“STUDY ON CHARACTERISTIC OF THE PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR”

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DECLARATION

I declare that this thesis entitled “STUDY ON CHARACTERISTIC OF THE PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR” 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 : HADI BIN ALLOHA

Date : 3rd July 2021

APPROVAL

I hereby declare that I have checked this report entitled “STUDY ON CHARACTERISTIC OF THE PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

Signature : ....

Supervisor Name : FAIRUL AZHAR ABDUL SHUKOR

Date : 5/7/2021

DEDICATIONS

To the most deservingly, my precious, God-sent parents.

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ABSTRACT

Conventionally, linear motion produced by electric machinery requires a motion translation process. Consequently, a lot of issues emerge such as slower time response and high maintenance due to the mechanical parts of the process. All of these constitute to a complex and complicated system. With the invention of linear motor, these drawbacks are completely ruled out. With no additional components to produce linear motion, linear motor has a lot of advantages. This project aims to study the characteristic of a previously built Permanent Magnet Linear Synchronous Motor (PMLSM). The scopes of this project are to measure the characteristics of the PMLSM such as static thrust, frequency characteristic as well as the current response. A 3-phase inverter was designed and fabricated to be used for the current response measurement. Unfortunately, due to time constraint the 3-phase inverter could not be tested out which then impeded the measurement for the PMLSM current response. The current response was only measured through simulation. The simulation revealed that the current response decreases as inverter frequency increases. It was also found out that the static thrust of the PMLSM is generally consistent when compared against the simulation profile. From the frequency characteristics measurement, it is suggested that the PMLSM to be supplied with frequency not more than 100 Hz as the value of resistance of the motor coils is much lower and stable within this range. This research will contribute to the whole future development of the project where the performance of the PMLSM is determined and later can be decided if modification to the motor design will be needed or not. Ultimately, with all the characteristics of the PMLSM known, a motor driver can be developed.

ABSTRAK

Secara konvensionalnya, gerakan linear yang dihasilkan oleh mesin elektrik perlu melalui atau menjalani proses penukaran pergerakan. Disebabkan adanya bahagian mekanikal dalam proses tersebut, pelbagai isu dan masalah yang timbul seperti tindak balas yang perlahan dan penyelenggaraan yang tinggi. Oleh hal yang demikian, sistem tersebut menjadi lebih rumit dan kompleks. Maka, dengan penemuan motor linear, masalah-masalah tersebut dapat diatasi. Motor linear mempunyai banyak kelebihan kerana ianya tidak memerlukan proses penukaran pergerakan untuk menghasilkan gerakan linear. Tujuan projek ini dijalankan adalah untuk mengkaji ciri-ciri sebuah motor segerak linear bermagnet kekal (PMLSM) yang telah pun dibina sebelum ini. Skop projek ini adalah untuk mengukur ciri-ciri PMLSM tersebut seperti tujahan statik, ciri frekuensi, dan juga tindak balas arus. Sebuah litar penyongsang 3 fasa telah direka bentuk bagi tujuan untuk mengukur tindak balas arus PMLSM tersebut. Papan litar bercetak (PCB) penyongsang tersebut telah pun difabrikasi dan parameter reka bentuk litar penyongsang 3 fasa ini telah pun disahkan oleh keputusan yang didapati melalui simulasi. Malangnya, disebabkan oleh kekangan masa, penyongsang 3 fasa tersebut tidak dapat diuji sepenuhnya. Oleh disebabkan ini, tindak balas arus dan tujahan PMLSM juga tidak dapat diukur secara eksperimen tetapi hanya diukur melalui perisian simulasi MATLAB Simulink. Tindak balas arus PMLSM tersebut didapati menjadi semakin perlahan apabila frekuensi penyongsang 3 fasa di naikkan. Hasil dapatan dari eksperimen tujahan statik pula, konklusi boleh dibuat bahawasanya keputusan eksperimen secara amnya sepadan dengan keputusan dari simulasi. Manakala hasil eksperimen ciri frekuensi mendapati bahawasanya frekuensi yang sesuai untuk digunakan untuk bekalan kuasa kepada PMLSM adalah dibawah 100 Hz. Hal ini kerana, di dalam linkungan frekuensi tersebut, rintangan gegelung PMLSM adalah rendah dan stabil. Kajian ini akan menyumbang kepada pembangunan keseluruhan projek pada masa hadapan. Melalui kajian ini, prestasi PMLSM dapat diuji dan keputusan samada perlu atau tidak untuk mengubah suai reka bentuk motor tersebut boleh diambil kira dan dipertimbangkan. Akhirnya, dengan mengetahui perincian tentang ciri-ciri PMLSM tersebut, sebuah pemacu boleh dibangunkan.

