Faculty of Electrical Engineering

DESIGN IMPROVEMENT OF PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR FOR OPTIMUM THRUST PERFORMANCE

Nur Ashikin binti Mohd Nasir

Master of Science in Electrical Engineering

2019

DESIGN IMPROVEMENT OF PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR FOR OPTIMUM THRUST PERFORMANCE

NUR ASHIKIN BINTI MOHD NASIR

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled "Design Improvement of Permanent Magnet Linear Synchronous Motor for Optimum Thrust Performance" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	……*Ashikin*……..
Name	:	……Nur Ashikin binti Mohd Nasir……..
Date	:	........10 November 2019...........................

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:	....*Fairul*..
Supervisor Name	:	....Dr.Fairul Azhar bin Abdul Shukor....
Date	:	....10 November 2019...........................

DEDICATION

TO MY BELOVED PARENTS

En. Mohd Nasir bin Mohd Zin and Pn. Zimira binti Jusoh

TO MY BROTHERS AND SISTERS

Mohd Nassarudin, Mohd Nazimie, Mohd Naim, Nuraini, Mohd Nazreen and Nur Anisa

And lastly to all the individuals who always be here to support and ease my days.

ABSTRACT

Permanent Magnet Linear Synchronous Motor (PMLSM) introduces excellent performances in terms static characteristics and thrust density compare to other types of linear motor. Previously, a Permanent Magnet Cylindrical Synchronous Linear Motor (PMCLSM) was designed and developed. However, measurement result shows that the thrust, *F* of the PMCLSM was saturated at the current, *I* lower than its estimated rated current. One of the factors that caused the saturation is the unbalanced dimensions between the stator yoke and the coil of the PMLCSM. Therefore, the PMLSM was designed in this research to overcome this problem. The design of the PMLSM was accomplished by modified the structure parameters of the PMLSM. It was completed in two stages. Each model of the PMLSM was simulated by using FEM software where the simulation outputs were analyzed and compared to identify the best model. In the first stage of the PMLSM design, the yoke thickness, t_y of the PMLSM was designed. From the simulation analysis, the PMLSM model with lower-side yoke thickness, t_{y2} is 3.0 mm was identified as the best model in the first stage of the PMLSM design. The model has an average thrust, F_{ave} of 167 N at the current, *I* of 3.0 A. The model was chosen based on its insignificant thrust reduction. For the second stage of the PMLSM design, the structure parameters of the selected model in the first stage of the PMLSM design was chosen as the reference. In the second stage of the PMLSM design, the design was focused on the slot opening parameters with two different permanent magnet magnetization direction arrangement. The parameters of the slot opening are slot opening length, l_t and slot opening height, h_t. Meanwhile, the permanent magnet arrangements varied are N-S axial arrangement and Halbach arrangement. Based on the simulation results analysis, the PMLSM with Halbach arrangement with a combination of slot opening length, l_t is 1.5 mm and slot opening height, h_t is 1.0 mm was identified as the best model in the second stage of the PMLSM design. The model hence selected for the fabrication. Since the PMLSM's driver design and development were not included in this research, the performance of the PMLSM was focused on the static characteristics. Therefore, the static thrust characteristics at each phase of the PMLSM was measured. The measurement results were then compared to the simulation outputs for result validation. However, due to the permanent magnet of the Halbach arrangement could not attached to the shaft permanently, the permanent magnet arrangement was changed to N-S axial arrangement. This is to ensure the sustainability of the PMLSM's function. From the measurement, it shows that the thrust, *F* of the PMLSM with axial arrangement was able to be captured at excitation current, *I* higher than 1.5 A. At the excitation current, *I* of 2.0 A, the static thrust produced by the PMLSM with axial arrangement for phase A is 154.82 N. As a conclusion, the PMLSM with axial arrangement was capable in overcoming the thrust saturation faced by PMCLSM.

