UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF MULTI-CYLINDER LINEAR MACHINE POWERTRAIN SYSTEM FOR ELECTRIC VEHICLE

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DEVELOPMENT OF MULTI-CYLINDER LINEAR MACHINE POWERTRAIN SYSTEM FOR ELECTRIC VEHICLE

By

NORRAMLEE BIN MOHAMED NOOR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2021

DEDICATION

Dedicated to
My Parents,
My lovely Wife, Hasnah Ismail and Noorrullhuda Abd Halim
My caring Son: Muhammad Irfan Aqil, and
My beautiful Daughters: Nur Ezzati, Nur Anis Aqilah, Nur Aina Shamina and Nur Elena Sofia
My teachers who providing me with best education,
All the people in my life who touch my heart
With Love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

DEVLOPMENT OF MULTI-CYLINDER LINEAR MACHINE POWERTRAIN SYSTEM FOR ELECTRIC VEHICLE

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March 2021

Chairman : Professor Ishak Aris, PhD
Faculty : Engineering

Electric vehicles (EVs) have been recognized as a crucial pillar of a solution to significantly mitigate the detrimental impacts of transportation while improving energy consumption efficiency. Electric machines are classified into two types: rotational machines and linear machines. These EVs utilize rotating electric machines to transmit power from the motor shaft to the transmission and, subsequently, to the wheels through differential gears.

However, the electric rotating machines of EV are expensive, have a complicated control system, heavy weight and must be larger in size to run the vehicle. Furthermore, the rotating electric motor of EVs suffers from excessive exposure temperature due to lengthy operation, which may cause the motor to fail, while the magnet is expensive. They also necessitate a specialised power transmission system in order to run the vehicle. This will increase the cost of the cars. On the other hand, the disadvantage of an internal combustion engine (ICE) is the friction between the piston rings, piston skirt, and cylinder linear that needs much effort to overcome friction, to outperform fuel efficiency.

Therefore, a new proposed linear machine, known as the multi-cylinder linear motor powertrain system (McLMPS), has been conceived and developed to minimize the weight, size, and fuel consumption of the ICE. The McLMPS does not require the use of a specific power transmission system to verify its performance in the EV. The McLMPS prototype comprises various parts, namely a multi-cylinder linear machine (McLM), a multi-plate crankshaft position sensor (MpCPS) system, other mechanical components, and the drive system, which includes a control unit and a machine operating algorithm. The proposed McLM structure was selected due to its simple structure, high thrust, lack of a magnet, and minimal cogging force issue.

The proposed McLMPS was simulated using MATLAB/Simulink. The high level class was simulated used current about 250A at 300V battery supply, the plunger output force was 55.1kN with a torque of about 97.5Nm and motor power was about 67.5kW. From the simulation results, the efficiency of the proposed McLMPS was about 90%, whereas the experimental results has an efficiency of around 75%. The experimental results show lower efficiency compared to simulation results because the first prototype of McLMPS was built based on quarter scale. On the other hand, the experimental results of the McLMPS is more efficient than the Perodua Kancil ICE, but less efficient than the Renault Zoe EV.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN SISTEM POWERTRAIN PELBAGAI SILINDER MESIN LELURUS UNTUK KENDERAAN ELEKTRIK

Oleh

NORRAMLEE BIN MOHAMED NOOR

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Kenderaan elektrik (EV) telah diakui sebagai pilar penting dari penyelesaian secara signifikan untuk mengurangkan kesan buruk terhadap pengangkutan sambil meningkatkan kecekapan penggunaan tenaga. Mesin elektrik diklasifikasikan kepada dua jenis: mesin putaran dan mesin lelurus. EV ini menggunakan mesin elektrik yang berputar untuk menghantar kuasa dari motor aci ke transmisi dan, selanjuttya, ke roda melalui gear yang berbeza.

Walau bagaimanapun, mesin kenderaan electric (EV) yang berputar adalah mahal, mempunyai sistem kawalan yang rumit, berat dan saiznya lebih besar untuk menjalankan kenderaan. Selanjutnya, motor kenderaan elektrik yang berputar mengalami suhu pendedahan yang berlebihan kerana beroperasi agak lama menyebabkan motor tersebut gagal berfungsi, manakala magnetnya adalah mahal. Ia juga memerlukan sistem penghantaran kuasa khusus untuk menjalankan kenderaan. Ini menyebabkan kos kereta meningkatkan. Sebaliknya, mesin pembakaran dalaman (ICE) mempunyai kelemahan iaitu geseran antara cincin omboh, skirt omboh, dan lelurus silinder dimana ia memerlukan banyak usaha untuk mengatasi geseran pada kecekapan bahan api.

