STUDY AND ANALYSIS OF SWITCHED RELUCTANCE LINEAR MOTOR FOR HIGH PERFORMANCE CHARACTERISTICS

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MASTER OF ELECTRICAL ENGINEERING

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DECLARATION

I declare that this thesis entitled "Study And Analysis of Switched Reluctance Linear Motor For High Performance Characteristics" 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	:	....
Name	:	....
Date	:	....

APPROVAL

I hereby declare that I have read this dissertation and in my opinion this dissertation is sufficient in terms of scope and quality as a partial fulfillment of Master of Electrical Engineering (Power Electronics and Drives).

Signature	:	....
Supervisor Name	:	....
Date	:	....

DEDICATION

TO MY HUSBAND AND CHILDRENS,

Mohd Nazrin bin Mahmood,

Nur'ain Hazirah, *Muhammad Haziq*, *Muhammad Hadif* ,

Muhammad Hafiy, *Muhammad Hakeem*

MY LATE FATHER,

Hj. Geno bin Marto,

MY BELOVED MOTHER,

Hjh. Sujiah binti Sitam

Lastly, to all my family.

ABSTRACT

Linear motion applications are more demanding than ever before. A traditional linear motion involves an intermediate element that converts the turning motion of rotary motor into straight line travel. Linear motor can drive a linear motion load without intermediate gears, screws, bearings or crank shafts. Linear motors with permanent magnet are among the best candidates for applications requiring high acceleration, high speed and high precision. However, permanent magnet usage such as Neodymium Iron Boron (NdFeB) has led to increment of material cost due to the fluctuate price of rare earth material problem. According to the requirement of the application environment and motor performance, the alternative solutions such as electromagnet have recently become popular. Switched reluctance linear motor (SRLM) has been an attractive alternative for linear motion systems due to the simple structure, low starting current and mechanically robust. In order to overcome the issue of SRLM on low thrust, the optimization of some important parameters will influence the inductance and magnetic flux. Thus, the study covered the variation of three parameters which are air gap length, δ, teeth pitch,τ_p and teeth ratio, w_t/τ_p. The parameter has been varied for every SRLM's model in order to observe the effect of the SRLM when the test is carried out. In this design, Solidwork software is used to modelling the SRLM. The static characteristics of the SRLM are calculated using a finite element method analysis (FEM) which capable of predicting the SRLM thrust to analyse the SRLM performance. The performance of every model has been compared. The SRLM model with optimal performance according to the parameter configurations is when the air gap length, of 0.1 mm, 4 mm teeth pitch and 0.4 teeth ratio, where the thrust reaches 51 N when 1.0 A current is applied. In conclusions, every parameter contributes to increasing the value of thrust. The thrust increase when the airgap decrease and the thrust also increase when the pitch increase. The smaller percentage of teeth ratio also affects the thrust increase. Finally, maximum performance of SRLM models with appropriate combination size of parameter has been exposed as a guideline to other researcher. In future, it is recomended to study the functionality of dynamic characteristics of SRLM by developed the motor drive system to enhance the performance of SRLM motor.