ABSTRAK

Motor Linear Segerak Bermagnet Kekal (PMLSM) mempunyai prestasi yang sangat baik dari segi ciri-ciri pegun dan ketumpatan teras berbanding motor linear jenis lain. Dalam kajian sebelumnya, Motor Linear Segerak Silinder Bermagnet Kekal (PMCLSM) telah direka dan dibangunkan. Namun, keputusan yang diukur menunjukkan teras, F yang dihasilkan PMCLSM tepu pada arus yang lebih rendah dari anggaran arus, I yang ditetapkan. Salah satu faktor penyebab ketepuan adalah ketidakseimbangan dimensi antara yok pemegun dan gegelung PMLCSM tersebut. Oleh itu, PMLSM telah direka bentuk dalam kajian ini bagi mengatasi masalah itu. Reka bentuk PMLSM telah dicapai dengan mengubah parameter struktur PMLSM itu. Ianya telah diselesaikan dalam dua peringkat reka bentuk. Setiap model PMLSM yang direka bentuk telah disimulasi menggunakan perisian FEM di mana hasil simulasi telah dianalisa dan dibandingkan untuk mencari model yang terbaik. Dalam peringkat pertama reka bentuk PMLSM, ketebalan yok pemegun, t_y telah direka. Daripada hasil simulasi, model PMLSM dengan ketebalan bahagian bawah yok, t_{y2} adalah 3.0 mm telah dipilih sebagai model terbaik dalam reka bentuk PMLSM peringkat pertama. Model ini mempunyai teras purata, F_{ave} sebanyak 167 N pada arus 3.0 A. Model ini dipilih berdasarkan penurunan terasnya yang tidak ketara. Untuk reka bentuk PMLSM peringkat kedua, parameter struktur PMLSM yang telah dipilih dalam reka bentuk PMLSM peringkat pertama telah dijadikan sebagai rujukan. Dalam reka bentuk PMLSM peringkat kedua, reka bentuk difokuskan kepada parameter pada pembukaan slot pemegun dengan dua susunan arah pemagnetan magnet kekal. Parameter pada pembukaan slot pemegun adalah panjang pembukaan slot pemegun, l_t dan tinggi pembukaan slot pemegun, h_t. Manakala, susunan magnet kekal yang diubah adalah susunan paksi N-S dan susunan Halbach. Berdasarkan analisa hasil simulasi, PMLSM dengan susunan Halbach yang mempunyai gabungan panjang pembukaan slot, l_t adalah 1.5 mm dan tinggi pembukaan slot, h_t adalah 1.0 mm telah dikenalpasti sebagai model terbaik dalam reka bentuk PMLSM peringkat kedua. PMLSM ini telah dipilih untuk difabrikasi. Memandangkan reka bentuk dan pembangunan pemacu PMLSM tidak termasuk dalam kajian ini, prestasi PMLSM hanya tertumpu kepada ciri-ciri pegun. Oleh itu, ciri-ciri teras pegun telah diukur pada setiap fasa PMLSM itu. Hasil yang diukur telah dibandingkan dengan hasil simulasi untuk pengesahan. Namun begitu, disebabkan magnet kekal dengan susunan Halbach tidak dapat melekat pada bahagian aci dengan kekal, susunan magnet kekal telah diubah daripada susunan Halbach kepada susunan paksi N-S. Ini bagi memastikan fungsi PMLSM tersebut dapat bertahan lama. Dari pengukuran, ia menunjukkan bahawa teras, F yang dihasilkan oleh PMLSM dengan susunan paksi N-S berjaya diukur pada arus, I yang lebih tinggi dari 1.5 A. Pada arus 2.0 A, teras pegun pada fasa A yang dihasilkan oleh PMLSM dengan susunan paksi N-S adalah sebanyak 154.82 N. Dengan ini, dapat disimpulkan bahawa PMLSM dengan susunan paksi N-S berjaya mengatasi masalah ketepuan teras, F yang dialami oleh PMCLSM.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to show my utmost gratefulness to Allah SWT for the blessing, the strength and the patience for me to overcome each challenge and difficulties in completing my thesis.

Second, I would like to express my greatest gratitude to my supervisor, Dr. Fairul Azhar bin Abdul Shukor from the Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his continuous, patience and kind guidance towards me in completing this thesis and my research.

Not forget to mention, a lot of thanks to my co-supervisor, Assoc. Prof. Dr. Raja Nor Firdaus Kashfi bin Raja Othman. Thank you for the advice and suggestion that help me to improve both my technical skills and soft skills.

I would also like to express my appreciation to all the members of the Machines Design Laboratory of the Faculty of Electrical Engineering for their assistance, time spent, and efforts in all my days there.

