THREE-PHASE SIGNAL PERMANENT MAGNET LINEAR GENERATOR (PMLG) USING FINITE ELEMENT METHOD

RAHIL HANIM BINTI GHAZALI

MASTER OF SCIENCE
(ELECTRICAL & ELECTRONICS ENGINEERING)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

2024

THREE-PHASE SIGNAL
PERMANENT MAGNET LINEAR GENERATOR
(PMLG) USING FINITE ELEMENT METHOD

RAHIL HANIM BINTI GHAZALI

Thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional Malaysia, in fulfilment of the requirements for the Degree of Master of Science (Electric and Electronics Engineering)

2024

ABSTRACT

This study focuses on harnessing wave energy to generate electrical energy. Although numerous renewable energy technologies have been implemented in Malaysia, the utilization of waves is still lacking, even though Malaysia is a country encircled by seas. Hence, this research attempts to design an effective permanent magnet linear generator (PMLG) that can fit Malaysian wave conditions. Most researchers concentrated their research on regions with waves unfit for Malaysian wave conditions. This study obtained wave data from different regions based on the nearest sea grids along Peninsular Malaysia's coastline. The wave data, including wave height and wave period, were collected daily from the webpage of Malaysian Meteorology Malaysia. Since the Northeast Monsoon season is believed to be Malaysia's primary rainfall season, data on wave height and wave period was gathered during this period. Moreover, the wave speed data has also been displaying an increment every month throughout the monsoon period. The minimum average speed collected was 0.048 m/s in the Southern Region, while the highest wave speed was 0.251 m/s. This study then examined each characteristic of a 3-phase linear generator and simulated the design using Ansys software. Different PMLG parameters, such as winding, stator, and permanent magnet configuration, were simulated to find suitable designs capable of producing a greater output voltage. This study also performs analysis for loaded and no-load calculations. For no-load calculations, the data was obtained by performing no-load calculations, while for loaded calculations, a simple equation was applied. Furthermore, a PMLG with a higher number of coil turns can produce a higher output voltage. Added to that, the optimum dimensions of the stator

and permanent magnet also play a crucial role in creating higher levels of an output voltage of 11.57 V per phase with a wave velocity of 0.14 m/s. Furthermore, the output power for loaded calculations has also been increasing, reaching about 117 watts.

ABSTRAK

Kajian ini memberi tumpuan kepada pengunaan tenaga ombak untuk menghasilkan tenaga elektrik. Terdapat pelbagai jenis teknologi tenaga boleh diperbaharui telah dilaksanakan di Malaysia, namun penggunaan tenaga ombak masih kurang, walaupun Malaysia sebenarnya adalah sebuah negara yang dikelilingi oleh laut. Oleh itu, penyelidikan ini mencuba untuk mereka bentuk sebuah penjana-linear magnet-tetap (PMLG) yang berkesan bersesuaian dengan keadaan ombak di Malaysia. Kebanyakan penyelidik lebih menumpukan kajian mereka ke arah kawasanyang justeru mempunyai keadaan ombak yang tidak bersesuaian dengan keadaan ombak di Malaysia. Di dalam kajian ini, data ombak dari pelbagai kawasan diperolehi berdasarkan grid laut terdekat sepanjang pantai Semenanjung Malaysia. Data ombak, termasuk ketinggian dan tempoh ombak, dikumpulkan setiap hari dari laman web Jabatan Meteorologi Malaysia. Memandangkan musim Monsoon Timur Laut dikenali sebagai musim hujan utama Malaysia, data mengenai ketinggian ombak dan tempoh ombak dikumpulkan sepanjang tempoh tersebut. Selain itu, data kelajuan ombak sewaktu tempoh ini juga telah menunjukkan peningkatan. Kelajuan purata minimum yang direkodkan adalah 0.048 m/s di Wilayah Selatan, manakala kelajuan ombak tertinggi direkodkan adalah 0.251 m/s di kawasan Pantai Timur. Kajian ini kemudiannya, mengkaji setiap ciri-ciri penjana linear 3 fasa, malah hasil reka bentuk tersebut kemudiannya akan di-simulasikan menggunakan perisian Ansys. Pelbagai dimensi PMLG, seperti penggulungan, pemegun, dan konfigurasi magnet kekal, disimulasikan untuk mendapatkan reka bentuk yang bersesuaian dan mampu

menghasilkan keluaran voltan yang lebih besar. Kajian ini juga melakukan analisis kiraan beban dan tanpa beban. Untuk kiraan tanpa beban, data diperoleh dengan melakukan proses simulasi perisian Ansys, manakala untuk kiraan beban, persamaan ringkas digunakan. Akhir sekali, PMLG dengan jumlah pusingan gulungan yang lebih tinggi mampu menghasilkan jumlah keluaran voltan yang lebih tinggi. Tambahan pula, dimensi optimum pemegun dan magnet kekal memainkan peranan penting dalam mencipta tahap keluaran voltan yang lebih tinggi iaitu 11.57 V bagi setiap fasa dengan kelajuan ombak 0.14 m/s. Selain itu, nilai kuasa yang diperolehi melaluai rumus kiraan beban juga telah meningkat kepada nilai 117W.