ABSTRAK

*Aplikasi pergerakan linear mendapat lebih permintaan daripada sebelum ini. Pergerakan linear secara tradisional melibatkan elemen pengantara yang menukarkan gerakan berputar ke pergerakan linear. Motor linear boleh memacu beban secara gerakan linear tanpa menggunakan perantara seperti gear, skrew , bebola keluli dan aci engkol. Motor linear yang menggunakan magnet kekal adalah antara yang terbaik untuk aplikasi pergerakan yang memerlukan pecutan tinggi, kelajuan tinggi dan ketepatan tinggi. Walau bagaimanapun, penggunaan magnet kekal seperti "*Neodymium Iron Boron" *(NdFeB) telah menyebabkan kenaikan kos disebabkan masalah turun naik harga bahan nadir bumi. Berdasarkan kepada aplikasi keperluan persekitaran dan prestasi motor, penyelesaian seperti penggunaan elektromagnet menjadi pilihan yang popular baru-baru ini. Motor Linear Galangan Tersuis (SRLM) menjadi tarikan untuk digunakan didalam sistem pergerakan linear disebabkan oleh strukturnya yang mudah dan teguh serta nilai arus permulaan yang rendah. Kajian ini meliputi tiga variasi parameter iaitu panjang jurang udara,* δ *, panjang gigi,* τ_p *dan nisbah antara lebar gigi dan panjang gigi,* w_t/τ_p. *Kemudiannya nilai parameter ini diubah bagi setiap model SRLM untuk melihat kesannya apabila diuji. Dalam reka bentuk ini, perisian Solidwork digunakan untuk merekabentuk model-model SRLM. Ciri-ciri tetap SRLM dikira menggunakan analisis kaedah unsur terhingga (FEM) yang berkemampuan untuk menjangka daya tujahan SRLM bagi menganalisa prestasi SRLM. Prestasi setiap model SRLM dibandingkan. Keputusan menunjukkan bahawa SRLM menghasilkan daya tujahan yang lebih baik dan dipercayai dengan panjang jurang udara,* δ *nya ialah 0.1 mm dan 4 mm panjang gigi,* τ_p *dan 0.4 nisbah gigi,* w_t/τ_p *di mana ia mencapai daya tujahan sehingga 51 N apabila arus 1.0 A dikenakan. Kesimpulannya, setiap parameter menyumbang kepada kenaikan nilai daya tujahan yang dihasilkan. Daya tujahan meningkat apabila panjang jurang udara berkurang dan juga apabila panjang gigi bertambah. Peratusan nisbah antara lebar gigi dan panjang gigi yang kecil juga memberi kesan kepada peningkatan daya tujahan. Akhirnya, model SRLM dengan prestasi maksimum yang dihasilkan daripada gabungan saiz parameter yang bersesuaian telah dipaparkan untuk dijadikan bahan panduan kepada penyelidik lain. Pada masa akan datang, adalah disarankan untuk mengkaji ciri-ciri dinamik SRLM dengan membangunkan sistem pemanduan motor bagi meningkatkan prestasi motor SRLM.*

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μ_o	-	Permeability of free space
A	-	Area
AC	-	alternating current
B	-	magnetic flux density
b_{m}	-	Magnet flux density
b_{rt}	-	Rotor flux density
b_{sp}	-	Stator pole flux density
c_{h}	-	Coil height
c_{s}	-	Coil wire diameter
c_{w}	-	Coil width
d_1	-	Distance slot opening
Dc	-	Direct current
FEM	-	Finite Element Method
F_x	-	Thrust
hc	-	Coil height
h_m	-	Height of mover
h_s	-	Height of Stator
H	-	Magnetic flux intensity
l	-	Copper wire length
I	-	Current

L	-	Inductance
LIM	-	Linear Induction Motor
LIM	-	Linear Induction Motor
LSM	-	Linear Synchronous Motor
LSTM	-	Linear Stepper Motor
N	-	Number of turn
NdFeB	-	Neodymium-iron-boron
$Ø_{c}$	-	Copper wire diameter
PM	-	Permanent magnets
PMLSM	-	Permanent Magnet Linear Synchronous Motor
SRLM	-	Switch Reluctance Linear Motor
th_{m}	-	Mover teeth height
th_{s}	-	Stator teeth height
w_{t}	-	Teeth width
w_{ts}	-	Stator teeth width
w_{tm}	-	Mover teeth width
w_{t}/τ_{p}	-	Teeth ratio
w_c	-	Coil width
w_m	-	Height of stator
w_s	-	Width of Stator
δ	-	Air gap
ε	-	Winding factor
τ_p	-	Teeth pitch
Φ	-	Flux
W	-	Energy stored

ρ	-	Copper resistivity

CHAPTER 1

INTRODUCTION

This chapter gives a brief introduction to the research on the design of the Switched Reluctance Linear Motor (SRLM). The main objective of the research is to model the SRLM, simulate and evaluate its performance characteristics and identify which model the best performance. It consists of a general introduction of SRLM, problem statement, objectives and scope of the study. Lastly, the summary of the content for each chapter is presented.

1.1 Introduction to the Switched Reluctance Linear Motor (SRLM)

In recent years, the SRLM became popular for research and development compared to Linear Induction Motor (LIM) or even to its counterpart which is the permanent magnet linear synchronous motor (PMLSM). The SRLM has been alternative due to a factor of its simple and robust structure where the windings only exist either on stator or mover part. It can perform well even in severe temperature variations due to the absence of permanent magnet. On top of that, the SRLM inherent easy maintenance, relatively low manufacturing and operational cost (Daldaban, F., Ustkoyuncu. N., 2006)(Hirayama, T., & Kawabata, S. 2017). The low manufacturing and operational cost feature of the SRLM are not only due to the simple structure, but also caused by the absence of permanent magnet inside the structure. The SRLM does not require a mechanical coupling, lead and brush screws, unlike conventional systems that use rotary motors to generate linear movement (W.Gan et. al, 2008).