Special thanks to all my peers, my laboratory mates, my beloved mother, my late father, my siblings, and all my family members who always supporting me either financially or morally in completing my master degree. And lastly, thank you to everyone who was involved directly or indirectly along my journey in finishing my research and study of Master of Science in Electrical Engineering.

TABLE OF CONTENTS

				PAGE
DECLARATION				
APPROVAL				
DEDICATION				
ABSTRACT				**i**
ABSTRAK				**ii**
ACKNOWLEDGEMENTS				**iii**
TABLE OF CONTENTS				**iv**
LIST OF TABLES				**vi**
LIST OF FIGURES				**vii**
LIST OF APPENDICES				**xi**
LIST OF ABBREVIATIONS				**xii**
LIST OF PUBLICATIONS				**xvii**
CHAPTER				
1.	**INTRODUCTION**			**1**
	1.1	Introduction		1
	1.2	Problem statements		4
	1.3	Research objectives		8
	1.4	Research scopes		8
	1.5	Thesis outlines		9
2.	**LITERATURE REVIEW**			**11**
	2.1	Introduction		11
	2.2	Introduction to linear motor		11
	2.3	Basic principle of the PMLSM		15
		2.3.1	Basic structure of the PMLSM	16
		2.3.2	Thrust equation	17
		2.3.3	Cogging force	19
		2.3.4	Magnetic equivalent circuit	22
	2.4	Permanent magnet magnetization arrangement		23
	2.5	Performance indexes		31
	2.6	Magnetic materials		32
		2.6.1	Ferromagnetic materials	32
		2.6.2	Non-ferromagnetic materials	35
		2.6.3	Permanent magnet materials	36
	2.7	Summary		39
3.	**RESEARCH METHODOLOGY**			**41**
	3.1	Introduction		41
	3.2	Introduction to the electrical machine design		42
	3.3	Design of the PMLSM		45
	3.4	First stage of the PMLSM design		47
	3.5	Second stage of the PMLSM design		52
		3.5.1	Design of the slot opening parameters	53
		3.5.2	Variation of the permanent magnet arrangement	56

	3.6	Performance comparison of the designed models		59
	3.7	Fabrication and performance measurement of the PMLSM		60
	3.8	Summary		62
4.	**RESULT AND ANALYSIS**			**64**
	4.1	Introduction		64
	4.2	First Stage of the PMLSM design		64
		4.2.1	The effects of the stator yoke thickness, t_y towards magnetic flux density, $\boldsymbol{B}$	64
		4.2.2	The effects of the stator yoke thickness, t_y towards thrust, F	67
		4.2.3	Selection of the best model in the first stage of the PMLSM design	70
	4.3	Second Stage of the PMLSM design		71
		4.3.1	The effects of the stator slot opening parameters towards thrust, F	71
		4.3.2	The effects of the stator slot opening parameters towards cogging force, F_{cog}	74
		4.3.3	Thrust ratio	77
		4.3.4	Selection of the final model	81
		4.3.5	Performance indexes comparison	82
	4.4	Fabrication of the PMLSM		84
	4.5	The first modification of the PMLSM's mover		88
		4.5.1	Modification of the shaft material for Halbach arrangement	89
		4.5.2	Static thrust characteristics of the PMLSM	94
	4.6	The second modification of the PMLSM's mover		102
		4.6.1	Replacement of the Halbach arrangement to the N-S axial arrangement	102
		4.6.2	Static thrust characteristics of the PMLSM with axial arrangement	104
	4.7	Comparison of the static thrust characteristics		110
	4.8	Summary		118
5.	**CONCLUSION**			**120**
	5.1	General conclusion		120
	5.2	Achievement of the research objectives		121
	5.3	Research contribution		122
	5.4	Recommendation and future works		124
REFERENCES				**125**
APPENDICES				**140**