ACKNOWLEDGEMENTS

All praises due to Allah S.W.T., Lord of universe, The Most Merciful and Gracious. Prayer for peace and prosperity for the prophet Nabi Muhammad S.A.W., his companion and his beloved friends.

Alhamdulillah, here I would like to express the deepest appreciation to my main supervisor Dr. Asnor Mazuan bin Hj Ishak, and my co-supervisor Dr. Ahmad Shukri bin Abu Hasim, and Dr. Syed Mohd Fairuz Bin Syed Mohd Dardin for his careful guidance, patience and advice which invaluable direction during the course of this project. Without his supervision and constant help this dissertation would not have been possible.

Furthermore, special thanks and sincere appreciation to my beloved family, Mr. Ghazali Bin Ibrahim and Mrs Faridah Binti Masod, parents, and other family for their support, prayer, encouragement and patience. Without them, none of this would have been possible. Not to forget, a million of gratitude to all my friends whom been involved while making this project until its success completion.

Finally, I would like to thank the National Defense University of Malaysia for giving the opportunity to pursue my Master of Science program.

APPROVAL

The Examination Committee has met on **20 September 2023** to conduct the final examination of **Rahil Hanim Binti Ghazali** on his degree thesis entitled **Three-phase Signal Permanent Magnet Linear Generator (PMLG) Using Finite Element Method.**

The committee recommends that the student be awarded the of Master of Science (Electric and Electronics Engineering).

Members of the Examination Committee were as follows.

Prof. Madya. Dr. Siti Nooraya Binti Mohd. Tawil
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Chairman)

Prof. Dr. Mohd Taufiq Bin Ishak
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Internal Examiner)

Prof. Madya. Dr. Kasrul Bin Abdul Karim
Faculty of Electrical Engineering
University Teknikal Melaka (UTeM)
(External Examiner)

APPROVAL

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Electric and Electronics Engineering)**. The members of the Supervisory Committee were as follows.

Dr. Asnor Mazuan bin Dato' Hj. Ishak
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Main Supervisor)

Dr. Ahmad Shukri bin Abu Hasim
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

Dr. Syed Mohd Fairuz bin Syed Mohd Dardin
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

Student's full name : RAHIL HANIM BINTI GHAZALI

Date of birth : 22 NOVEMBER 1993

Title : THREE-PHASE SIGNAL PERMANENT MAGNET LINEAR GENERATOR (PMLG) USING FINITE ELEMENT METHOD

Academic session : 2020 / 2023

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

I further declare that this thesis is classified as:

☐ **CONFIDENTIAL** (Contains confidential information under the official Secret Act 1972)*

☐ **RESTRICTED** (Contains restricted information as specified by the organisation where research was done)*

☒ **OPEN ACCESS** I agree that my thesis to be published as online open access (full text)

I acknowledge that Universiti Pertahanan Nasional Malaysia reserves the right as follows.

1. The thesis is the property of Universiti Pertahanan Nasional Malaysia.
2. The library of Universiti Pertahanan Nasional Malaysia has the right to make copies for the purpose of research only.
3. The library has the right to make copies of the thesis for academic exchange.

Signature	**Signature of Supervisor/Dean of CGS/ Chief Librarian
931122-06-5300	Asnor Mazuan Bin Hj Ishak
IC/Passport No.	**Name of Supervisor/Dean of CGS/ Chief Librarian
Date:	Date:

*If the thesis is CONFIDENTAL OR RESTRICTED, please attach the letter from the organisation with period and reasons for confidentiality and restriction.
** Witness

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE NO. **TITLE** **PAGE**

LIST OF ABBREVIATIONS

NEM	-	Net Energy Metering
SAG	-	Smart Automation Grants
Gita	-	Green Investment Text
RE	-	Renewable Energy
TNB	-	Tenaga Nasional Berhad
WEC	-	Wave Energy Converter
OWC	-	Oscillating Water Columns
PMLG	-	Permanent Magnet Linear Generator
PM	-	Permanent Magnet
EU	-	European Union
IGEM	-	International Greentech and Eco Products Exhibition and Conference Malaysia.
EPSM	-	Environmental Protection Society Malaysia
MENGO	-	Malaysian Environment NGOs
TRESS	-	Treat Every Environment Special
PV	-	Photovoltaic
IEA	-	International Energy Agency
LFG	-	Landfill Gas
PTO	-	Power Take-off
TAPCHAN	-	Tapered Channel device.
OBREC	-	Overtopping Breakwater for Energy Conversion