The SRLM is an electromechanical device that develops motion in a single axis, without the use of a mechanism to convert rotary motion to linear motion. Unlike rotary electric motors, the linear motor has a start and an end to its travel. The stator and rotor are unrolled so that instead of producing a torque it produces thrust along its length. Motion is produced as a result of the variable reluctance in the air gap between the mover and the stator. Generally, the SRLM operations are nearly the same with rotational switch reluctance motor. A magnetic field is created in the mover by sending current through the copper coil. When a mover winding is energized, reluctance thrust is produced by the tendency of the mover to move to its minimum reluctance position.

The advanced development of power electronic devices, digital signal processing and control strategies increase the reliability and effectiveness of the switched reluctance type machine, also contributes the SRLM usage wider. The SRLM usually used as the control objects for the high-precision position control applications, high power application, high temperature and high current (Li et. al. 2018). The SRLM were used in closed-loop control especially in robotics and biomedical application by using PI controller, hysteresis controller and FDF (Zaafrane et. al. 2013). The SRLM commonly used in transportation like Light Rail Transit (LRT), lift, pick and place application, conveyor belts, printing and scanning equipment.

However, the SRLM has some drawbacks such produces high thrust ripples and acoustic noise. The thrust ripples production cannot be avoided due to the operating method by AC voltage. It usually causes vibration and acoustic noise during the operation process, hence it reduce the motor integration in high precision position and speed application. The vibration and acoustic noise are usually high in SRLM because of the topology of the structures (N C Lenin and Arumugam, 2010). While (Bianchi N et. al, 2002 cited in Garc’ıa Amoros.J, 2015) found that the SRLM generate lower thrust compared to the hybrid type of SRLM which contain permanent magnet for approximately 60%.

1.2 Problem Statement

There are various types of linear motors currently available in the market. It comes in different types, shapes and sizes, operating principles and control. The linear motor can be classified as permanent magnet type and switched reluctance type. Generally, the permanent magnet types of linear motor are known as the high performance machine. Due to the excellent performance of permanent magnet type especially in term of dynamic response and thrust density made many researchers put a lot of effort to develop it.

The main component of a linear motor is the permanent magnet. Recently, the motor development facing supply chain problem due to the price of rare earth material fluctuates greatly. The price of neodymium-iron-boron (NdFeB) permanent magnets (PM) has fluctuated greatly in 2010 and 2011, owing to geopolitical concerns relating to the security of supply (Widmer et. al., 2015). It's led to an increment of the material cost. The permanent magnet linear motor is expensive due to the use of the permanent magnets used in the motor and the sensing technologies used in the design. The amount of permanent magnet increase with the length of the motor which increases the cost of the linear motor. It became the main constraint for system designers to consider the linear motor design. Whilst the price has become more stable and more reasonable, responsibilities in the environmental sustainability of these materials have further encouraged users to consider alternatives. (Dorrell et. al., 2010) conclude whatever the price of rare earth magnets, it is generally recognized that their elimination from electrical machines will lead to a cost reduction.

The cost and difficulty of developing suitable electromagnets had motivated the researcher to study more on SRLM especially on the motor design due on the absence of permanent magnet inside the structure. The different type of magnet material is affected on their respond to magnetic fields thus affecting motor performance. Figure 1.1 shows the comparisons of the maximum energy product between the magnetic materials.

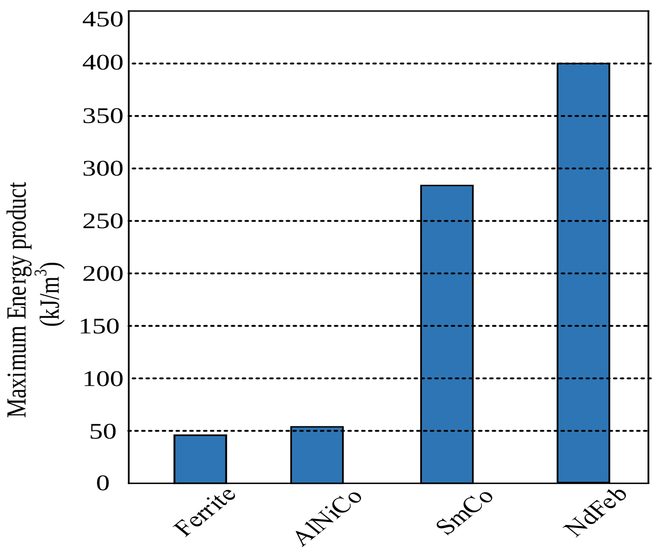

Figure 1.1: Comparison between the Maximum Energy Product of differing hard magnetic materials (Widmer et. al., 2015)