Oleh itu, mesin linier yang baru dicadangkan, dikenali sebagai sistem powertrain pelbagai-silinder mesin lelurus (McLMPS), telah dirancang dan dikembangkan untuk meminimumkan berat, ukuran, dan penggunaan bahan api pada ICE. McLMPS ini tidak memerlukan penggunaan sistem penghantaran kuasa khusus untuk mengesahkan pretasinya dalam situasi di EV. Prototaip McLMPS merangkumi pelbagai bahagian iaitu pelbagai silinder mesin lelurus (McLM), system sensor pelbagai plat kedudukan crankshaft (MpCPS), komponen mekanikal, dan sistem pemacu, yang merangkumi unit kawalan dan algoritma operasi mesin. Struktur reka bentuk yang dicadangkan

oleh model McLM dipilih kerana strukturnya yang ringkas, tujahan tinggi, kekurangan magnet, dan isu kekuatan cogging yang minimum.

McLMPS yang dicadangkan itu disimulasikan dengan menggunakan perisian MATLAB /Simulink. Kelas tahap tinggi disimulasikan dengan menggunakan arus sebanyak 250A dan bekalan bateri adalah 300V, keluaran pelocok ialah 55.1kN dengan tork adalah 97.5Nm dan kuasa motor iailah 67.5kW. Dari hasil simulasi itu, kecekapan McLMPS yang dicadangkan adalah 90% manakala hasil eksperimen pula mempunyai kecekapan adalah 75%. Hasil eksperimen menunjukkan kecekapan yang lebih rendah berbanding dengan hasil simulasi kerana ini merupakan prototaip pertama McLMPS dibina berdasarkan skala seperempat. Sebaliknya, hasil eksperimen McLMPS lebih cekap daripada Perodua Kancil ICE, tetapi kurang cekap daripada Renault Zoe EV.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF SYMBOLS

N	number of turns
$\emptyset$	magnetic flux
t	time
E	electromotive force
k_f	thrust constant
F_r	thrust of the slot-less linear motor
I	input current
V	input voltage
B_m	magnetic flux density
H	magnetic field intensity
J	total current density
μ_0	magnetic permeability
A	area of magnetic field intensity
$\boldsymbol{\Phi}$	magnetic reluctance
R	resistance
P	permeance
R_m	magnetic reluctance
a_g	air gap area
l	air gap length
I_a	armature current
K_h	hysteresis constant
f	frequency
K_e	eddy current constant
$\boldsymbol{L}$	inductance
Cr	average radius
$\boldsymbol{C_h}$	thickness of the winding
$\boldsymbol{C_l}$	coil Length
X_1 & X_2	distance
Y_L	yoke length
$\boldsymbol{Y_{rf}}$	yoke radius front

Y_{odf}	yoke outer diameter front
Y_{rb}	yoke inner radius back
Y_{odb}	yoke outer diameter back
T_L	yoke teeth length
T_h	yoke teeth height
P_L	plunger rod length
P_{rf}	plunger rod radius front
P_{odf}	plunger rod outer diameter front
P_{rb}	plunger rod radius back
P_{odb}	plunger rod outer diameter back
C_h	coil width
C_L	coil length
C_{ir}	coil inner radius
C_{id}	coil inner diameter
C_{or}	coil outer radius
C_{od}	coil outer diameter
G	air gap
R_t	total magnetic reluctance
W	magnetic energy
F	magnetic force
ε	coil coefficient
ρ	coil resistivity
L_T	total self-inductance
W_d	diameter of a single coil
A_c	coil cross-section area
A_{ow}	area occupied by wire
T_c	turn of the coil
N_{tc}	number turn of the coil
N_{tcs}	number turn of coil for simulation
N_{layer}	number of coil layers
$Fmcoil$	magneto-motive force
L_{coil}	length of the coil