LIST OF TABLES

TABLE	TITLE	PAGE
1.1	Parameters of the PMLSM	9
2.1	PMLSM structure parameters	17
2.2	Cogging force reduction method	21
3.1	PMLSM stage 1 design parameters	49
3.2	PMLSM structure parameters	54
3.3	The permanent magnet dimensions	57
4.1	Percentage of thrust reduction (I = 3.0 A)	70
4.2	Highest average thrust for different permanent magnet arrangement	73
4.3	Lowest cogging force for different permanent magnet arrangement	76
4.4	Highest maximum thrust ratio, F_{max}: F_{cog}	80
4.5	Highest average thrust ratio, F_{ave}: F_{cog}	81
4.6	Structure parameters of the designed PMLSM	82
4.7	Performance indexes comparison of PMLSM	83
4.8	Specification of manufactured PMLSM	86
4.9	Average thrust of the PMLSM for different shaft combination	93
4.10	Thrust constant of the PMLSM with Halbach arrangement	102
4.11	Thrust constant of the PMLSM with Halbach arrangement	110
4.12	Maximum static thrust comparison	117
4.13	Static thrust comparison (Phase A, I = 2.0A)	118

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Types of linear motor	2
1.2	Comparison of the previous designed PMLSM with commercialized PMLSMs	5
1.3	F_{max} and F_{min} of phase C of the PMCLSM	5
1.4	Magnetic flux density, ***B*** distribution of the PMCLSM	7
2.1	Basic structure of the SRLSM	13
2.2	Basic structure of the hybrid LSTPM	15
2.3	Skeleton of the PMLSM (unit: mm)	16
2.4	Magnetic equivalent circuit of the PMLSM	23
2.5	Various permanent magnet arrangements	24
2.6	Distribution of magnetic flux lines of the PMLSM under radial arrangement	27
2.7	Distribution of magnetic flux lines of the PMLSM under axial arrangement	27
2.8	Distribution of magnetic flux lines of the PMLSM under Halbach arrangement	28
2.9	Distribution of magnetic flux density of the PMLSM with radial arrangement	28

2.10	Distribution of magnetic flux density of the PMLSM with axial arrangement	29
2.11	Distribution of magnetic flux density of the PMLSM with Halbach arrangement	30
2.12	***B*-*H*** saturation curve	34
2.13	***B*-*H*** curve of the SUS304	36
2.14	***B*-*H*** curve of the permanent magnets	39
3.1	Sample of FEM analysis	43
3.2	Flowchart of PMLSM design	46
3.3	Magnetic flux density, ***B*** of previous designed PMLSM	48
3.4	PMLSM basic structure parameters (unit: mm)	49
3.5	Flowchart of PMLSM stator yoke thickness design	50
3.6	Stator coil area	52
3.7	Flowchart of the second stage design	53
3.8	Stator slot opening structure parameters	55
3.9	Permeance model of slot opening	56
3.10	Various permanent magnet magnetization arrangement	57
3.11	Permeance model for Halbach arrangement	59
3.12	Permeance model for axial arrangement	59
3.13	Fabricated PMLSM	61
3.14	Flowchart of the PMLSM static thrust measurement	62
4.1	The position of stator where magnetic flux density, ***B*** distribute (unit: mm)	65
4.2	Magnetic flux density, ***B*** distribution on the PMLSM yoke	66
4.3	Thrust characteristics	68

4.4	Final PMLSM structure of the first stage (unit: mm)	70
4.5	PMLSM average thrust, F_{ave} (I = 3.0 A)	73
4.6	PMLSM cogging force, F_{cog}	75
4.7	Peak thrust to cogging force ratio, F_{max}: F_{cog}	78
4.8	Average thrust to cogging force ratio, F_{ave}: F_{cog}	78
4.9	PMLSM final model (unit: mm)	82
4.10	Fabricated PMLSM	87
4.11	Ring-shaped permanent magnet	88
4.12	Magnet bonder	88
4.13	Ring-shaped permanent magnets mounted on the SUS304 shaft	90
4.14	PMLSM with combination shaft (unit: mm)	91
4.15	Distribution of magnetic flux lines for different shaft combination	92
4.16	Average thrust of the PMLSM of different shaft combination	93
4.17	PMLSM mover with the modified shaft	93
4.18	Experiment setup for static thrust characteristic measurement	95
4.19	Schematic diagram for static thrust characteristic measurement	96
4.20	Comparison of cogging force, F_{cog} (Halbach arrangement)	97
4.21	Thrust characteristic of Phase A (Halbach arrangement)	98
4.22	Thrust characteristic of Phase B (Halbach arrangement)	99
4.23	Thrust characteristic of Phase C (Halbach arrangement)	100
4.24	Comparison of maximum and minimum thrust, F_{max} and F_{min} between simulated and measured results (Halbach arrangement)	101
4.25	Mover of the PMLSM with the modified shaft (after measurement)	103
4.26	PMLSM shaft with the axial arrangement	103
4.27	Cogging force, F_{cog} characteristics (Axial arrangement)	104