EMF	-	Electromotive Force
IDEAS	-	Informative Display of Enhances Forecasting Aid System.
MET	-	Malaysian Meteorology Department
Malaysia		
SWG	-	Standard Wire Gauge
AWG	-	American Wire Gauge
FEA	-	Finite Element Analysis
SCORE	-	Sarawak Corridor of Renewable Energy

LIST OF SYMBOLS

kWh	-	Killowatthour
MW	-	Megawatt
m/s	-	Meter per second
Km	-	Kilometer
RM	-	Ringgit Malaysia
%	-	Percent
kW	-	Kilowatt
F	-	Fahrenheit
GW	-	Gigawatt
Mm	-	Millimeter
M	-	Meters
S	-	Seconds
V	-	Voltage
Kg	-	Kilogram
kg/m^3	-	Kilogram per cubic metre
Ω	-	Ohms
A	-	Ampere
W	-	Watts

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter will provide an introduction to the study by describing the study's general background, followed by the problem statement, objective, research scope, and significance of the study. This chapter also featured the thesis outline, which consists of a summary idea regarding each chapter.

1.2 Background

Today’s world energy consumption is predicted to increase by almost 50% from the year 2020 to 2050. Globally, the main source of energy generation depends on non-renewable resources such as oil, coal, and gases. Meanwhile, the process of burning fossil fuels will devote 83% of global energy creation, which in turn has caused an enormous greenhouse effect contributing to humanity and environmental problems at an alarming state [1]. Developing countries currently consume a larger part of the world’s energy and their demand is expected to enlarge over the past 15 years [2]. High consumption of electricity cannot be avoided in a densely populated country. Countries namely China, India, Japan, South Korea, and Saudi Arabia are the top five countries with the highest energy consumption in the Asian region, with China being listed as the top electricity consumer for both Asia and the global sector consuming more than 6.3 trillion kilowatts per hour (kWh). On the other hand, India scored as the second-largest populated country and utilizes about 1.54 trillion kWh of electrical energy. Countries such as Japan, South Korea, and Saudi Arabia have an annual electricity consumption of 0.93 trillion kWh, 17.70 billion kWh, and 193 million kWh, respectively [3]. According to current estimations, Malaysia's electricity demand is expected to increase from 18 MW in 2000 to 24 MW by 2039. Nevertheless, a report on March 2021 by Suruhanjaya Tenaga, the Malaysian energy authority, stated that the net energy demand of 24 MW in 2039 can be reduced to 23 MW by applying renewable energy resources to the distribution network [4].

Previously, Malaysia has engaged in the agreement of the Kyoto Protocol in 1999 [5] and Paris Agreement in 2015 [6]. The Kyoto Protocol was the first legally binding climate agreement aimed at reducing six major greenhouse gasses in industrialized countries. In this agreement, the developed countries need to reduce the gas emission by an average of 5%. Despite the positive approach, the Kyoto Protocol was discontinued due to several complications. Next, in 2015, the Paris Agreement came into formation, with the urge for all countries to set an emission reduction pledge to achieve global net-zero emissions. These agreements also intended to increase the ability to impact climate change without affecting food production [7], [8]. In 2017, the Malaysian prime minister stated in his keynote speech that, the country's plan on reducing carbon emissions for a cleaner environment was on target. Starting the year 2015, the carbon emission had been gradually lessened to 33% in 2015. Malaysia's goal was to reduce carbon emissions by 45% by 2030 and become a carbon-neutral country as early as 2050 [9]. This statement put Malaysia ahead of its neighboring country in aiming to achieve carbon neutrality. Indonesia intended for net zero emissions by 2060, Thailand targeted the year 2070, while Singapore hopes to achieve net-zero emissions once feasible [10]. Hence, in 2019, Malaysia managed to generate approximately 2% of its energy from renewable sources. However, this percentage was still far compared to the total generation mix targets, which are 20% by 2025 [11]. Hence, the government has been launching multiple initiatives and policies to support the renewable energy industry, such as Net Energy Metering (NEM), Smart Automation Grants (SAG), and Green Investment Text (Gita) [12]. Aggravation of these policies displays the government's dedication to developing renewable energy (RE) in the country. Next, as announced in September 2021, the 12th Malaysia Plan focuses on three main themes, which are resetting the economy, strengthening security, and advancing sustainability. Focusing on the 3rd theme, the theme of advancing green growth for sustainability and resilience is stated in Chapter 8, while Chapter 9 focuses on matters related to enhancing energy sustainability [13].

