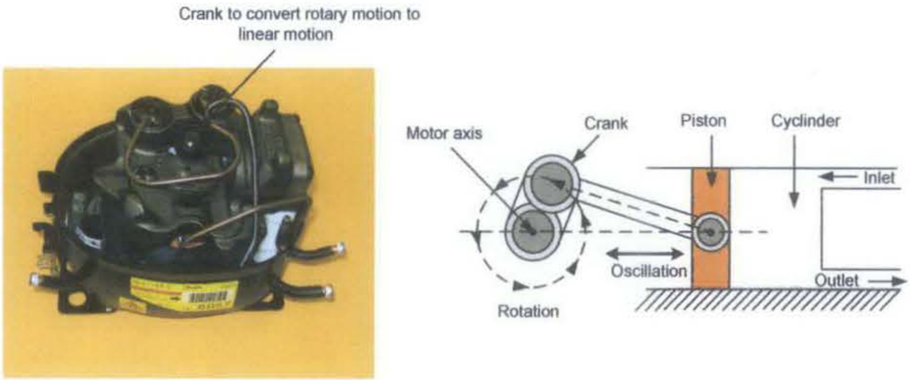

Figure 2 Schematic of conventional compressor [1].

The overall efficiency of the conventional compressor is relatively low due to the inherently low efficiency of induction motors and the mechanical friction of the crank-driven piston movement, and the overall efficiency is around 60% [1].

The application of linear motor arises due to the advantages or the motor compared to more traditional mechanical system of motor. Which is, more significantly improved throughput, system accuracy and system life. Linear motors directly develop an electromagnetic force, called thrust, along the direction of the travelling field motion in the air gap [2].

The linear motor works under the process as does its counterpart the rotary motor [3]. By an imaginary process, this device can be transformed into a linear motor is the stator is cut open and unrolled [3]. Also a conducting sheet of plate replaces the rotor. The flat plate rotor is referred to as the secondary and the unrolled stator is the primary [3].

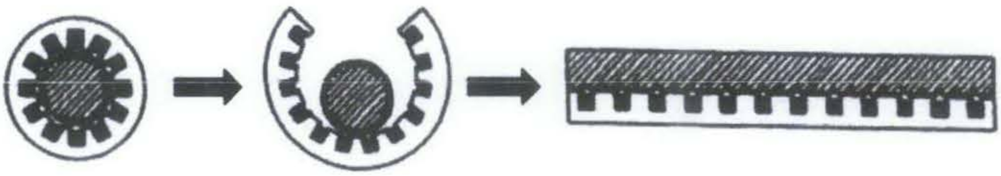

Figure 3 Imaginary process of unrolling a conventional motor to obtain a linear induction motor [3].

The study or linear motor shows that linear motor will give an important influence on the operation of a direct-drive reciprocating compressor. As the linear machines would produces a thrust force directly to a load. With all doubly-excited electromagnetic machines, the thrust force is developed when a straight current carrying conductor is placed in a magnetic field, the direction of the force was determined by Fleming's Left-hand rule.

Figure 4 denotes the schematic of a direct-drive linear compressor, the elimination of friction loss due to the crank and facilitating continuous by variable cooling capacity, by varying the supply current and the frequency [1]. A small stroke will compromise the volumetric efficiency [1].

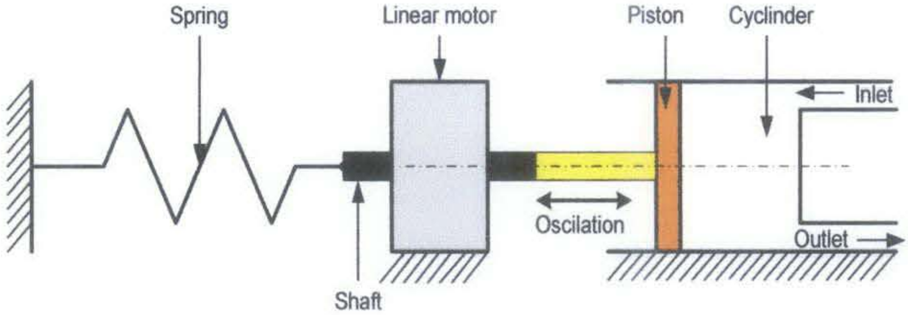

Figure 4 Schematic of direct-drive linear compressor [1].

1.2 Problem Statement

The increasingly of the energy consumptions in most of countries beyond the years, become one of the factors for our global warming. These energy consumptions are the overcome from our daily routine of using electricity, which is at home and facilities. Refrigeration loads is the best example for the most energy consumption used, where this load needs more energy as to achieve the better performance. While the performance also related to their efficiency of compressor system. The conventional refrigerator system comprise of single phase induction motor result with very low efficiency. The low efficiency will result with higher energy consumption. Thus, the measured improving these compressors are really desirable and demanded.

Most of the refrigerators nowadays employ simple on-off refrigeration system with the on-off duty cycle of a fixed-speed compressor determined by the refrigerator temperature setting and load. The variable-speed compressor are available to enable varies refrigerant gas flow rate, continuously as to meet the cooling requirement and the efficiency improved to ~85% [1]. To have the low speed operation is not possible as the piston of lubricant problem also the variable speed will result in increasing manufacturing cost, as the product sector is very cost-sensitive, the commercial take-up of variable cooling capacity refrigerator has been poor [1].

1.3 Objective and Scope of Study

1.3.1 Objectives

The aim of project is to design and modeling of a short-stroke linear permanent magnet motor for air-vapor compressor system. The specific objectives are:

- To identify the most promising design topologies of linear reciprocating motor in terms of their strokes, mass, efficiency and cost.
- To establish the analysis and design optimization of the appropriate linear reciprocating motors and to validate the results by the finite element analysis.
- To undertake design optimization, using finite element analysis.

1.3.2 Scope of Study

The project covers on, designing and modeling short-stroke linear permanent magnet motor. The scope relates more on the studies of linear machine technology, air-vapor compressor for the refrigeration application and the permanent magnet motor. Also the application of the Fleming left hand rule's over the design of the motor.

Studies on various type of linear machine would result in better understanding and in the effective design. The linear machine introduce as the counter part of the rotary motor with the stator is cut open and unrolled as the used of flat plate conduction rotor. There were five type of linear machine was taking count for the design.

Using finite element analysis for the design optimization required better understanding on the design concept with the first parameter to be indentified is the air-gap flux distribution produce by the motor that would result for performance of the motor.

Thus, optimization for the proposed design will cover the main dimension parameter that give influence to motor performance and this optimization also are performed to identify the proposed design with higher efficiency. The design with higher efficiency is choose to be the most suitable design for a short-stroke linear permanent magnet motor for air-vapor compressor.

CHAPTER 2

LITERATURE REVIEW

2.1 Theory

A study shows energy consumption has risen by around 30% in the last 25 years and the increasing rate become greater by year. Industrial countries consume about four times as much energy as developing countries [1]. The electrical power consumption of household refrigeration load is accounting approximately 20% of the total power consumption and is related to the efficiency of their compressor system [11][1]. Thus, cost effective measures for improving efficiency are highly desirable and demand on a global scale [1].

The conventional refrigerator compressor comprises a single-phase induction motor with rotary electric motor, which drives a reciprocating pump through a crank and the overall efficiency is relatively low [1].

Air- vapor compressor widely used for refrigeration application such air-conditioning of buildings, private residences, hotels, hospitals and theatres [4]. Mostly, this compressor mainly used in the industrial countries, and also used in domestic and commercial refrigerators, large scale ware houses for storage [4].

Oil refineries, petrochemical and chemical processing plant, and natural gas processing plants are among the many types of industrial plants that often utilize large vapor compressor refrigeration systems [4]. The high energy power consumption mostly affected from the industrial countries which consistently use the power energy. Including the air-vapor compressor for refrigeration application, which the efficiency of the system will effect the energy consumption [1][4].

Thus, the various studies and design was made over the years as to provide the most efficient motor for linear application. Design and modeling a short-stroke linear motor using permanent magnet material, is trusted could improve the efficiency of the compressor and reduced the energy consumption.

2.2 Type of linear motors

Over the years, many research being made and a lot of international papers and monographs have discussed with the topic of linear motors in a variety of applications. The risen of applications for linear motor had proved the advantages of the linear motor over the conventional mechanical motor. Essentially, there are five linear machine technologies which can be considered to taking count for linear compressor refrigerator systems design which,

2.2.1 Linear induction machines

Linear induction machines have been developed predominantly for producing continuous linear motion, especially for heavy duty applications such as transportation, conveyor systems and more recently; lift [2][1]. Generally, its require poly-phase power supply and a multi-phase primary winding in order to produce a travelling magnetic field and induced current in the secondary part[1]. However, the used of linear induction machine in low power reciprocating applications is very limited.

2.2.2 Linear synchronous machines

Linear synchronous machines with permanent magnet excitation have been employed widely in high performance systems, especially for long stroke applications [1]. The application is limited due to the relatively complexity of the stator winding and the power supply requirement [1]. The production of reciprocating motion also requires a reversal of the multi-phase voltage sequence or a power electronic inverter to facilitate speed reversal, whereby this position feedback is required to sense the end of the travel [1].