4.28	Thrust characteristic of Phase A (Axial arrangement)	106
4.29	Thrust characteristic of Phase B (Axial arrangement)	107
4.30	Thrust characteristic of Phase C (Axial arrangement)	108
4.31	Comparison of maximum and minimum thrust, F_{max} and F_{min} between simulated and measured results (Axial arrangement)	109
4.32	Static thrust characteristic comparison for phase A	113
4.33	Static thrust characteristic comparison for phase B	114
4.34	Static thrust characteristic comparison for phase C	115

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	The PMLSM construction drawing and detail.	140
B	Technical datasheet of LOCTITE AA 331	151
C	Technical datasheet of LOCTITE SF 7387	158
D	Performance indexes comparison data	160

LIST OF ABBREVIATIONS

a	-	Coil area
A	-	Coil total area
AC	-	Alternating current
$\boldsymbol{B}$	-	Magnetic flux density
$\boldsymbol{B}_{mg1}$	-	Amplitude of the first harmonic of the air gap magnetic flux density
DC	-	Direct current
$\boldsymbol{E}$	-	Electric field
E_f	-	No-load rms voltage induced
EMF	-	Electromotive force
F	-	Thrust
F_{cog}	-	Cogging force
F_{dx}	-	Electromagnetic thrust
F_{dxrel}	-	Reluctance thrust
F_{dxsyn}	-	Synchronous thrust
F_{left}	-	Force acting on the stator left-side end
F_{max}	-	Maximum thrust
F_{min}	-	Minimum thrust
F_{right}	-	Force acting on the stator right-side end
F_{slot}	-	Force acting on the stator slot
FEM	-	Finite Element Method

G	-	Motor constant square density
h_{pm}	-	Permanent magnet height
h_{st}	-	Stator height
h_t	-	Stator slot opening height
$\boldsymbol{H}$	-	Magnetic field intensity
$\boldsymbol{H}_c$	-	Coercivity
$\boldsymbol{H}_{ci}$	-	Remnant intrinsic coercivity
I	-	Current
$\boldsymbol{J}$	-	Current density
k	-	Magnetic susceptibility
k_f	-	Thrust constant
k_m	-	Motor constant
k_w	-	Armature winding coefficient
kg	-	Kilogram
l_{ave}	-	Stator average length
l_i	-	Stator core effective length
l_{st}	-	Stator length
l_t	-	Stator slot opening length
l_{total}	-	Stator total length
L	-	Inductance
LIM	-	Linear induction motor
LSM	-	Linear synchronous motor
LSTM	-	Linear stepper motor
m	-	Armature mass
m	-	Meter

N	-	Newton
N	-	Number of turns
N_1	-	Number of series per turn
NdFeB	-	Neodymium Iron Boron
NI	-	Magneto motive force
P_{in}	-	Input power
P_{elm}	-	Electromagnetic power
PAM	-	Permeance Analysis Method
PM	-	Permanent magnet
PMLSM	-	Permanent Magnet Linear Synchronous Motor
PMCLSM	-	Permanent Magnet Cylindrical Synchronous Linear Motor
r_{mover}	-	Mover radius
r_{pm}	-	Permanent magnet radius
r_s	-	Shaft radius
r_{total}	-	Total radius
rms	-	Root mean square
R_1	-	Armature winding resistance
$R_{T,st}$	-	Stator total resistance
R_{y1}	-	Permeance on the right-side and lower-side yoke thickness
R_{y2}	-	Permeance on the lower-side yoke thickness
R_{y3}	-	Permeance on the upper-side yoke thickness
R_{slot}	-	Permeance on the stator slot opening
SRLSM	-	Switched Reluctance Linear Synchronous Motor
t_y	-	Stator yoke thickness
t_{y1}	-	Upper-side stator yoke thickness

