Magnetic Circuit Study of a Permanent Magnet Linear Generator for Wave Energy Recovery

André Manuel Marques Magro

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Supervisor: Prof. Paulo José da Costa Branco

Examination Committee
Chairperson: Prof. Rui Manuel Gameiro de Castro
Supervisor: Prof. Paulo José da Costa Branco
Member of the Committee: Prof. Gil Domingos Marques

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Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
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Resumo

Os desenvolvimentos na conversão da energia das ondas têm sido largamente dificultados pelos altos custos associados à operação e manutenção dos conversores em alto mar, não acompanhando assim o desenvolvimento das outras fontes de energia renovável. Com o decréscimo dos custos de produção de magnetos permanentes verificado nos últimos anos (que são também mais leves e oferecem alta densidade energética) os geradores lineares de magnetos permanentes estão a tornar-se cada vez mais uma opção viável no que diz respeito à conversão de energia das ondas, com vários investigadores a procurar resolver os principais problemas através de geradores inovadores.

Ao longo desta dissertação, estuda e analisa-se um gerador linear de magnetos permanentes, previamente desenvolvido no Instituto Superior Técnico, nas suas dimensões magnéticas. O principal objetivo deste trabalho foi estudar o circuito magnético do gerador de forma a melhorar, se possível, a alta dispersão de fluxo magnético e as elevadas forças eletromagnéticas que actuam no transladador durante a sua operação normal. Para isso, foram analisados geradores de última geração com diferentes topologias concebidas e analisadas recorrendo ao método de elementos finitos. Primeiramente verificou-se que a análise a três dimensões produz, para este gerador, resultados mais precisos em cerca de vinte por cento em relação a simulação 2D. As variações de tipologia compreenderam estudos de transladadores de diferentes arranjos magnéticos, diferentes direções de magnetização e magnetos com diferentes geometrias. Os resultados demonstraram que uma variação de volume de magneto por altura produz menor dispersão que por largura, que magnetos não rectangulares não produziram efeitos positivos na redução dispersão magnética e redução de forças parasitas e, por último, que um transladador de orientação axial com espaçadores de ferro produz menor dispersão e força parasita que orientações verticais ou do tipo quasi-Halbach.

Palavras-chave: Gerador linear de magnetos permanentes, energia das ondas, fluxo magnético longitudinal, dispersão de fluxo magnético, forças parasitas.
Abstract

The developments on wave energy conversion have been hindered by the high costs associated to the operation and maintenance of the converters, lagging considerably behind the other renewable energy sources. As the production costs of rare-earth magnets that are both light and offer a high energy density have been reducing over the last few years, permanent magnet linear generators are now becoming a viable option in what concerns wave energy conversion with several researchers aiming to solve their major problems with new state-of-the-art generators.

Throughout this dissertation, a permanent magnet linear generator, previously developed in Instituto Superior Técnico, is studied and analyzed in its magnetic dimensions. The main objective was to study the generator’s magnetic circuit in order to improve, if possible, the high magnetic flux dispersion and electromagnetic forces experienced in the translator along its normal operation. To do that, state-of-the-art generators were analyzed and different translator topologies were conceived recurring to finite element analysis software. Firstly, it has been found that the three-dimensional analysis produces, for this generator, more accurate results by twenty percent when compared to a two dimension approach. The variations comprised translators with different magnet arrangements, magnetization directions and different magnet shaping studies. The results showed that magnet volume variation by height produces less dispersion than by width, that non-rectangular magnets did not produce positive effects in the reduction of magnetic dispersion and parasitic forces and, finally, that an axial translator with iron spacers produces less dispersion and detent force than surface or quasi-Halbach arrangements.

Keywords: Permanent magnet linear generator, wave energy, longitudinal flux, flux dispersion, detent force.
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<th>Description</th>
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<tbody>
<tr>
<td>AWS</td>
<td>Archimedes Wave Swing</td>
</tr>
<tr>
<td>BBDB</td>
<td>Backward Bent Duct Buoy</td>
</tr>
<tr>
<td>Btu</td>
<td>British Thermal Units</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Power</td>
</tr>
<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>LFPM</td>
<td>Longitudinal Flux Permanent Magnet</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium Iron Boron</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Economic Cooperation and Development</td>
</tr>
<tr>
<td>OTE</td>
<td>Ocean Thermal Energy</td>
</tr>
<tr>
<td>OWC</td>
<td>Oscillating Water Column</td>
</tr>
<tr>
<td>PMLG</td>
<td>Permanent Magnet Linear Generator</td>
</tr>
<tr>
<td>PTO</td>
<td>Power Take-off</td>
</tr>
<tr>
<td>QH</td>
<td>Quasi-Halbach</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Sources</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SSG</td>
<td>Seawave Slot-Cone Generator</td>
</tr>
<tr>
<td>TAPM</td>
<td>Tubular Air-cored Permanent Magnet</td>
</tr>
<tr>
<td>TFPM</td>
<td>Transverse Flux Permanent Magnet</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>VHM</td>
<td>Vernier Hybrid Machine</td>
</tr>
<tr>
<td>VRPM</td>
<td>Variable Reluctance Permanent Magnet</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave Energy Converter</td>
</tr>
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</table>
Chapter 1