The complexity of the stator winding configuration and the multi-phase power supply makes the conventional topology of linear synchronous machine not suitable for low power reciprocating applications [1].

2.2.3 Linear switched reluctance machines

Linear switched reluctance machines are available in various commercial sectors and their design, optimization and control remain the subject of ongoing research [1]. Generally, the machine requires position feedback to synchronize the commutation of the phase currents with the relative position between the stator and mover teeth [1]. The switched reluctance machines are very robust and simple, but cheaper than other technologies.

The relatively poor operating characteristics in term of their force capability and efficiency, means that machines are generally inappropriate for low power with high efficiency reciprocating applications [1].

2.2.4 Linear DC machines

Linear DC machines are usually used for long stroke applications, with position feedback with applications such as robotics and positioning tables [1]. The advantages are, smooth, easy and accurate control of force and position [1]. Variants of brushed DC linear motors in which the armature consists of a helical winding on a cylindrical armature which is energized via brushes [1]. Thus, the motor are expensive to manufacture with brush and highly maintenance also relatively noisy operation.

2.2.5 Linear permanent magnet brushless machines

Linear permanent magnet machines offer certain advantages for reciprocating compressor applications. Which the machines are required to produce a high force capability and have high efficiency, also required a low power supply and easy to control [1]. No field winding required since permanent magnet produce excitation flux for the motor [1].

Generally, the permanent magnet linear motors can be classified into three categories;

- moving-coil
- moving-iron
- moving-magnet

Moving magnet topology has necessary high force capability per moving mass and essential to facilitate resonant operation at electrical supply frequency.

Table 1 Comparison of permanent magnet linear motors

Permanent magnet linear motors	Advantages	Disadvantages
Moving-coil	i. Stationary permanent magnet ii. Rare-earth magnet use to produce more thrust force	i. Flying leads ii. Low air-gap flux density iii. Difficulty in dissipating heat from coils iv. Limited access to moving coil v. Limited stroke and thrust force capability
Moving-iron	i. Simple design ii. Require to have unidirectional force capability iii. Use mechanical spring to reverse	i. Heavy moving mass reduce the dynamic capability of motor ii. Low thrust force capability due to low air-gap flux density
Moving-magnet	i. No flying leads ii. Reliable and rugged iii. High efficiency iv. Higher air-gap flux density v. Suitable for higher duty operation vi. Facilitate resonant operation	i. Copper loss ii. Eddy current loss

2.3 Permanent Magnet

Permanent magnet motor has some advantages, which is no energy is absorbed by the field excitation system. Thus, there are no excitation losses which mean substantial increase in the efficiency [5]. Have higher torque and output power per volume. Also permanent magnet motor gives, better dynamic performance than motor with electromagnetic excitation (higher magnetic flux density in the air gap) [5]. Permanent magnet motor will give simple of construction and maintenance, which eventually reduction of cost.

2.4 Quasi-Halbach magnetization

The quasi-Halbach magnetized armature generates a magnetic field which is linked with the single-phase stator coil. Reciprocating thrust force is produced as the result of the interaction between the permanent magnetic field and the stator current when it is synchronized with the armature movement [6]. The flux due to permanent magnet returns through the back-iron of the armature, and therefore the stationary back iron is not needed.

This will not only improves the thrust force capability of the motor, but also greatly reduces the eddy current loss due to stray magnetic field in the surrounding metallic structure [6]. A unique feature of the quasi-Halbach magnetization is that the axially magnetized magnets, essentially provide a return path for the radial air-gap flux, and hence, the flux in the inner bore of the magnets is relatively small [6][7]. As a result, the use of a very thin ferromagnetic tube or even a non-magnetic tube on which to mount the magnets will not significantly compromise the thrust force capability [6][7].

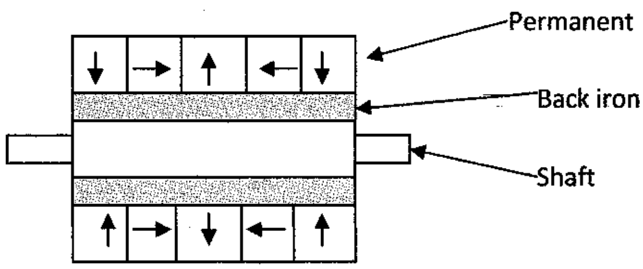

Figure 5 Armature for moving-magnet tubular permanent magnet motor with quasi-Halbach magnetization [1]

2.5 Slotted or Slotless motor

Slotted stator is more durable and reliable compare to slotless. A core having many slots is usually desirable, because the greater number of slots, the less the cogging torque and electromagnetic noise [8]. For the motor quality, ferromagnetic cores with odd number of slots are preferred due to low cogging torque [8]. Meanwhile, the slotted motor facing higher iron loss and also cogging torque in the winding.

Slotless motor is extremely having low cogging torque by producing the fixing the winding on a cylindrical steel core without any slots. The torque is exerted on the conductors uniformly distributed on the rotor surface [8]. The flux decrease in comparison with slotted rotor since the gap between the rotor core and the pole shoes is larger [8]. Large the volume of permanent magnet must be used to get sufficient magnetic flux.

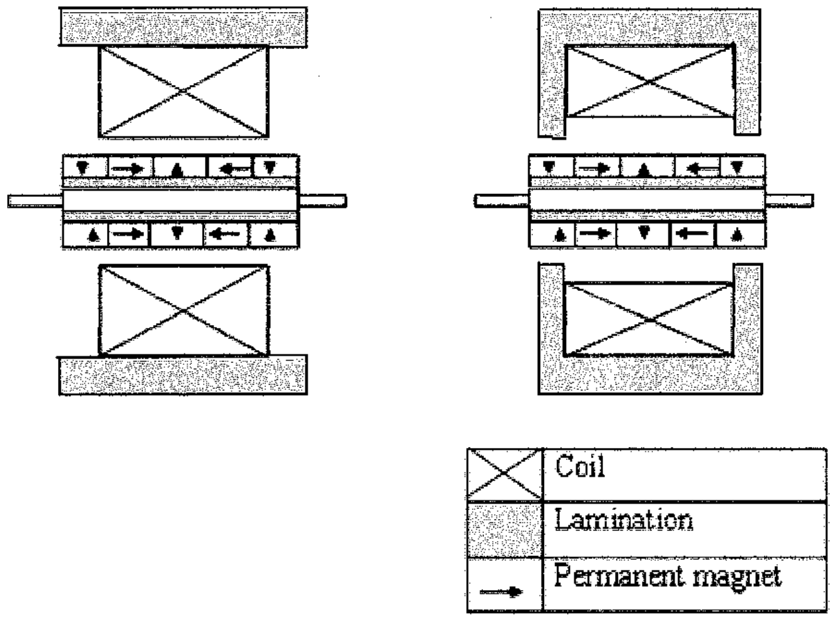

Figure 6 Slotless and Slotted moving-magnet linear motor with quasi-Halbach magnetization.

2.6 Cogging Torque

Cogging torque of electrical motors is the torque due to the interaction between the permanent magnets of the rotor and the stator slots of a permanent magnet machine [9]. It is also known as detent or no-current torque [9]. Cogging torque is an undesirable component for the operation of such a motor [9]. It is especially prominent at lower speeds, with the symptom of jerkiness [9].

There were several techniques could be taking consideration for reducing the cogging torque in designing the motor which [9],

- Odd number of stator coils and even number of magnets
- Skewing stator stack or magnets
- Using fractional slots per pole
- Modulating drive current waveform
- Optimizing the magnet pole arc or width

Almost all the techniques used against cogging torque have effect on reducing the motor back emf and also reduce the resultant running torque [9]. Meanwhile, slotless permanent magnet motor does not have any cogging torque [9].

2.7 Proposed design

The most important criteria for the evaluation of linear motors for air-vapor compressor applications are based on their force capability, simplicity and cost-effectiveness. From that, the most suitable for the compressor application was single-phase, moving-magnet tubular linear motor with a slotted stator manufactured from a soft magnetic composite is considered.

As the result, two design variants has been selected for further analysis, single-slotted and double slotted tubular moving-magnet linear motor with magnet configuration, iron cored and quasi-Halbach magnetized magnets having a trapezoidal cross-sectional .

Both designs will undergo the analysis using finite element software. These finite elements software used to design and optimized both single slot and double slot motor. The result will be verified as to compare which design would have better performance and become most promising motor design, for linear air-vapor compressor system under consideration. The design process involves evaluating the open-circuit flux distribution, the air-gap flux distribution and the output power for the designs.