The NdFeB magnet has high performance compared to other magnetic material like Aluminium Nickel Cobalt (ALNiCo), Samarium Cobalt (SmCo) and Ferrite. Maximum Energy Product is the measure of the magnetic energy which can be stored, per unit volume, by a magnetic material, it is calculated as the maximum product of a material's residual magnetic flux density or degree of magnetisation and its coercivity (the ability to resist demagnetisation once magnetised) (Widmer et. al., 2015) . NdFeB magnets generate a very strong magnetic field even in a very small volume but the major drawback is a higher cost. This material is more valuable, so the price of raw materials is doubly more expensive. At the same time, the cost of manufacturing and production of machine prices also increased. Reducing the volume of the high performance NdFeB magnets will reduce the machine cost at the expense of some flux density. Many manufacturer companies shifted from rare earth permanent magnet to ferrite magnet. However, the use of ferrite causes the performance of the motor drop and the weight of the motor increase (Ding, 2014).

Other important considerations relate to permanent magnet usage is the limitation in the performance of motor when using this material. A permanent magnet is always ‘on’ whether the motor there are used is operational or not. This means that when a permanent magnet exists, even with no electrical current applied, magnetic flux still present. Thus, it leads to undesirable effect occur. Cogging is caused by the attraction between permanent magnets and ferromagnetic cores. It is the term used to describe the way in which the motors, when not under load, may produce a fluctuating thrust as they move.This cogging has been identified as a cause of vibration, friction, noise and problems in electric drive systems that can cause the motor performance drop.

A further drawback is that the performance of any device working with permanents magnets varies with temperature. Permanent magnet flux density will change as temperature changes. The flux density decreases temporarily and will begin to recover after the magnet cools. If the maximum temperature rating called curie point of the magnets is exceeded, partial demagnetization will occur and permanently alter the performance of the permanent magnet hence affect the motor performance. The energy will free the magnetic dipoles from their order. The long range order is destroyed and the material will have little to no magnetization. The application on transportation usually facing this problem (Ravikumar et. al., 2016).

It is therefore, worthwhile to consider alternatives other than the use of rare earth permanent magnets, whether intended to reduce the amount of rare earth materials or replace them completely. Some researcher suggests use ferrite magnet (Eklund et. al., 2014). Ferrite magnet results from combination iron oxide with the metals Strontium, Barium or Cobalt. There have low remanance flux density and low coercivity that need to concern. According to expert, (TDK, 2014), ferrite magnet having only one third of the remanance flux density of NdFeB magnets to obtain a competitive thrust density. While the coercivity of ferrite magnet is about one fifth to one third of the NdFeB magnet. However, the ferrite magnet has characteristics which the coercivity increase with temperature and making them to less sensitive to sudden demagnetization in demanding application. The performance will be drop despite the weight of the motor increased.

A second effort has been reported is by using a non-permanent magnet machine (Widmer et. al., 2015). Some manufacturer currently prefers to use the non-permanent magnet machine in order to ensure stability and competitive cost. The induction motor one of the most commonly used. Induction motors contain no permanent magnetic materials, thus no magnetic attraction occurs at the assembly. Instead, they operate by inducing electrical currents in conductors in the mover from the stator, and these currents in turn give rise to a magnetic field in the mover and thus produce thrust. The dependency from the stator to enable the mover run, showing that induction motor has lower thrust density. An induction motor is also known as an asynchronous motor because it runs at speed less than its synchronous speed. This difference between the actual speed and synchronous speed is called the slip. Hence slip is an essential feature for the proper working of the induction motor and is necessary for producing torque. Without slip, the motor cannot operate, but slip become to the limitation of induction motor due to the speed constant and it is not inherently capable of providing variable speed operation. The slip increases with