D_{sol}	diameter of inside linear motor
L_{wire}	total length of the wire
R_{wire}	resistance of the wire
P_{dh}	power dissipated at the heat
R_{radgap}	reluctance across the air gap
$A_{plunger}$	surface area of the plunger
$R_{plunger}$	reluctance through the plunger
$L_{plunger}$	plunger length
R_{stroke}	reluctance through plunger end
R_{case}	reluctance through the case
L_{case}	length includes the end of case
D_{case}	diameter casing surrounding the coil
A_{case}	casing area surrounding the coil
$F_{plunger}$	force of the plunger
T_{EMPM}	thrust or torque of linear motor
N_{Ys}	no of yoke slot
N_{Mp}	no of mover plunger pole
P_{rf}	ratio of mover plunger diameter
Y_{rf}	total yoke diameter
Y_{TL}	ratio of yoke teeth length diameter
Y_{TW}	yoke teeth width diameter
τ	torque
r	radius freewheels
F_{fr}	friction force
F_e	electromagnetic force
F_L	load force
I_a	armature current
F_k	piston force
p	pressure
A	area of cylinder

LIST OF ABBREVIATIONS

ICE	Internal combustion engine
EV	Electric vehicles
HEV	Hybrid electric vehicle
EMC	Equivalent magnetic circuit
McLMPTS	Multi-cylinder linear machine powertrain system
MpCPS	Multi plate crankshaft position sensor
McLM	Multi-cylinder linear machine
PAM	Permeance analysis method
FEM	Finite element method
SAE	Society of automotive engineers
IMLM	Iron moving linear motor
CMLM	Coil moving linear motor
MMLM	Magnet moving linear motor
DC	Direct current
TLRM	Tubular linear reluctance motor
LEAM	Linear electromagnetic actuator
LOA	Linear oscillator actuator
PMLM	Permanent magnet linear motor
TPMLM	Permanent tubular magnet linear motor
MMLA	Moving magnet linear actuator
EPS	Electric power steering
EMV	Electromagnetic valve actuator
ELL	Electromagnetic linear launcher
TVS	Triggered vacuum switch
IM	Induction motor
PMSM	Permanent magnet synchronous machines
BEV	Battery electric vehicles
FCV	Fuel cell electric vehicle
PHEV	Plug-in hybrid electric vehicles
TDC	Top dead center

BDC	Bottom dead center
MEC	Equivalent magnetic circuit
FEA	Finite element analysis
AWG	American wire gauge

CHAPTER 1

INTRODUCTION

This chapter presents an overview of the whole thesis, which includes the background of the research, the problem statement, research objectives, scope of the research and finally, the organization of the thesis.

1.1 Background of the Thesis

Today's linear motion applications are more challenging than ever before, according to Parker and Memon [1][2]. Linear machines are electromagnetic devices that develop mechanical thrust without the need for gears or a rotary device. Some of the advantages of using linear motors include quieter operation, reduced operating costs, and a broader range of operations due to the gearless feature [3]. Linear machines are also more efficient and simpler in construction. The performance of a linear machine depends on the size of the magnet, structure, and efficiency. Thus, it is essential to provide the correct parameters during the process of designing a linear machine. Research investigation and feasibility testing are being carried out in the implementation of linear machines in automobiles [4][5][6].

The linear machine replaced the piston engines, and the working principle was equivalent to the reciprocating motion in the ICE. The structure of linear machines was similar to the solenoid actuator, which is designed using CATIA software. The linear machine model consists of three main parts: a yoke, a coil, and a plunger rod as stated by Noor [7]. The FEM analysis method and the PAM analysis method were used in designing the linear machine. The initial magneto-static analysis was carried out by the finite element method (FEM) to predict the magnetic flux relationship. The experiment aimed to revise the possible measures of the coils electromagnetic flux properties and validate the simulation of the linear machines model. Furthermore, the finite element (FE) modelling and analysis have followed a MATLAB/Simulink software calculation to predict the linear machines. The mechanical components, or the moving parts of the operating mechanism, were designed and analysed analytically. The dimensions of the parts were validated using the failure theory and fatigue concept as required. All the components and the linear machine were fabricated and tested to validate the results.

The main focus of this research is the design and development of a linear machine and its operating mechanisms which can be used in electric vehicle (EV) application known as the multi-cylinder linear machines powertrain system (McLMPS). In addition, the experimental model was to establish and obtain the result without load and load for a linear machine. Finally, the simulation results have produced a plunger force, thrust, plunger distance, speed, and motor power at the linear machine models. It will be evaluated, compared, and measured as a counterpart from the experimental setup.

1.2 Significance of the Study

The Malaysian Automotive Technology Roadmap (MATR) identified the six pillars to guide the acquisition of technology development in line with the development of the global automotive industry. As seen in **Figure 1.1**, the six areas are very much attributed as these features-environmentally friendly, energy-saver and efficient.