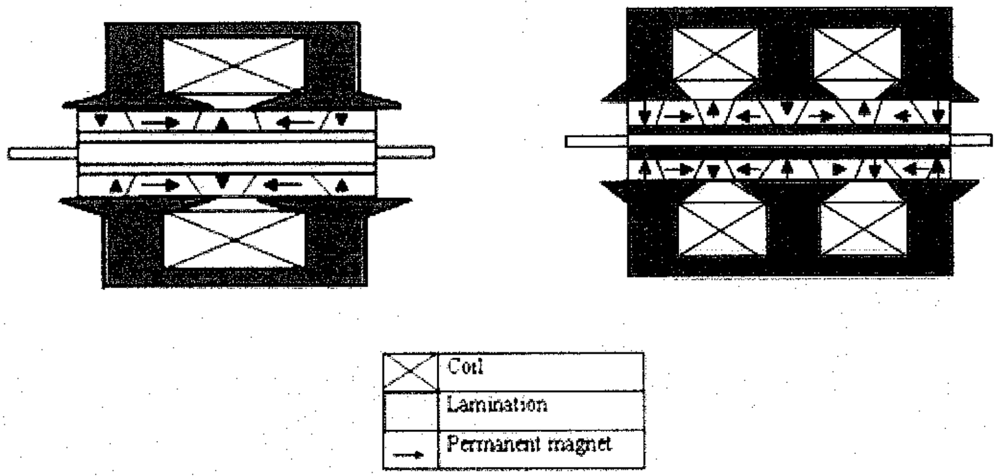

Figure 7 Single-slot and double-slot quasi-Halbach magnetized motor with trapezoidal magnets.

CHAPTER 3

METHODOLOGY

3.1 Procedure Identification

The whole project would start with the knowledge gathering and theoretical studies. Understand the literature review and feasibility study on the air vapor compressor and short-stroke linear permanent magnet motor. Then, the works start with designing the new topology based on the studies and information gather from the various researches. The design being evaluates by supervisor and finalized.

Analysis the final design practically or as prediction based on the Fleming's Left-hand rule and studies of various type linear motors. The modeling works start on the analysis using finite element software. The experiment continues for optimizing the short-stroke linear permanent magnet motor using finite element software.

Then analysis carried out to correlate the theoretical knowledge with practices. Meanwhile, further research and development would be continuously practiced to ensure satisfactory results are achieved.

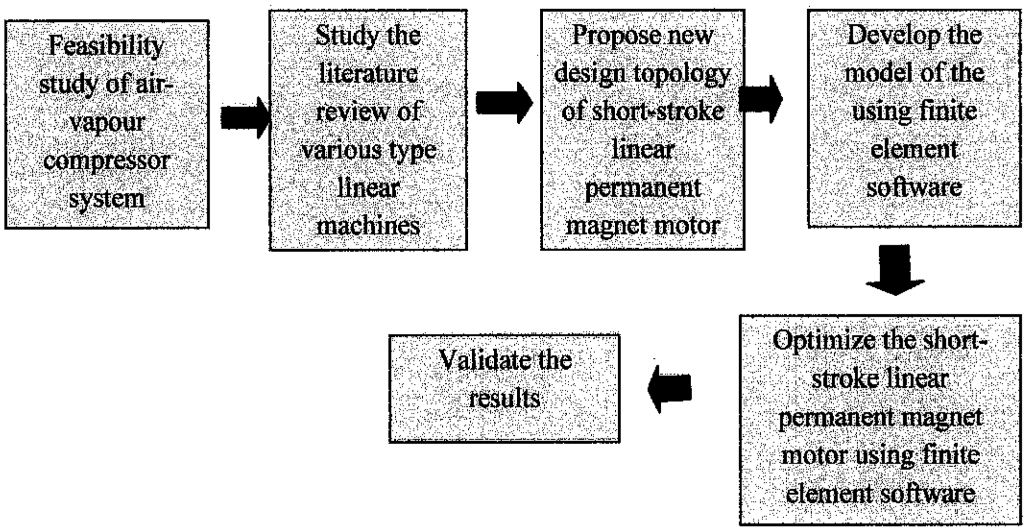

Figure 8 The overall sequences of project works.

3.2 Project activities

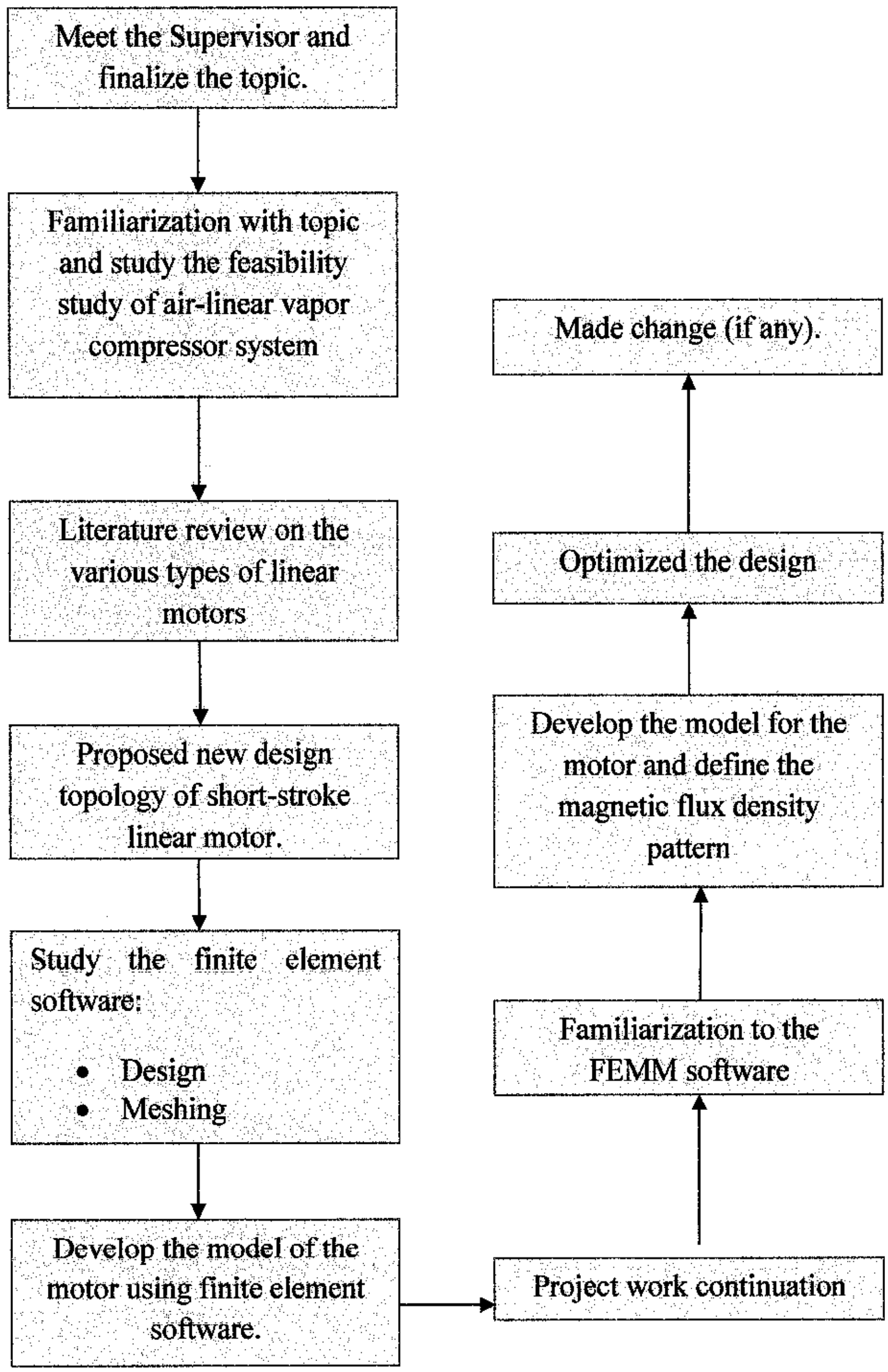

Figure 9 The project approach for the FYP 1 and FYP 2

3.3 Tools and equipments

This project required to use the software as for the design and analysis or optimization. There were two finite element software used, which;

- ANSOFT Maxwell.

This software used during first semester, as to design and analysis the design criteria for the motor.

- Finite Element Method Magnetics (FEMM)

This software used during second semester as to design the motor and thus, optimize the design. From the optimization, the designs will be verified and finalize.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will describes the process of designing linear motor using finite element software, four proposed design were identified. The analysis starts by performing the study on the open circuit flux density from the proposed design which is, air cored and iron cored. The analysis together generates the meshing for the motor design. Finite element software used for this approach was Finite Element Method Magnetics (FEMM).