t_{y2}	-	Lower-side stator yoke thickness
T	-	Tesla
T_c	-	Curie temperature
v_s	-	Motor speed
V	-	Volt
V_1	-	Input voltage
V_{mot}	-	Motor volume
w_c	-	Coil width
w_{pm}	-	Permanent magnet width
W	-	Magnetic energy
W	-	Watt
Wb	-	Weber
X_{sq}	-	q-axis armature reactance
X_{sd}	-	d-axis armature reactance
α	-	Load angle
β	-	Slot opening angle
δ	-	Air gap length
$\mathcal{E}_F$	-	Measurement error of the thrust
ξ	-	Winding space factor
$\o_c$	-	Copper wire diameter
Φ_c	-	Flux induced by excited coil
Φ_f	-	Flux induced by permanent magnet
Φ_{f1}	-	Fundamental harmonic of the excitation magnetic flux density
ρ	-	Copper wire resistivity
τ	-	Torque

τ_c	-	Coil pitch
τ_{PM}	-	Permanent magnet pitch
μ	-	Permeability
Ω	-	Ohm
ΔP_{1w}	-	Armature winding loss

LIST OF PUBLICATIONS

Journal:

1. Mohd Nasir, N.A., Azhar, F., Firdaus, R.N., Wakiwaka, H., Tashiro, K., and Nirei, M., 2018. Design of the Permanent Magnet Linear Synchronous Motor for High Thrust and Low Cogging Force Performance. *Progress in Electromagnetics Research M* (*PIER M*), 63, pp. 83–92.

Conference:

1. Mohd Nasir, N.A., Azhar, F., Firdaus, R.N., 2018. Modification of the Permanent Magnet Linear Synchronous Motor's Shaft for Fixing Ring Shape Permanent Magnet. *Proceedings of Symposium on Electrical, Mechatronics and Applied Science 2018 (SEMA'18)*.
2. Azhar, F., Nasir, N.A.M., Firdaus, R.N., Wakiwaka, H., Tashiro, K., and Nirei, M., 2016. Comparison and Prediction of Performance Index of Permanent Magnet Linear Motor. *2016 IEEE International Conference on Power and Energy (PECon)*, pp. 558–563.

Book Chapter:

1. Mohd Nasir, N.A., Abdul Shukor, F.A., Raja Othman, R.N.F.K., Wakiwaka, H., and Tashiro, K., 2017. Design of Permanent Magnet Linear Synchronous Motor Stator to Improve Magnetic Flux Density Profile Toward High Thrust Density Performance. *Mohamed Ali M., Wahid H., Mohd Subha N., Sahlan S., Md. Yunus M., Wahap A. (eds.),*

Modeling, Design and Simulation of Systems, AsiaSim 2017, Communications in Computer and Information Science, 751, Singapore: Springer.

Other Publications:

1. Azhar, F., Mohd Nasir, N.A., Aqilah, F., Firdaus, R.N., Tashiro, K., and Wakiwaka, H., 2018. Performance Comparison of Permanent Magnet Linear Generator under 15S14P and 15S16P Configuration. *9th Asia-Pacific Symposium on Applied Electromagnetics and Mechanics (APSAEM 2018)*.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Over the years, linear motion is produced by a combination of rotational motor and motion translator. The motion translator such as ball screws, gears and belts are attached to the rotational motor shaft to convert rotational motion to linear motion (Wu and Yin, 2017). Despite vast applications of the linear motion system, it inherits several drawbacks such as low-acceleration performance, mechanical complexity and limitation, backlash and low impact load capacity (Huang et. al., 2012).

As an alternative, a linear motor is introduced to provide linear motion with the absence of all the mentioned motion translators. Due to the direct linear motion without motion translator, the linear motor can reduce some parts from its structure thus makes it has a simple structure, improve reliability and higher efficiency. Apart from that, it also has high dynamic response, high speed, high accuracy and vastly used in applications that require precise control (Wang and Howe, 2005).

Comprising of many advantages, linear motors are widely used in many industries for various type of applications. The implement of linear motors can be varied from low size system to large-scale high power applications. The examples of applications of linear motors for the low size system are the healthcare (Peng et. al., 2010) and household appliances (Suzuki et. al., 2017), (Kameda et. al., 2017). Meanwhile, large-scale applications including automated manufacturing (Gieras, 2013), embedded power generation (Yamanaka et. al., 2017), high-speed transportation (Inagaki et. al., 2017), and machine tools for various