Figure 1.1: Six areas of technology development identified under MATR [8]

One of the technology development pillars is green vehicle technology, in which the focus is on vehicle design and development, and powertrain and related control system development. According to the Malaysian Automotive Robotics and IoT Institute (MARii), the main objective of the announced National Automotive Policy 2014 (NAP2014) is to make Malaysia a regional automotive hub of Energy Efficient Vehicles (EEVs). This policy is in line with the provision of green technologies and green energy in line with the global trends of the future powertrains and fuel consumption patterns as well as the CO_2 emission requirement.

Electric vehicles (EV) become a key component of a solution to reduce the negative effects of transportation dramatically and to improve energy consumption efficiency

[9][10][11]. As seen in **Figure 1.2**, the development phase and fleet penetration have been set for 2014-2040. The EV and FCV are currently in the developing phase until 2025 [12].

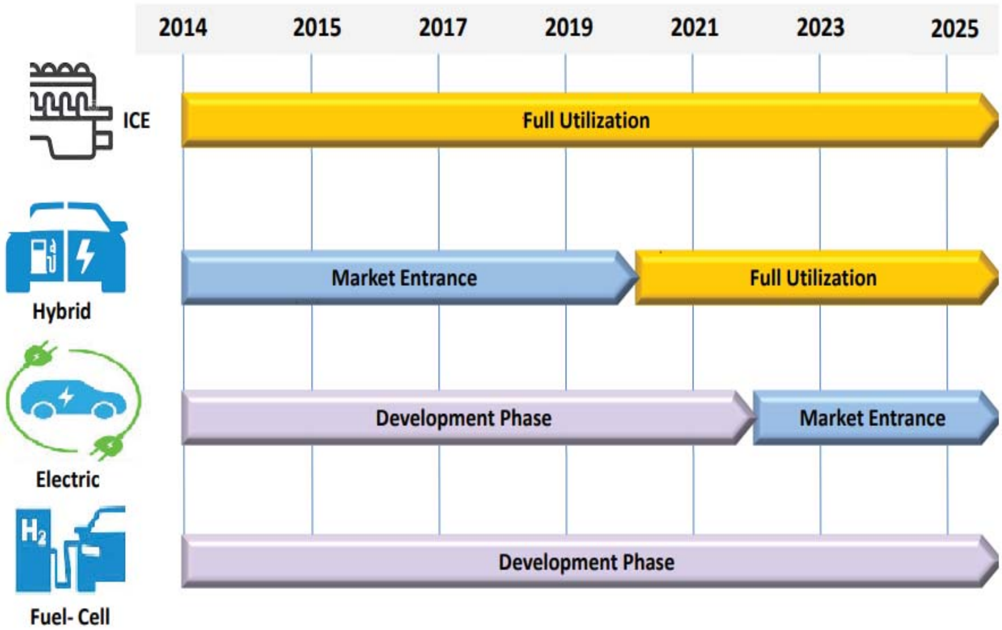

Figure 1.2: Malaysian's Automotive Technology Projection 2014-2040 [12]

1.3 Problem Statements

Electric vehicles (EV) have been recognised as a crucial pillar of a solution to significantly mitigate the detrimental impacts of transportation while still improving energy consumption efficiency. Electric machines are classified into two types: rotational machines and linear machines [14][15][16]. These EVs utilise rotating electric machines to transmit power from the motor shaft to the transmission and, subsequently, to the wheels through differential gears.

The electric machines of EVs use a rotating motor compared to a linear motor. Therefore, it causes many changes in the design of the vehicle, which require high costs, complex control systems, and the size of the machine needs to be bigger, etc [17]. However, the rotating electric motor suffers from excessive exposed temperature due to long operation that may cause the motor to fail, and the cost of the magnet is higher. On the other hand, electric motors in Evs require complex control algorithms and specialised power transmission systems in order to operate the vehicle. This will add an additional cost to the vehicles.

On the other hand, an internal combustion engine (ICE) uses gasoline to generate the necessary power to move the wheels through the transmission and gearbox. The friction issue between the piston rings, piston skirt and the cylinder linear at internal combustion engines is one of the drawbacks. As a result, there is no side thrust on the piston, and the piston does not travel radially in the cylinder [19][20]. This phenomenon gives linear machines an edge over rotating engines since less effort is required to overcome friction, making them more fuel-efficient.[21] [22].