These four types motor design consist of single slot and double slot linear permanent magnet motor with iron-cored, single slot and double slot linear permanent magnet motor with air-cored. The dimension and specification were compatible on the specification with the refrigerator compressor pump;

Table 2 The dimension and specification of design

Item	Value	Units
Axial length	60	mm
Outer diameter of stator	100	mm
Output Power	88.5	W
Current	0.5	A
Length of stroke	10	mm
Permanent magnet material	Sintered NdFeB	-
Remanence	1.05	T

The specific dimensions develop on finite element software;

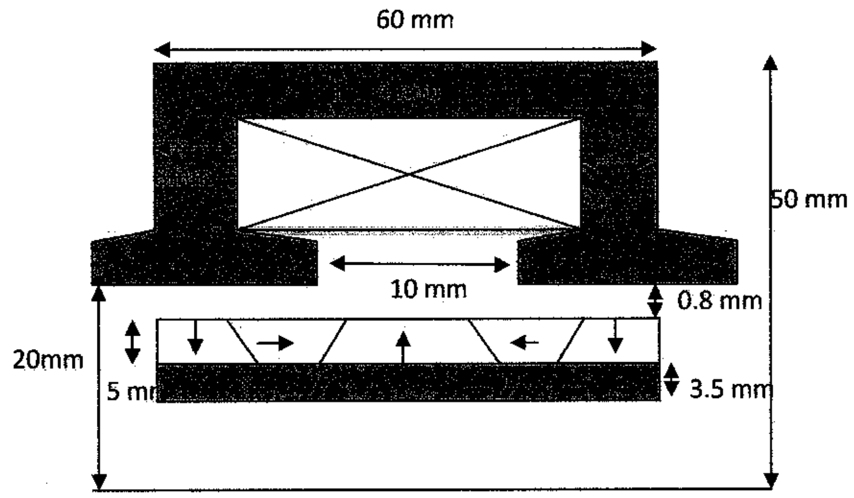

Figure 10 Specified Dimension of the Single Slot Motor Design

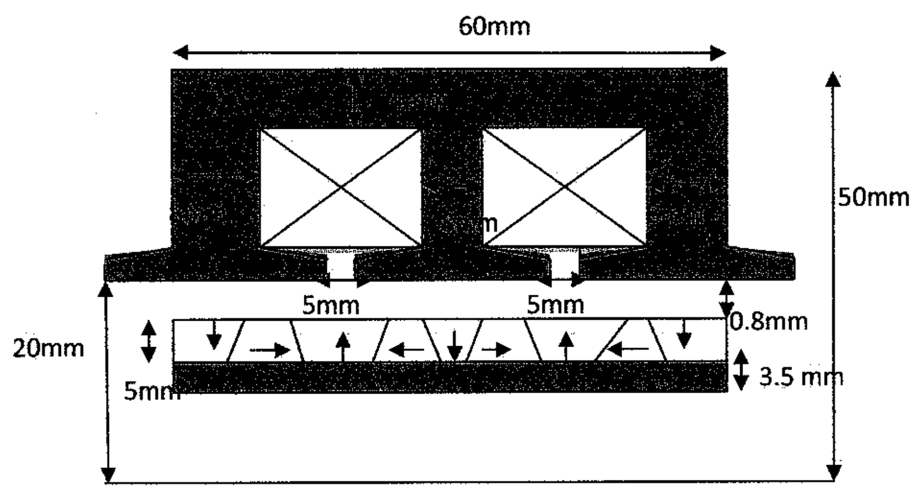

Figure11 Specified Dimension of the Double Slot Motor Design

4.2 Open Circuit Flux Distribution

From the specified dimension, the design built using the FEMM finite element software. The design undergo the analysis in identified the pattern of the open circuit flux density. In order to perform the analysis on the open circuit flux density, the parameter of current were assigned to zero as the motor was at zero position. During this time, there is no current source applied on the motor and the flux distribution flowing through the back iron path is produced by the permanent magnet itself.

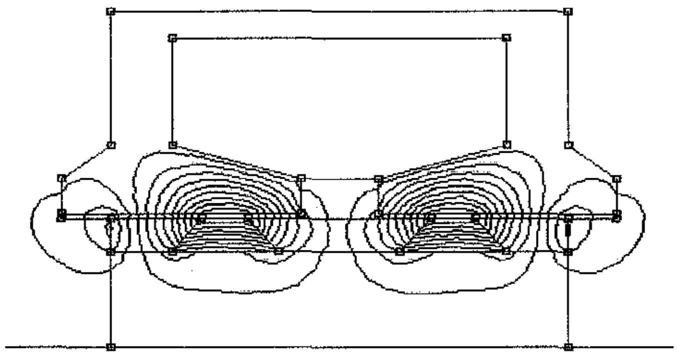

Figure 12 Single Slot Linear Permanent Magnet Motor with Air Cored

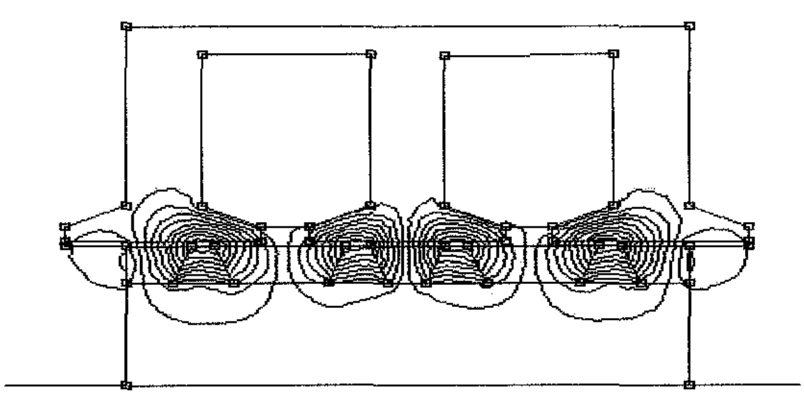

Figure 13 Double Slot Linear Permanent Magnet Motor with Air Cored

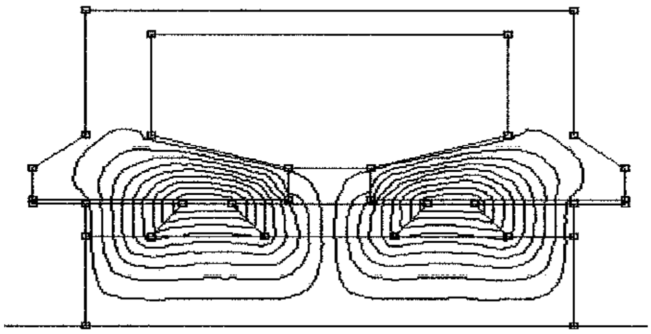

Figure 14 Single Slot Linear Permanent Magnet Motor with Iron Cored

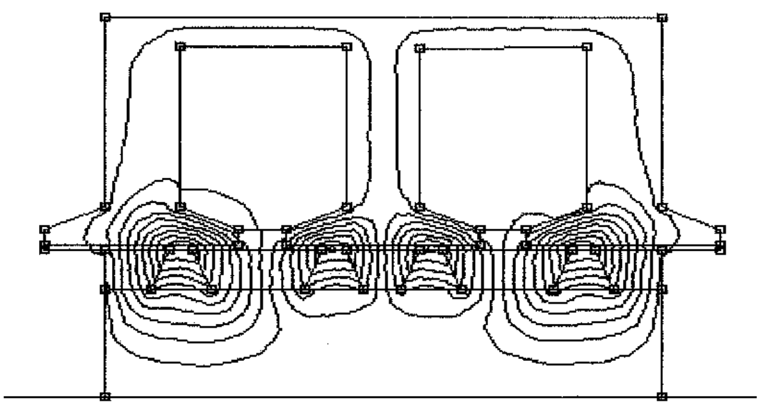

Figure 15 Double Slot Linear Permanent Magnet Motor with Iron Cored

4.3 Optimization

The optimization of the design was started after the verification of the open circuit flux distribution. The optimization process is for achieving the maximum efficiency produced by the motor.

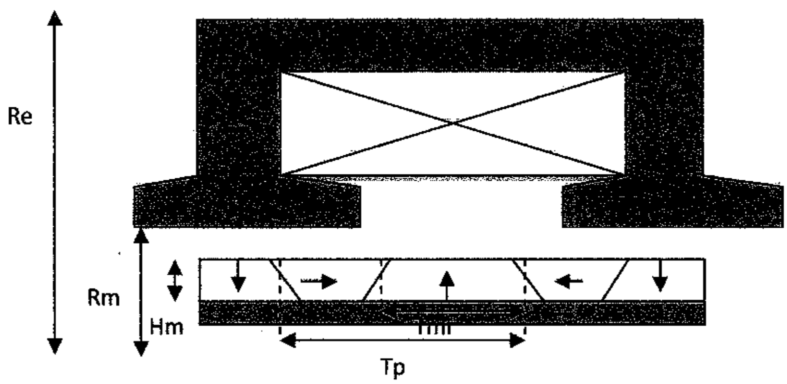

Figure 16 The legend for parameter to be optimized

In order to achieve the maximum efficiency, the dimension ratios $\frac{Tmr}{Tp}$, $\frac{Rm}{\text{Re}}$ and Hm are optimized since these parameter give influences to the motor performance. These dimension parameters are varied through specified fixed design dimension as to have higher efficiency with the same output power.

4.3.1 The ratio of the axial length of the central radially magnetized and the pole-pitch, $\frac{Tmr}{Tp}$.

The $\frac{Tmr}{Tp}$ represents the combination effect of radially and axially magnetized magnets in order to produce a maximum fundamental radial flux density in the air-gap [1].