Introduction

1.1 The global energy profile

Over the last decades energy consumption has been constantly increasing and according Patrick Moriarty and Damon Honnery on [1] it is estimated to escalate to 1000 EJ\(^1\) (or 948 quadrillion Btu\(^2\)) or more by 2050. The number is also supported by projections from Energy Information Administration’s (EIA) 2017 International Energy Outlook [2] report where an 28% increase in world energy usage (demand) is expected between 2015 and 2040 to 736 quadrillion Btu (see Figure 1.1). This raise, mainly due to the accelerated growing of non-OECD\(^3\) countries which heavily depend on fossil fuel to sustain their development, will consequently promote an increase in energy-related carbon dioxide emissions. Given this and for the same time period, (CO\(_2\)) emissions are projected to grow roughly 15%, averaging 0.6% per year.

![Figure 1.1: EIA’s 2017 projections. Adapted from [2]](image)

This unsustainable increase in worldwide energy demand allied to the growing awareness of the environmental and economical problems caused by relaying on fossil sources is starting to lead a major shift in energy production policies towards the use of Renewable Energy Sources (RES). Under the recently signed Paris Agreement, whole world governments have compromised to reduce greenhouse

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\(^1\) Exajoules, EJ = 10\(^{18}\) J

\(^2\) British Thermal Units

\(^3\) OECD - Organization for Economic Cooperation and Development
gas emissions in order to limit the global average temperature rising. Receiving the agreement as an additional driver to fossil fuel divestment, several initiatives like the European Union's (EU) 2020/2030 framework for climate and energy and RES Directive were put into practice to accelerate the rate of RES implementation and incentivize R&D (other incentives like the feed-in tariff policy had also been adopted with positive results on several countries).

It became clear that implementing RES does not only contribute to climate change mitigation through the reduction of greenhouse gas emissions but also helps to achieve a sustainable development, protect the environment and improve citizens' health. The requirements for further developments are clear: these alternatives must be sustainable, ideally accessible and offer low running costs in order to be competitive. Presently, not all sources are explored to the same extent.

Examining data from REN21's 2017 Renewables Global Status Report, 24.5% of 2016 global energy production came from RES. The main contributors are hydropower with 16.6% of the global value followed by Wind (4%), Bio (2%) and Solar power (1.5%), all together producing 900 Gigawatts. Ocean energy is currently found here as an underdeveloped source in the end of the capacity contribution list with a less expressive 0.4% along with Geothermal and Concentrated Solar Power (CSP). It is though one of the most underdeveloped renewable energy source with also the most availability and widely disseminated over our planet.

![Figure 1.2: Renewable Power Capacities in World, 2016. Adapted from REN21, Renewables 2017 Global Status Report - [3].](image)

**1.2 Wave energy as an alternative**

Oceans represent approximately 70% of the earth’s surface and if explored correctly are able to provide large amounts of energy in very different forms. Currently there are several ways of harnessing energy from this mean which naturally lead to the use of different technologies being tidal and marine.
current power, osmotic power (salinity gradient), ocean thermal energy (OTE) and wave energy the most relevant.

Wave Energy

Wave energy, as the name implies, is the energy carried in waves, captured and harnessed to produce useful energy. The more common, wind-generated waves, are caused by the interaction of wind with the body of water and are hence an indirect form of solar energy [4]. As the wind blows, the kinetic energy contained in the air molecules is transferred to the water’s surface causing a surface perturbation (disturbing force) which is then reinstated by surface tension or gravity (restoring force). This continuous iteration between these two elements results in an vertical motion that can be propagated for considerable distances with little losses. Waves are thus capable of storing and transmitting energy as the ocean acts as an energy reservoir.

Waves are characterized by several strands which impact the amount of carried energy (or potentially explored). Depending on the weather and terrain conditions, waves can differ in amplitude (A), in wavelength (L) and period (T). The distance between the highest part of the wave (crest) and the lowest (trough) denotes the waves’ height (H) where wavelength is measured by the distance of two consequently crests (see Figure 1.3).

\[
P = \frac{1}{8} \rho g H^2 C_g [W]
\]

Figure 1.3: Wave characteristics [5]

Waves are characterized by several strands which impact the amount of carried energy (or potentially explored). Depending on the weather and terrain conditions, waves can differ in amplitude (A), in wavelength (L) and period (T). The distance between the highest part of the wave (crest) and the lowest (trough) denotes the waves’ height (H) where wavelength is measured by the distance of two consequently crests (see Figure 1.3).