Adnan [23] and Norhisam [24][25][26] performed thrust calculation and study of thrust constant, electrical time constant, and mechanical time constant of slot-less moving magnet linear actuators. FEM and PAM were utilised to design and develop the actuator in this case. The goal of this study was to produce high thrust with a broad stroke. However, only 250N of force and a 10 mm stroke were obtained. On the other hand, the magnets are attached to the mover, it becomes heavy. This can increase the magnet utilised and maintenance issues, which can raise the cost of the linear motor. [27][28].

Adnan [23] asserted that he conceived and developed a moving magnet linear actuator for linear compressor applications. The fundamental properties of linear actuators in terms of force, thrust, efficiency, and stroke are covered in this section. This study generated a force of 150N and a stroke of around 4.5 mm. Norhisam [24][25][26] performed thrust calculation and study of thrust constant, electrical time constant, and mechanical time constant of slot-less moving magnet linear actuators. FEM and PAM were utilised to design and develop the actuator in this case. The goal of this study was to produce high thrust with a broad stroke. However, only 250N of force and a 10 mm stroke were obtained.

Therefore, a new proposed linear machine has been designed and developed in order to test its performance in EV settings at an early stage. The operation of this linear machine does not need the use of a particular power transmission system. It can run the car using the current internal combustion engine (ICE) transmission system. It will offer cheaper price, save space and less complex in its control system.

1.4 Objectives of Research

This research aims to design, fabricate, and test a novel multi-cylinder linear machine powertrain system (McLMPS) for EV application. In order to achieve the main objective, the following research activities and tasks have been carried out:

i. To develop, implement and model the novel multi-cylinder linear machine (McLMPS) with a tubular structure using CATIA, ANSYS Maxwell and MATLAB/Simulink software.

ii. To develop, build, and implement the novel multi-plate crankshaft position sensor system (MpCPS) used to assist the McLMPS operation.

iii. To design, build, and fabricate that optimal prototype of the McLMPS including the McLM, MpCPS, and other mechanical components using the CNC machines.

iv. To develop the drive system of McLMPS and its control algorithm.

v. To validate and test the effectiveness of the controller algorithm and McLMPS experimentally.

1.5 Scopes of Work and Limitations

To attain the scope of work and limitations, the following research activities are proposed:

i. The proposed McLMPS is the first prototype designed and developed for this EV application. It has been fully modeled and simulated using ANSYS Maxwell and MATLAB/Simulink software.

ii. The control algorithm has been developed in C language programming to manage the proposed McLMPS and control the full operation of the entire system.

iii. The fabrication of the proposed McLMPS has been performed based on the scale-down version due to the limited financial budget given to this project.

1.6 Thesis Contributions

This study is significant for the following contributions it makes to the existing body of knowledge as presented below:

i. Designing, modelling and fabricating the McLMPS is the first prototype developed for this EV application.

ii. Designing and fabricating MpCPS consists of four components as namely a photoelectric sensor, a gear spurs, a disc sensor plate, and a sensor holder. It's controlling the plunger rod position at a certain angle of the crankshaft and full operation of the McLMPS.

iii. Designing and fabricating the device system of the McLMPS with its control algorithm. The Arduino system is a controller devices with the coding software that used in C language to perform a digital signal controller for further tuning of the controller at the McLMPS.

1.7 Thesis Outline

This thesis comprises five chapters covering the comprehensive states of the research.

Chapter One presents the introduction, which covers a description of the multi-cylinder linear machine powertrain system (McLMPS). Also, it discusses the problem statement, objectives, scope of work limitation and contributions.
Chapter Two presents the literature review of a linear machine during the study. This chapter provides the study of various works done to design electric machines and linear machines for electric vehicles. The construction and working principle of linear machines are also explained. The introduction to the finite element method (FEM) and overview of related research on linear machines are discussed.

Chapter Three presents the methodology used in designing the multi-cylinder linear machine powertrain system. This chapter explains designing, modelling, simulating and fabricating processes such as the multi-cylinder linear motor (McLM), multi-plate crankshaft position sensor system (MpCPS), and drive system algorithms. It also discusses the proposed McLMPS system in terms of the designed, fabricated, and experimental set-up system.

Chapter Four explains the multi-cylinder linear machines powertrain system (McLMPS) using the FEM simulation, calculated and experimental results. The simulation and experimental test are obtained to be compared and discussed.
Chapter Five presents the study's conclusion done in terms of the performance of a multi-cylinder linear machine powertrain system (McLMPS). The recommendations for future studies are also presented in this chapter.

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