From the analysis, Figure 17 till Figure 20 shows the graph for efficiency with variation of $\frac{Tmr}{Tp}$ ratio for all four proposed design. There is optimal ratio of

$\frac{Tmr}{Tp}$ that result in the higher efficiency. For the single slot linear permanent magnet motor with air-cored, $\frac{Tmr}{Tp}$ = 0.60 give efficiency 93.20% is higher compare to single slot linear permanent magnet motor with iron-cored, $\frac{Tmr}{Tp}$ = 0.60 with efficiency 86.51%. For the double slot linear permanent magnet motor with air-cored, $\frac{Tmr}{Tp}$ =0.53 give efficiency 92.70% is higher compare to double slot linear permanent magnet motor with iron-cored, $\frac{Tmr}{Tp}$ = 0.67 with efficiency 74.44%.

Thus, the ratio which gives higher motor efficiency is chosen for the next optimization and there only two motor designs will undergoes for next optimization parameter as their efficiency were above 90%. Both single slot and double slot linear permanent magnet motor with air-cored are chosen for the next optimization.

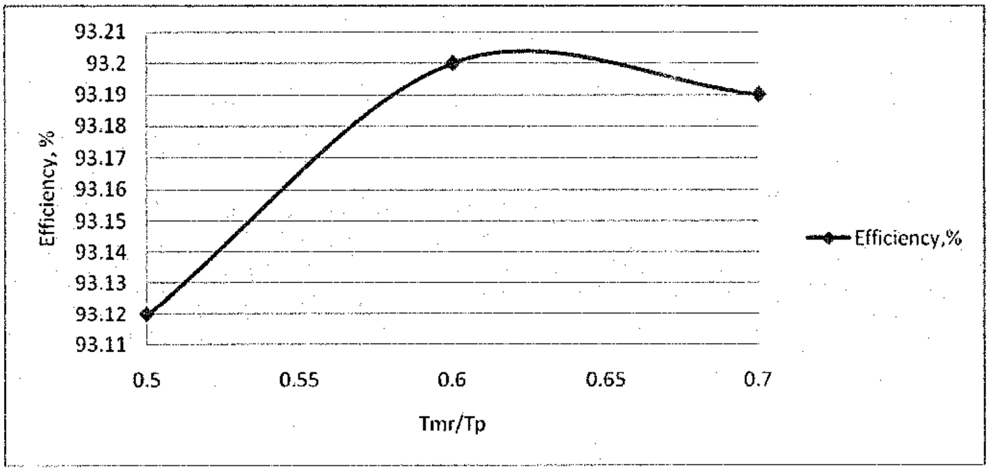

Figure 17 The Efficiency versus $\frac{Tmr}{Tp}$ of the Single Slot Linear Permanent Magnet Motor with Air-Cored.

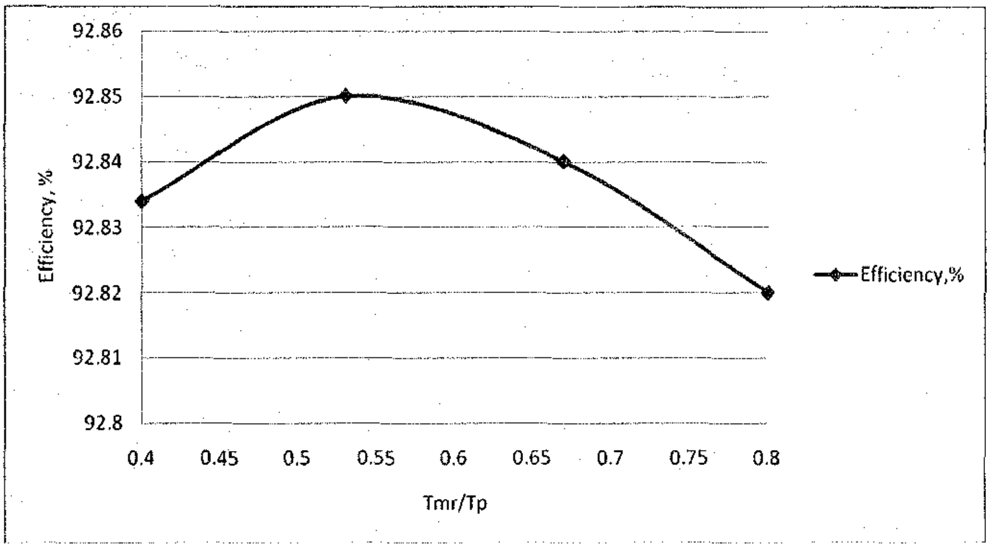

Figure 18 The Efficiency versus $\frac{Tmr}{Tp}$ of the Double Slot Linear Permanent Magnet Motor with Air-Cored.

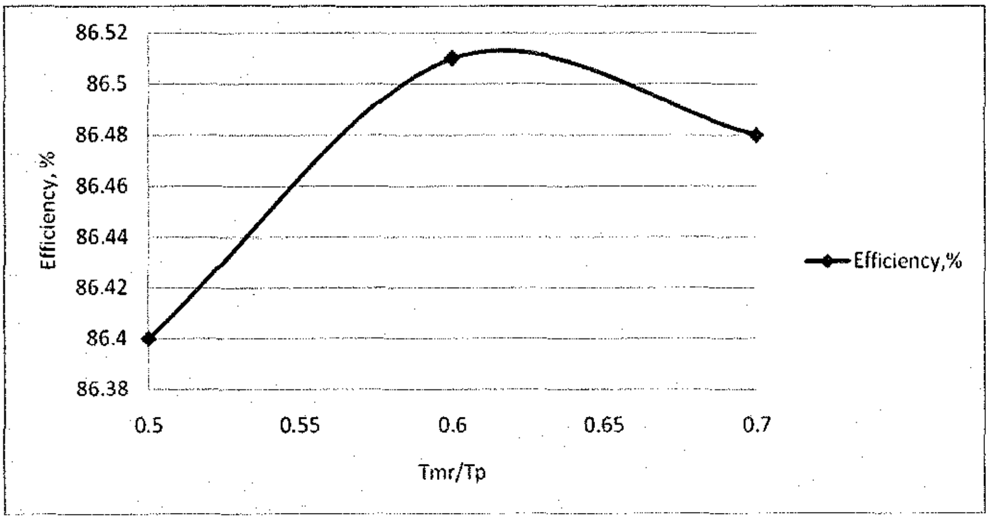

Figure 19 The Efficiency versus $\frac{Tmr}{Tp}$ of the Single Slot Linear Permanent Magnet Motor with Iron-Cored.

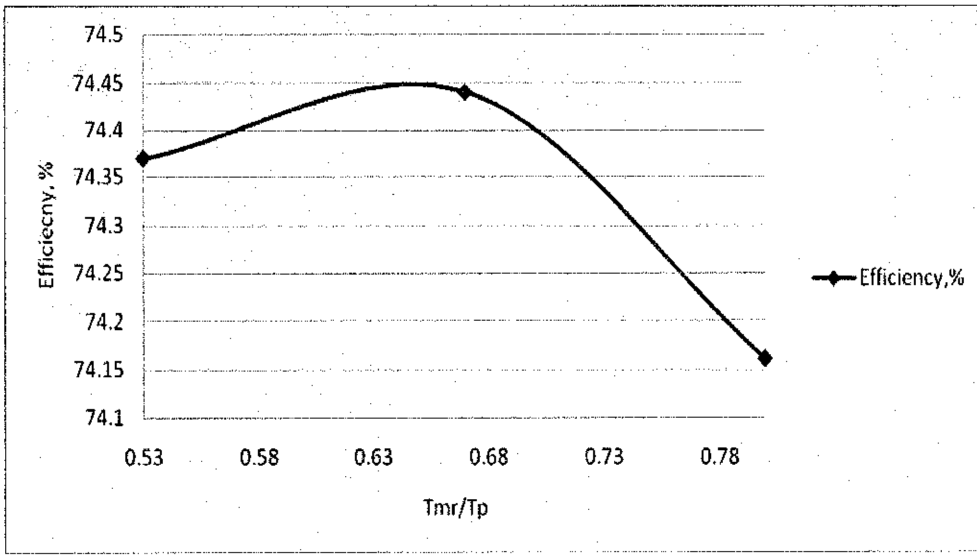

Figure 20 The Efficiency versus $\frac{Tmr}{Tp}$ of the Double Slot Linear Permanent Magnet Motor with Iron-Cored.

4.3.2 The ratio of the radius magnet and the radius of stator, $\frac{Rm}{\mathrm{Re}}$.

Ratio of $\frac{Rm}{\mathrm{Re}}$ represent the optimal balanced between electrical loading and magnetic loading in the order to achieve maximum motor efficiency [1].

With this parameter, $\frac{Rm}{\mathrm{Re}}$ the copper loss could be decreased when $\frac{Rm}{\mathrm{Re}}$ increased. It is because the slot area is decreasing when $\frac{Rm}{\mathrm{Re}}$ increasing and it also will increase the resistance of the coil. In same way, the output power also decreased due to increasing the coil flux per turn [1] but still result with decreasing the copper loss. It shows that at specified ratio of $\frac{Tmr}{Tp}$ will yield the optimal ratio of $\frac{Rm}{\mathrm{Re}}$ in order to have the maximum efficiency [1].