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LIST OF SYMBOLS AND ABBREVIATIONS

PMLSM	-	Permanent Magnet Linear Synchronous Motor
SRLSM		Switch Reluctance Linear Synchronous Motor
PM	-	Permanent Magnet
NdFeB	-	Neodymium Iron Boron
FEM	-	Finite Element Method
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
BJT	-	Bipolar Junction Transistor
PCB	-	Printed Circuit Board
Al	-	Aluminium
Ni	-	Nickel
Co	-	Cobalt
Fe	-	Iron
REO	-	Rare-earth oxide
EMF	-	Electromotive force
AC	-	Alternating current
DC	-	Dircet current
E_f	-	No-load rms voltage induced
k_w	-	Armature winding coefficient
Φ_f	-	Magnetic flux from permanent magnet
Φ_{f1}	-	Fundamental harmonic of the excitation magnetic flux density
r_{total}	-	Total radius
L_i	-	Effective length of stator core
B_{mg1}	-	Amplitude of the first harmonic of the airgap magnetic flux density
τ	-	Pole pitch
Wb	-	Weber
P_{elm}	-	Electromagnetic power
Xsd	-	*d*-axis armature reactance
δ	-	Load angle between input voltage and E_f
F_{dx}	-	Electromagnetic thrust
W	-	Watt
N	-	Newton
F_{dxsyn}	-	Synchronous thrust
F_{dxsrel}	-	Reluctance thrust
H	-	Magnetic field intensity
B	-	Magnetic flux density
μ	-	Magnetic permeability
dA	-	Differential unit of area
L	-	Inductance
R	-	Resistance
Z	-	Impedance
θ	-	Phase difference
ω	-	Angular frequency
T	-	Period

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CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter describes the introduction of the project in general. It starts with the project background that narrates the big picture of the whole thing. Then, it follows with the problem statement which will highlight why this research project needs to be conducted. With all the problems laid out, the objectives, scopes and limitations of the project will be discussed.

1.2 Project Background

An electric machine is an instrument that is capable to convert both electrical energy to mechanical energy and mechanical energy to electrical energy. The former is called a motor and the latter is called a generator [1]. Primarily, there are two types of motor which are DC and AC motors. Since most power supply comes in AC form, it is quite normal to see a lot of AC motors are used in many field [2]. The most common used of AC motors type are induction motor and synchronous motor. Due to its constant-speed characteristics, synchronous motors are widely used in application where a specific acceleration or speed must be maintained at all times. It is also known for its capability for a power factor correction. To compare with other types of AC motor, synchronous motor can be rather expensive for lower power rating. Be that as it may, for power rating of 100 horsepower and higher, it may be economically feasible [2]. Synchronous motor can be categorized further into rotational and linear synchronous motor. Without the need for translation of motion, linear motor can produce direct linear movement [3]. Generally, there are two types of linear synchronous motor namely switch reluctance linear synchronous motor (SRLSM) and permanent magnet linear synchronous motor (PMLSM). Because of the usage of permanent magnet (PM) in the PMLSM, it has the advantage of a higher thrust density [4]. That being the case, characteristics of a PMLSM will be studied in this research project.

1.3 Problem Statement

Conventionally, to produce a linear motion from a rotary motor, components such as screws, gears and shaft will be required. Under those circumstances, the design of the entire system will be complex and complicated. Not to mention, with the need for a motion translator, skilled workers are needed to install the bolts, screws, and beltings as these tasks cannot be simply done by just anyone without the competency and experience in mechanical work. Pertaining to mechanical parts, lubrication is just another additional concern that should be well-maintained [5]. Other disadvantage of a rotary motor in producing linear motion is slower time response. This is understandable since the rotational motion needed to be converted via motion translator first in order to produce a linear motion. As introduced in the previous sub-chapter, linear motor can eliminate of all the drawbacks especially the motion translator [6]. Not only a linear motor is proven to have higher speed and high accuracy [7], the structure is a lot simpler due to the cutback of the mechanical components such as gears and belts [3].

In regards to linear motor, a PMLSM has been built and presented in [8]. Nevertheless, to date, only the thrust is measured. Other characteristics are yet to be measured. Hence, this is why this project research is very much needed to study the characteristics of the PMLSM.