In Malaysia, the main source of renewable energy includes solar, wind, biomass, and mini-hydro system, Malaysia has the highest potential for solar radiation as the location is situated near the equator. The irradiation is higher during the North-East monsoon, while lower irradiation is obtained during the South-West monsoon. 6500 MW is the estimated potential power for solar generation in Malaysia. Wind power in Malaysia is considered at a low speed compared to other countries with a mean wind speed between 1.5 to 4.5 m/s. Areas such as Johor, Terengganu, and Sabah have been identified as high-wind areas that may harness energy between 9 to 11 m/s. Next, for biomass energy, Malaysia produces about 168 million tons of biomass.

Rating as the second largest palm oil producer, Malaysia has adequate resources for generating biomass energy. Next, in terms of hydro technology, elements such as high temperature, humidity, and high rainfall volume boost Malaysia's potential for developing hydro technology. Tenaga Nasional Berhad (TNB) is a Malaysian national utility corporation that frequently develops significant hydroelectric projects such as Kenyir Hydro Power Station, Sungai Perak Hydro Scheme, Sungai Piah Hydro, Cameron Highlands Hydro Power Stations, and Pergau [11]. Wave energy research and development have been underway since the early 1980s in response to the global oil crisis. Meanwhile, Solar and hydropower energy are the most famous kinds of renewable energy in Malaysia. Despite being surrounded by sea and having a total coastline of 4,675 km, its adoption of wave energy lags behind other countries [14]. Factors such as wave availability, impact on marine habitats, expensive production expense, and noise pollution, had made wave energy being left extensively unutilized.

1.3 Problem Statement

Malaysia is a country with numerous islands. According to Malaysia's Department of Survey and Mapping, the country is made up of 878 islands [15]. However, most Malaysian islands are not connected by the grid system. Several households have been provided with diesel generators but remained insufficient to cover the remaining residents. Additionally, the main fuel source for generators is diesel [16]. In Malaysia, the current diesel price is RM 2.15 per liter, while the oil prices are determined according to the current market price. If the global oil price rises, so will the retail price of oil [17]. The ongoing utilization of diesel as the main ingredient in generating electricity might not only raise expenses but will also have an impact on the environment since diesel is non-renewable, hazardous, and emits pollutants.

Wave Energy Converter (WEC) technologies used to exploit wave energy include technologies such as attenuators, oscillating water columns (OWC), overtopping, and point absorbers. However, technological research has been focusing on particular locations, mainly in European countries due to the extreme weather that may result in higher wave heights [18]. Examples of wave farms include the Agucadoura Wave Farm in Portugal [19], the Siadar wave farm in the United Kingdom [20], and the Perth Wave Energy project in Australia [21]. For Malaysians to embrace the technology, extensive research regarding the Malaysian wave condition must be conducted.

Following that, existing WEC technologies consist of a large and fixed structure, such as hydraulic or turbine systems has resulting in mechanical complexity in their power take-off system. Furthermore, massive mechanical systems consisting of a gearbox, hydraulic, turbine, and pneumatic systems would only raise maintenance costs, lower the system efficiency, and reliability. Furthermore, WEC devices are more likely to be constructed from high-quality materials that are capable of withstanding the harsh and unpredictable conditions of ocean weather. Thus, buoy-type linear generators can be utilised in WECs to overcome mechanical complexity. As a consequence of their simple mechanical construction, suitability for a lower frequency range, and fewer environmental impacts, buoy types are recommended. On top of that, since linear generators are smaller in size than other types of WEC technology, maintenance costs are also lower [22].

The fundamental design of the permanent magnet linear generator (PMLG) can also be categorized as either a totally submerged design or a floating buoy depending on the location. The different topologies associated with the PMLG design such as the structure, translator size, stator form, core type, and PM (Permanent Magnet) installation methods, can also be developed in order to categorize the design. For instance, the PMLG structure can be either tubular or flat design. The tubular layout is better suited for extracting sea wave energy even if the planar layout is simpler to build. Next, there are three different configurations method for PM installations: radial, axial, or Halbach array. Hence, various configurations of linear generator design will have a significant impact on the generator's ability to provide an appropriate capacity of output power.

Finally, despite wave energy is considered renewable energy, its utilization is still relatively young, especially across Malaysia. One of the barriers to WEC technology deployment are a lack of information concerning Malaysian wave conditions. Due to the uncertainty of the output provided by the PMLG design, instead of a fabrication process, this study applied Ansys software for simulation. Numerous benefits entrails by applying simulation process such as, ability for researchers to explore new scenarios, utilising different kinds of material or information, and early defection of flaw in products. Furthermore, the simulation methods assist researchers in determining the specific variables produce major effects on system performance. An analysis solution software known as Ansys software was used to carry out the simulation process in this study. The software has been used by industry to address problems involving structures, heat transfer, fluid dynamics, and electromagnetic.