From the optimization parameter, $\frac{Rm}{\mathrm{Re}}$ the single slot linear permanent magnet motor with air-cored having higher efficiency, 93.34% when the $\frac{Rm}{\mathrm{Re}}$ = 0.364. Compared to the double slot linear permanent magnet motor with air-cored which efficiency 92.76% with $\frac{Rm}{\mathrm{Re}}$=0.364. Both designs having not much different of efficiency, thus both design required to undergo next optimization.

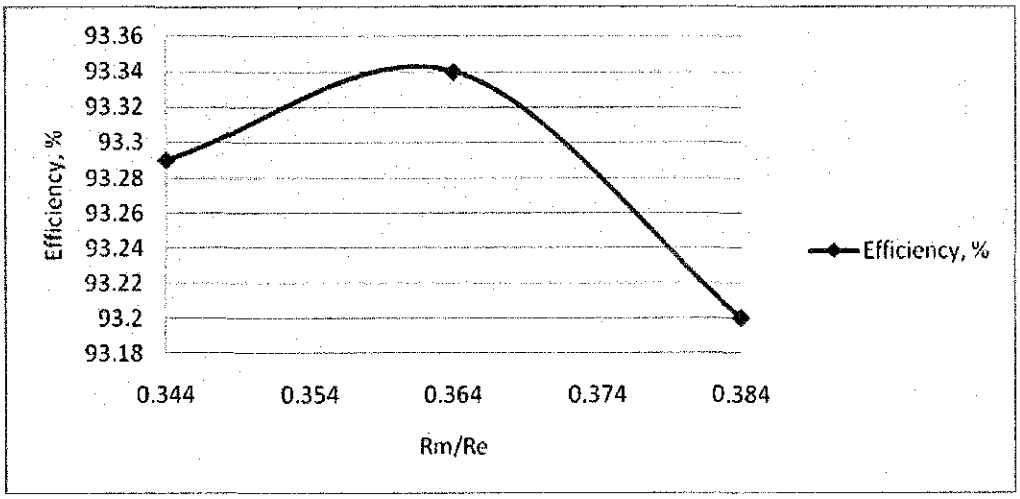

Figure 21 The Efficiency versus $\frac{Rm}{\mathrm{Re}}$ of the Single Slot Linear Permanent Magnet Motor with Air-Cored.

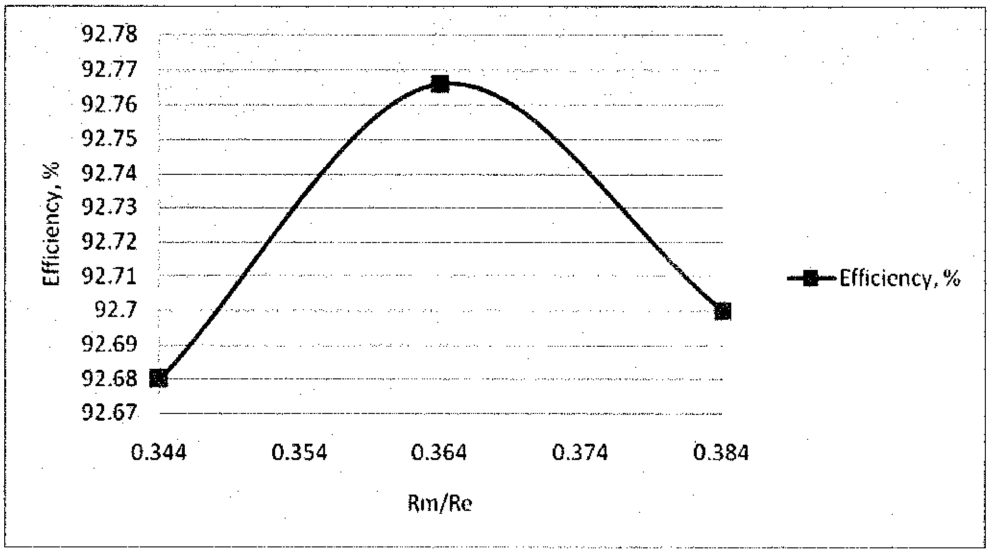

Figure 22 The Efficiency versus $\frac{Rm}{Re}$ of the Double Slot Linear Permanent Magnet Motor with Air-Cored.

4.3.3 The height of the permanent magnet, Hm.

When increasing the height of permanent magnet, *Hm* the efficiency of motor also increased but the cost for the permanent magnet will also increased. Thus, optimization of the height permanent magnet is highly required as to optimal the design and the cost effect.

From the optimization of *Hm*, the single slot linear permanent magnet motor with air-cored design give high efficiency, 93.34% compared to the double slot linear permanent magnet motor with air-cored, 92.76% at same *Hm* height, 5 mm. This indicates that single slot linear permanent magnet motor with air-cored is the most promising design topologies of linear reciprocating motor in terms of their strokes, mass, efficiency and cost.

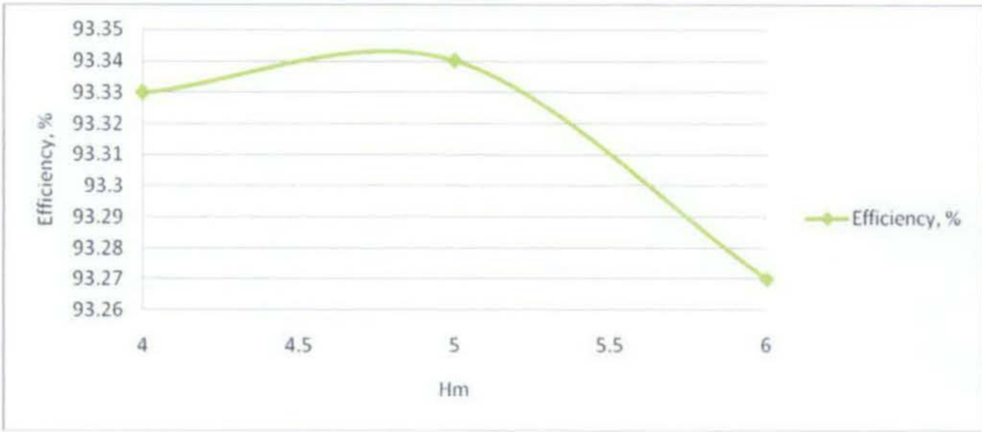

Figure 23 The Efficiency versus *Hm* of the Single Slot Linear Permanent Magnet Motor with Air-Cored.

Figure 24 The Efficiency versus *Hm* of the Double Slot Linear Permanent Magnet Motor with Air-Cored.

4.4 Discussion

From the simulation result, the distribution fluxes are the flux produce by the permanent magnet during zero current applied at the zero position. The pattern of the flux flowing indicates the arrangement of the permanent magnet.

Based on the observation, the iron-cored linear permanent magnet motor has more air gap flux density compare to air-cored linear permanent magnet motor. Therefore, the performance of the iron cored believed is better than air cored. This is due to the ferromagnetic material used in the armature of the motor. However, the thickness of ferromagnetic material need to be reduced, as review from the double slot iron cored linear motor design with the flux distribution occurs in the back iron. The optimization believes would verify the proposed design dimension.

For the optimization parameter of $\frac{Tmr}{Tp}$, while increasing the ratio, the iron loss also increased as due to the increased in the flux density. Thus, the optimization for this parameter has to be optimal in order to obtain the right $\frac{Tmr}{Tp}$ ratio. Means while, the optimization of $\frac{Rm}{\mathrm{Re}}$, also give significant effect on the increasing iron loss. It is due to the flux density increased in the stator core. Both design dimension parameter; $\frac{Tmr}{Tp}$ and $\frac{Rm}{\mathrm{Re}}$ become most important dimension to be optimized which will direct influence the motor performance.

The optimization of the design is as to produce the maximum efficiency of the motor. The efficiency can be calculated by;

$$\eta = \frac{Pout}{Pin} \times 100\%$$ where,

$$Pout = Pin - Ploss$$ where,

$$Ploss = Pfe + Pcu$$

Pin = Input Power

Pout = Output Power

Ploss = Power Loss

Pfe = Iron Loss

Pcu = Copper Loss

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study of short-stroke linear permanent magnet motor has proved could improve the efficiency of the compressor system for refrigerator application. The advantages of linear permanent magnet motor which are, no field winding required for the motor since the permanent magnet will produce the excitation flux for the motor. Even though it has higher cogging torque but it also has higher output power. In other aspect, the permanent magnet motor believes would give better dynamic performance.

The developed design methodology to achieve the better design topology for refrigerator compressor system have shown the most promising result with the efficiency of the motor is improved with 93.34% as compared to conventional system which only 60%. Thus, the improved linear machine technology proved could help to reduce the energy power consumption which recently approaches the critical rate.

Even though, the proposed design for the single slot and double slot of quasi-Halbach magnetized linear motor had undergoes comprehensive analysis. Which the result have been validated with the single slot linear permanent magnet motor with air-cored become most promising design, but the proposed design should also undergoes the mathematical analysis and experimental analysis. It is to ensure the proposed designs are properly verified as this linear machine technology become one of the solution for our high energy consumption.