1.4 Motivation

As the world moving forward towards Industrial Revolution 4.0, industry players are anticipating major shift on how things work. Among other things, the main changes will specially affected and benefited to the manufacturing method and process [9]. With this paramount change, the industry is looking for a better machine with better performance. Among other things, advance tools such as the use of robots is one of the eight components of Industrial Revolution 4.0. The use of state-of-the-art robots in the new dawn of the industrial era aims to make everything works faster with minimal conventional manpower [10]. The manufacturing industry especially, are starting to convert their business into smart factories that focuses on design principle of interoperability. The significance of this design principle will increase the machine life cycle, decrease industrial waste and most importantly will yield in faster and more efficient processes [11].

Linear motor is known for its high accuracy and controllability which just might fulfill the needs of the industry in the preparation for the upcoming and unavoidable new industrial paradigm. Currently, the developed PMLSM is not fully utilized. This is because, the characteristics of the PMLSM are yet to be measured and determined. Through this research, the information required for the development of a dedicated motor drive for the PMLSM can be acquired. Hence, together with the exclusively designed motor drive, the full potential of the PMLSM could be maximally utilized.

1.5 Objectives

The objectives of the project research are:

1. To design and perform experimental setup to acquire PMLSM performance characteristics.
2. To design and develop a simple motor driving circuit to be used during the performance characteristics experiment.
3. To suggest operational condition for the PMLSM based on the performance characteristics obtained.

1.6 Scope and Limitation

There are two main focal points of the project. The first focus of the research is to measure PMLSM characteristics namely static thrust, frequency characteristics and last but not least current response. In doing so, which brings to the second subject matter, a 3-phase inverter must be designed for the purpose of the current response measurement.

As for the limitation of the project, the maximum current for coil winding of the PMLSM is only up to 2A. The range of frequency for the measurement of frequency characteristic is 12Hz-10kHz. Meanwhile the frequency (inverter frequency) for the simulation of the current response measurement is 12 Hz, 30 Hz, 50 Hz and 70 Hz.

1.7 Thesis Outline

This project thesis consists of five main chapters. **Chapter 1** introduces to the project background, problem statement, objectives, scope and limitation. In short, this chapter describe the overview of the whole project. **Chapter 2** narrates the literature review about the PMLSM. This chapter also unfolds the underlying concepts or theory behind the PMLSM. **Chapter 3** covers the details of the method and procedure that are used to successfully achieved all of the objectives of the project. **Chapter 4** presents the preliminary results of the project. The results are also discussed and analyzed in this chapter. **Chapter 5** describes the conclusion of the overall progress of the project as well as the recommendation and suggestion for future project development.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Linear Synchronous Motor (PMLSM)

The main feature of a PMLSM, unlike a normal rotary motor, it can produce linear motion without any additional components such as gears, screws, or shafts. The mechanical motion of a linear synchronous motor (LSM) is in synchronism with the magnetic field [12]. This means that the speed of the motor is the same to the speed of the travelling magnetic field. Since the PMLSM use Neodymium Iron Boron Magnet or NdFeB (N-42) [13], it does not need DC excitation current which makes it a self-starting motor. Similar to a rotary motor, the PMSLM structure consists of rotor as well as stator. Nevertheless, for the moving part, it is labelled as mover instead of rotor. The PMLSM produces linear force, F instead of torque (rotational force) as it moves along the specified length [13].

Due to no additional use of mechanical parts to produce linear motion as mentioned earlier, the PMLSM has advantages in terms of reliability. This is because, the wear and tear in the gears or shafts are completely eliminated which also makes the PMLSM to have a lower and cheaper maintenance. Not only that, without the need of having motion translation elements to convert rotary to linear motion, the PMLSM yields a higher efficiency as the losses due to frictions can be ruled out [6]. In addition, its excellent performance in high speed accuracy as well as the high controllability [14] are another contributing factors to the wide usage of PMLSM in many fields.

Just as much as the PMLSM to have outstanding advantages, it would be naïve and ignorant for one not to consider the disadvantages. On account of having permanent magnets in its structure, the PMLSM can be rather expensive. This is because the rare-earth permanent magnet (REPM) that are usually used in the PMLSM structure such as neodymium or samarium-cobalt magnets is very costly in the markets [15]. However, Figure 2.1 shows that the trend of Neodymium Oxide worldwide price has reduced since 2011 and expected to continue to decrease because of the China's mass production of rare-earth oxide (REO) in recent years [16]. Apart from that, cogging force produced as a result of interaction between the stator core and the mover (permanent magnet) is just another drawback or downside of the PMLSM. Consequently, the efficiency, controllability and the average thrust force of the motor may deteriorate due to the cogging [17].