5.2 Future works

5.2.1 Validation using mathematical approach.

The design for the linear motor are only based on the finite element simulation thus, the further analysis using mathematical approach for the design is highly recommended. As the validation of the design using finite element software also required to be validating with the mathematical design.

5.2.2 Validation using experimental approach.

The designs for the linear motor have to be validated using experimental approach as well. This to ensure the linear motor works properly as the finite element analysis and mathematical analysis result.

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APPENDICES

- **APPENDIX A**
  - Gantt Chart For FYP 1 and FYP 2
- **APPENDIX B**
  - Air-gap Flux Distribution
- **APPENDIX C**
  - Optimization Result and Analysis

APPENDIX A

Gantt Chart FYP 1

	ACTIVITY	WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FYP 1	Briefing from Coordinator; Meet Supervisor and finalize topic.																
	Familiarization with topic and prepare the Preliminary Report.																
	Submission of Preliminary Report.																
	Feasibility study of air-vapor compressor system and Literature review on various type of linear motors																
	Mid-Term Seminar																
	Design the new topology.																
	Submission of Progress Report.																
	Develop analytical model for the motor finite element software																
	Prepare the Draft Report.																
	Submission of Draft Report (19 Oct. 2009) and prepare the Draft Report.																
	Submission of Interim Report (26 Oct. 2009) and prepare for the Oral Presentation.																
	Oral Presentation.																

Gantt Chart FYP 2

	ACTIVITY	WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
FYP 2	Project works continue																
	Familiarization with the finite software																
	Submission of Progress Report 1																
	Design and optimization of a short-stroke linear permanent magnet motor using finite element software																
	Submission of Progress Report 2								MID SEM								
	Poster Exhibition																
	Submission of Draft Report																
	Made changes (if any)																
	Submission of Final Dissertation (soft Cover) & Technical Report																
	Oral Presentation																
	Submission of Final Dissertation (Hard Cover)																

APPENDIX B

Air-gap Flux Distribution

Beside the open circuit flux distribution, the air-gap flux distribution also very important to be verified at the initial stages of designing a motor. This air-gap flux distribution relates to the magnetic flux density and also indicates the path for the flux moving in the motor. As the used of quasi-Halbach magnetized magnet, the flux have it own return path for the radial air-gap flux.

Based on the graph generated, the linear permanent magnet motor with iron-cored have more flux density compare to the linear permanent magnet motor with air-cored.

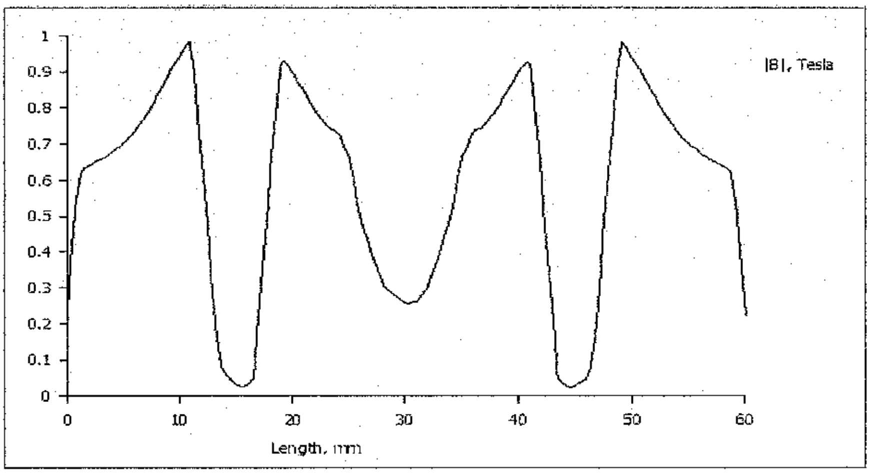

Figure 1 Single Slot Linear Permanent Magnet Motor with Air Cored

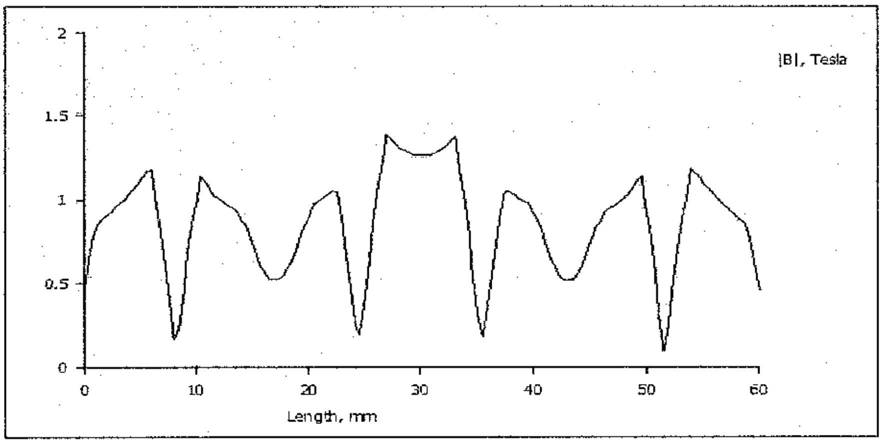

Figure 2 Double Slot Linear Permanent Magnet Motor with Air Cored

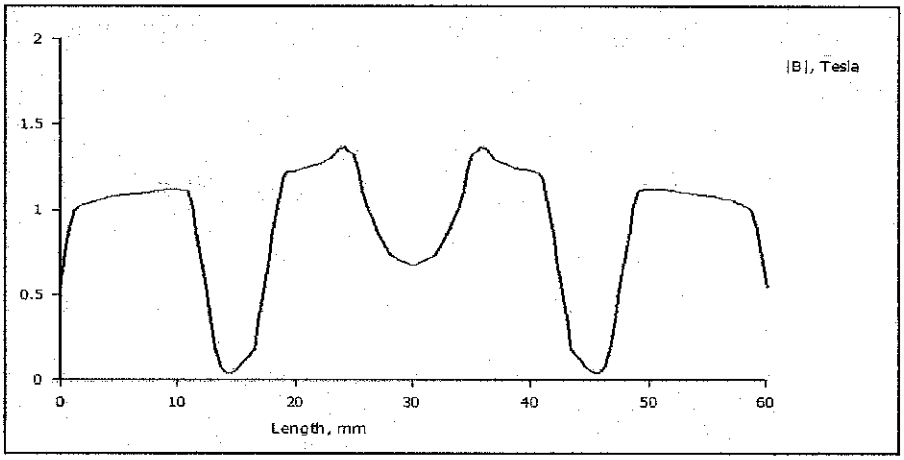

Figure 3 Single Slot Linear Permanent Magnet Motor with Iron Cored

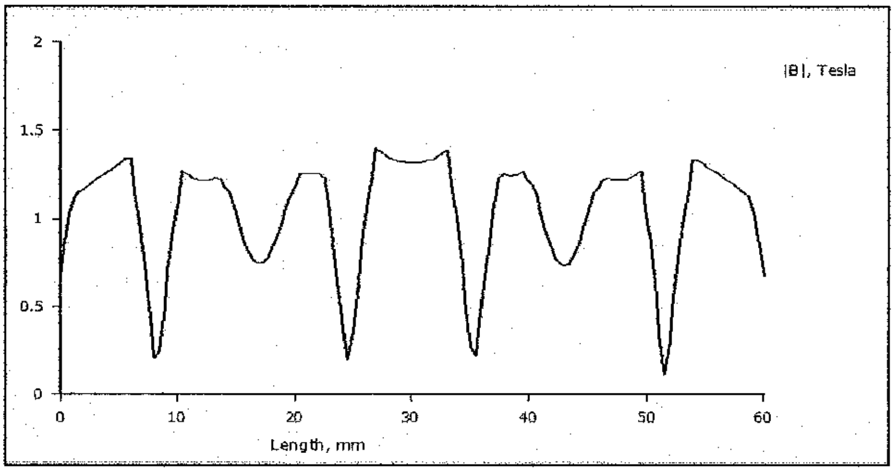

Figure 4 Double Slot Linear Permanent Magnet Motor with Iron Cored

APPENDIX C

Single Slot Linear Permanent Magnet Motor
Tmr/Tp: 0.5

Air Cored

Current (I)	Total Loss (W)
0.1	0.1398
0.2	0.5513
0.3	1.252
0.4	2.2525
0.5	3.4281
-0.1	0.1415
-0.2	0.5533
-0.3	1.2472
-0.4	2.1894
-0.5	3.5457
Total	15.3000
Average Loss	1.5300

Input Power: 22.2589 W
Efficiency : 93.12%

Iron Cored

Current (I)	Total Loss (W)
0.1	0.799
0.2	3.0629
0.3	6.0126
0.4	9.505
0.5	13.2421
-0.1	0.8027
-0.2	2.9799
-0.3	6.0668
-0.4	9.3782
-0.5	13.4777
Total	65.3269
Average Loss	6.5326

Input Power: 48.0543 W
Efficiency: 86.40%

Tmr/Tp: 0.6

Air Cored

Current (I)	Total Loss (W)
0.1	0.1389
0.2	0.543
0.3	1.2688
0.4	2.1863
0.5	3.5316
-0.1	0.138
-0.2	0.5582
-0.3	1.2269
-0.4	2.2481
-0.5	3.4317
Total	15.2714
Average Loss	1.5271

Input Power : 22.4790 W
Efficiency : 93.20%

Iron Cored

Current (I)	Total Loss (W)
0.1	0.7916
0.2	3.0252
0.3	6.2853
0.4	9.0714
0.5	13.4142
-0.1	0.7855
-0.2	3.0137
-0.3	5.8629
-0.4	9.5187
-0.5	13.0671
Total	64.8356
Average Loss	6.4835

Input Power: 48.0543 W
Efficiency: 86.51%

Tmr/Tp: 0.7

Air Cored

Current (I)	Total Loss (W)
0.1	0.1354
0.2	0.5639
0.3	1.2453
0.4	2.1974
0.5	3.5407
-0.1	0.1379
-0.2	0.5509
-0.3	1.2456
-0.4	2.2143
-0.5	3.472
Total	15.3034
Average Loss	1.5303

Input Power : 22.5038 W
Efficiency : 93.19%

Iron Cored

Current (I)	Total Loss (W)
0.1	0.783
0.2	3.0744
0.3	5.9558
0.4	9.3012
0.5	13.4864
-0.1	0.8016
-0.2	2.9758
-0.3	5.8604
-0.4	9.4326
-0.5	13.2557
Total	64.9269
Average Loss	6.4926

Input Power: 48.0543 W
Efficiency: 86.48%

Double Slot Linear Permanent Magnet Motor
Tmr/Tp: 0.53

Air Cored

Current (I)	Total Loss (W)
0.1	0.3621
0.2	1.4644
0.3	3.2713
0.4	5.7991
0.5	9.2025
-0.1	0.3627
-0.2	1.6671
-0.3	3.474
-0.4	5.8018
-0.5	9.4025
Total	40.8066
Average Loss	4.0806

Input Power: 55.899 W
Efficiency : 92.70%

Iron Cored

Current (I)	Total Loss (W)
0.1	1.9844
0.2	7.0322
0.3	13.5693
0.4	20.8685
0.5	28.5839
-0.1	2.7047
-0.2	7.2525
-0.3	14.0896
-0.4	20.8688
-0.5	28.8042
Total	145.757
Average Loss	14.5757

Input Power: 56.869 W
Efficiency: 74.37%

Tmr/Tp: 0.67

Air Cored

Current (I)	Total Loss (W)
0.1	0.3669
0.2	1.4806
0.3	3.3126
0.4	5.87307
0.5	9.0787
-0.1	0.3672
-0.2	1.6608
-0.3	3.3357
-0.4	5.8969
-0.5	9.1525
Total	40.5239
Average Loss	4.0524

Input Power: 56.629 W
Efficiency : 92.84%

Iron Cored

Current (I)	Total Loss (W)
0.1	1.9676
0.2	6.9878
0.3	13.3373
0.4	20.6388
0.5	28.9169
-0.1	2.5423
-0.2	7.4878
-0.3	13.8311
-0.4	21.2088
-0.5	29.4209
Total	146.3393
Average Loss	14.6339

Input Power: 57.253 W
Efficiency: 74.44%

Tmr/Tp: 0.8

Air Cored

Current (I)	Total Loss (W)
0.1	0.3636
0.2	1.4758
0.3	3.2793
0.4	5.7708
0.5	9.2804
-0.1	0.3786
-0.2	1.4889
-0.3	3.3521
-0.4	5.868
-0.5	9.3339
Total	40.5909
Average Loss	4.0591

Input Power: 56.565 W
Efficiency : 92.824%

Iron Cored

Current (I)	Total Loss (W)
0.1	1.9685
0.2	7.1335
0.3	13.4691
0.4	20.9838
0.5	29.0742
-0.1	2.9051
-0.2	7.3254
-0.3	13.6484
-0.4	20.9856
-0.5	29.2667
Total	145.2579
Average Loss	14.5258

Input Power: 56.214 W
Efficiency: 74.16%

Single Slot Linear Permanent Magnet Motor

Rm/Re : 0.344

Current (I)	Total Loss (W)
0.1	0.1212
0.2	0.4831
0.3	1.0793
0.4	1.9672
0.5	3.0291
-0.1	0.121
-0.2	0.479
-0.3	1.0909
-0.4	1.9115
-0.5	3.1052
Total	13.3875
Average Loss	1.3387

Input Power : 19.9594 W
Efficiency : 93.29%

Rm/Re : 0.364

Current (I)	Total Loss (W)
0.1	0.1318
0.2	0.5156
0.3	1.1432
0.4	2.0179
0.5	3.2279
-0.1	0.1304
-0.2	0.5086
-0.3	1.1324
-0.4	2.0263
-0.5	3.0945
Total	13.9286
Average Loss	1.3928

Input Power : 20.9234 W
Efficiency : 93.34%

Rm/Re : 0.384

Current (I)	Total Loss (W)
0.1	0.1389
0.2	0.543
0.3	1.2688
0.4	2.1863
0.5	3.5316
-0.1	0.138
-0.2	0.5582
-0.3	1.2269
-0.4	2.2481
-0.5	3.4317
Total	15.2714
Average Loss	1.5271

Input Power : 22.4790 W
Efficiency : 93.20%

Double Slot Linear Permanent Magnet Motor

Rm/Re : 0.344

Current (I)	Total Loss (W)
0.1	0.3222
0.2	1.3138
0.3	2.8759
0.4	5.19745
0.5	7.9681
-0.1	0.3535
-0.2	1.6133
-0.3	2.8865
-0.4	5.1995
-0.5	7.9788
Total	35.70809
Average Loss	3.5708

Input Power : 48.7814W
Efficiency : 92.68%

Rm/Re : 0.364

Current (I)	Total Loss (W)
0.1	0.3293
0.2	1.3521
0.3	3.0043
0.4	5.3152
0.5	8.2704
-0.1	0.3285
-0.2	1.3052
-0.3	3.2063
-0.4	5.4466
-0.5	8.3005
Total	36.8584
Average Loss	3.6858

Input Power : 50.951W
Efficiency : 92.766%

Rm/Re : 0.384

Current (I)	Total Loss (W)
0.1	0.3621
0.2	1.4644
0.3	3.2713
0.4	5.7991
0.5	9.2025
-0.1	0.3627
-0.2	1.6671
-0.3	3.474
-0.4	5.8018
-0.5	9.4025
Total	40.8066
Average Loss	4.0806

Input Power: 55.899 W
Efficiency : 92.70%

Single Slot Linear Permanent Magnet Motor

Hm: 4 mm

Current (I)	Total Loss (W)
0.1	0.1265
0.2	0.496
0.3	1.1154
0.4	1.9221
0.5	3.1676
-0.1	0.1198
-0.2	0.477
-0.3	1.1277
-0.4	1.9528
-0.5	3.061
Total	13.5659
Average Loss	1.3565

Input Power : 20.344 W
Efficiency : 93.33%

Hm: 5 mm

Current (I)	Total Loss (W)
0.1	0.1318
0.2	0.5156
0.3	1.1432
0.4	2.0179
0.5	3.2279
-0.1	0.1304
-0.2	0.5086
-0.3	1.1324
-0.4	2.0263
-0.5	3.0945
Total	13.9286
Average Loss	1.3928

Input Power : 20.9234 W
Efficiency : 93.34%

Hm: 6 mm

Current (I)	Total Loss (W)
0.1	0.1312
0.2	0.52119
0.3	1.1988
0.4	2.0637
0.5	3.1951
-0.1	0.1309
-0.2	0.5262
-0.3	1.1841
-0.4	2.0869
-0.5	3.2728
Total	14.331
Average Loss	1.4331

Input Power : 21.3028 W
Efficiency : 93.27%

Double Slot Linear Permanent Magnet Motor

Hm: 4 mm

Current (I)	Total Loss (W)
0.1	0.3224
0.2	1.3022
0.3	2.9243
0.4	5.2397
0.5	8.0636
-0.1	0.322
-0.2	1.2035
-0.3	2.9311
-0.4	5.3347
-0.5	8.0775
Total	35.7205
Average Loss	3.57205

Input Power : 49.1352 W
Efficiency : 92.73 %

Hm : 5 mm

Current (I)	Total Loss (W)
0.1	0.3293
0.2	1.3521
0.3	3.0043
0.4	5.3152
0.5	8.2704
-0.1	0.3285
-0.2	1.3052
-0.3	3.2063
-0.4	5.4466
-0.5	8.3005
Total	36.8584
Average Loss	3.6858

Input Power : 50.951W
Efficiency : 92.766%

Hm: 6 mm

Current (I)	Total Loss (W)
0.1	0.3506
0.2	1.3699
0.3	3.0519
0.4	5.428
0.5	8.5305
-0.1	0.3327
-0.2	1.3478
-0.3	3.1005
-0.4	5.4392
-0.5	8.6588
Total	37.6095
Average Loss	3.7609

Input Power : 51.8530 W
Efficiency : 92.747%