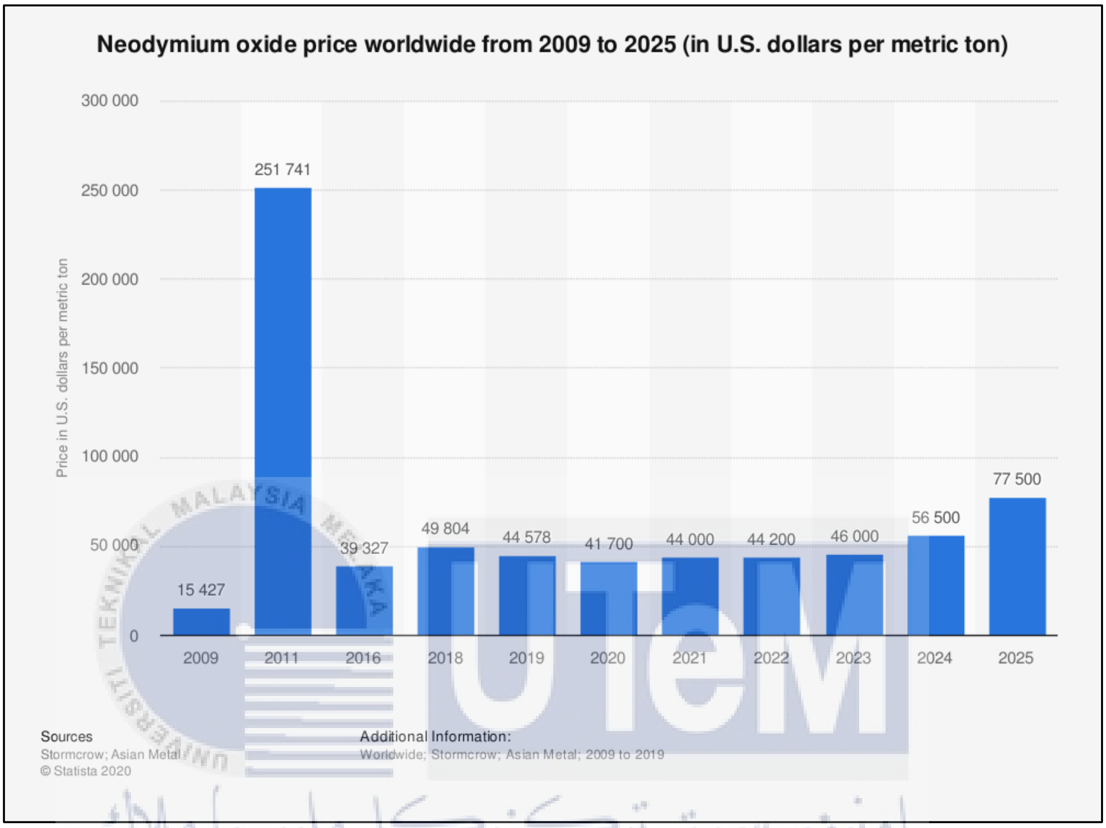

Figure 2.1 Neodymium oxide price trend worldwide from 2009 to 2025

2.2 Basic Principle of the Designed PMLSM

The previously designed PMLSM for this project is an 8-pole type that comes with a 3-phase supply and comprise of 6 cylindrical slots. As shown in Figure 2.2 below, for the stator, every each of the six slots is built with its own coil. On the other hand, the mover part is made up of an array of ring-shaped permanent magnets fixed and fastened to a shaft. The total radius, r_{total} of the PMLSM is 25mm [8].

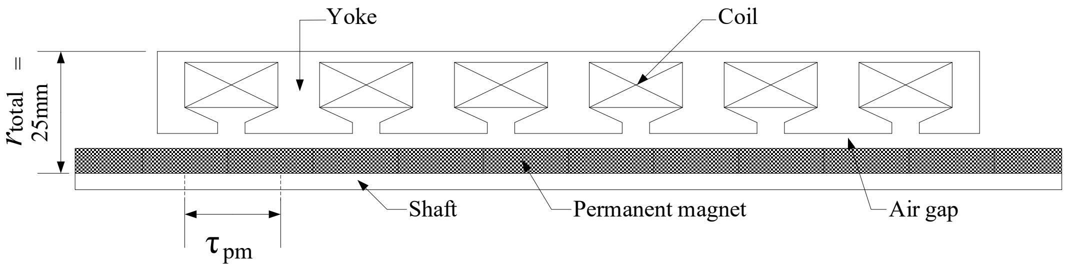

Figure 2.2 Axial cross-section of the designed PMLSM structure

Theoretically, the thrust generation from the PMLSM is determined by electrical and magnetic sources. Electrical source comes from the current, *I* fed to the coil at the stator. On the other hand, for the magnetic element, the PM and coil influenced the magnetic flux density as well as the inductance which then affect the production of the thrust [8].

The no-load rms voltage induced (EMF), E_f in one phase of armature winding by PM excitation flux is expressed in the Equation (2-1) below where N_1 is the number of the armature turns per phase, k_w is the armature winding coefficient and Φ_f is the magnetic flux from the PM [12].

$$E_f = \pi\sqrt{2}f\ N_1 k_w \Phi_f \tag{2-1}$$

The fundamental harmonic of the excitation magnetic flux density Φ_{f1} without armature reaction is expressed in Equation (2-2) where L_i is the length that is effective of the stator core in mm, B_{mg1} is the amplitude of the first harmonic of the airgap magnetic flux density, and the τ is the pole pitch [12]. The unit of Φ_{f1} is Weber (Wb).

$$\Phi_{f1} = L_i \int_0^T B_{mg1} \sin\left(\frac{\pi}{T}x\right) dx = \frac{2}{\pi}\tau L_i B_{mg1} \tag{2-2}$$

Since the armature core loss can be neglected, the electromagnetic power, P_{elm}, can simply be calculated by subtracting the armature winding loss from the input power, ΔP_{1w}. Hence, the electromagnetic power, P_{elm} can be denoted as in Equation (2-3) where m is the number of phases, V_1 is the input voltage in volt (V), *X*sd is the *d*-axis armature reactance (Ω), and the δ is the load angle between V_1 and E_f. Noted that, the equation is derived by assuming that the armature winding resistance is equal to zero [12].

$$P_{elm} = m\left[\frac{V_1 E_f}{X_{sd}} \sin\delta + \frac{{V_1}^2}{2}\left(\frac{1}{X_{eq}} - \frac{1}{X_{sd}}\right)\sin 2\delta\right] \tag{2-3}$$

The electromagnetic thrust, F_{dx} developed by a salient-pole LSM can be expressed in the Equation (2-4). By neglecting the armature core loss, the general equation can be derived further by taking the Equation (2-3) into Equation (2-4) to form a new Equation (2-5) where v_s is the velocity in (m/s) [12]. The unit of P_{elm} and F_{dx} are Watt (W) and Newton (N) respectively.

$$F_{dx} = \frac{P_{elm}}{v_s} \tag{2-4}$$

$$F_{dx} = \frac{m}{v_s}\left[\frac{V_1 E_f}{X_{sd}}\sin\delta + \frac{{V_1}^2}{2}\left(\frac{1}{X_{eq}} - \frac{1}{X_{sd}}\right)\sin 2\delta\right] \tag{2-5}$$

As shown in Equation (2-6), the electromagnetic thrust, F_{dx} produced by a salient pole-synchronous motor is made up of two components namely synchronous thrust, F_{dxsyn} and reluctance thrust, F_{dxsrel}. The synchronous thrust is a function of both input voltage, V_1 and the excitation EMF, E_f. Meanwhile, the reluctance thrust depends only on the input voltage, V_1 and also exists in an unexcited machine ($E_f = 0$) provided that the value of the d-axis synchronous reactance, X_{sd} and the q-axis synchronous reactance, X_{sq} are not equal ($X_{sd} \neq X_{sq}$). For surface configurations of PMs, $X_{sd} \approx X_{sq}$ (if the magnetic saturation is neglected). Hence, the electromagnetic thrust, F_{dx} developed by the PMLSM can be expressed as in Equation (2-7) [12].

$$F_{dx} = F_{dxsync} + F_{dxrel} \tag{2-6}$$

$$F_{dx} \approx F_{dxsyn} = \frac{m_1}{v_2}\frac{V_1 E_f}{X_{sd}}\sin\delta \tag{2-7}$$

From the Equation (2-7), it can be concluded that the input voltage, V_1 and the excitation EMF, E_f are directly proportional to the electromagnetic thrust, F_{dx} produced by the designed PMLSM.

2.3 Fundamental Concepts

When dealing with any electric machine, electromagnetic theory (EMT) is the first elementary and most basic knowledge that needs to be comprehend. This is because just about all practical motor or generators transform energy from one type to another by magnetic field operation [1].