Naturally, power carried by the waves (P) is not equal across the world. Such can be written as

\[
P = \frac{1}{8} \rho g H^2 C_g [W]
\]

Figure 1.3: Wave characteristics [5]

where \( \rho \) is fluid density (\( \sim 1027 \text{kg/m}^3 \) for sea water), \( g \) the gravity acceleration, \( H \) the water head and \( C_g \) the group velocity. To allow comparisons, \( P \) is usually normalized with the height of wave crest (A), obtaining power in kilowatts per meter of wave crest (\( P_A \)).

\[
P_A = \frac{P}{A} [\text{kW/m}]
\]

Figure 1.4 evidences the global distribution of wave power potential. It is between 40° and 60° of latitude for both hemispheres, that we found the most powerful waves with potential values generally above 90 kW/m. The Portuguese coast, being localized around 40° has a mean potential value around 3
49.2kW/m, as evidenced by the scatter table found in the appendix A. The particulars are, as expected, correlated with a decade of the wind speed recordings (see Figure 1.5). For the same latitude values, wind speeds measured 50 meters above sea level are higher than any other regions, excelling 9 m/s.

Figure 1.4: Global distribution of annual mean wave power [6]

![Global Annual 50m Average Wind Speed](image)

Figure 1.5: Global Annual 50m Average Wind Speed [7]

Presently, tidal and wave energy are at a more advanced stage of development than the remaining peers with the European Union (EU) hosting more than 50% of tidal energy and 45% of wave energy projects [8]. Comparing the theoretical potential of both with the other ocean harnessing technologies, wave energy is the one with greater potential to be explored (see table 1.1).
Table 1.1: Ocean Energy Theoretical Potential. Adapted from [9]

<table>
<thead>
<tr>
<th>Ocean Energy Technology</th>
<th>Annual theoretical Energy [TWh/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal</td>
<td>+300</td>
</tr>
<tr>
<td>Marine Current</td>
<td>+800</td>
</tr>
<tr>
<td>Osmotic</td>
<td>2000</td>
</tr>
<tr>
<td>OTE</td>
<td>10000</td>
</tr>
<tr>
<td>Wave</td>
<td>8000 to 80000</td>
</tr>
</tbody>
</table>

Power availability of surface waves (waves up to 100m deep) is estimated to be between 1 to 10 TW (terawatt$^5$) globally [10]. Although impossible to explore the entire extent of the ocean, adequate exploration would be enough to supply up to 10% world energy demand [11].

1.3 Wave energy conversion systems

The exploitation of wave energy is possible through a series of conversion devices named wave energy converters (WEC). The idea of using such is not new having the first patent being registered on the XVIII century, more specifically in 1799 in Paris by Girard. Today, there are more than 1500 distinct patents registered much of them by the pressure of the 1970s oil crisis and later concerns of the depletion of natural resource reserves in the 1990s [12].

The existence of different concepts and therefore dissimilar topologies to maximize energy capture lead to different methods of classifying WECs [4]:

- According to location: depending on WEC distance from the shore, it can be categorized as either a onshore, near shore or offshore device. The first are generally fixed onto the shoreline with one submerged section and other in open air whereas the near and offshore devices are usually floating or completely submerged (inwards or over the breaker zone, respectively);

- According to type, size and directioning: Point absorbers (single or multi-body), Terminators or Attennuators (see Figure 1.6)

![Figure 1.6: Classification according to type, size and orientation. Adapted from [13]](image)

- According to the working principle (see Figure 1.7).

$^5$1 terawatt = $10^{12}$ watts
According to development season and cost: WEC of first, second or third generation.

Figure 1.7: Wave energy converters classification and their main projects [14]

Following the work principle classification method proposed in [14], WEC devices may be in the form of an Oscillating Water Column (OWC), Oscillating Bodies or Overtopping device.

1.3.1 Oscillating Water Column (OWC)

OWCs, also known as first generation WEC, generally comprise a bottom-opened hollow structure positioned slightly below still-water level (chamber), an air turbine (usually Wells) and an electric generator. Due to the incident wave's rising motion, the air contained in the chamber is trapped and forced through an up-mounted turbine which then feeds an electrical generator. As the wave falls, air reenters the chamber and the process is repeated.

Figure 1.8: Bottom-standing OWC (Pico plant) [4]
These WECs can be found as fixed or floating-structure types. The first (represented above) are normally nearshore or onshore located and settled into seabed or the shoreline, respectively. Several prototypes with this specifications were developed and installed in Toftes-tallen (1985, Norway), Sakata (1990, Japan), Vizhinjam (1990, India), Port Kembala (Australia, 2005), Scotland (the LIMPET plant, 2000) and Pico (Azores, 1999) [4][11]. Both Pico and LIMPET\(^6\) (400 and 250kW) remained the most successful projects.

![Examples of fixed-structure OWC](image)

Figure 1.9: Examples of fixed-structure OWC. Adapted from [4][11]

Another approach is used by the floating-structure OWCs where the trio chamber, generator and turbine is attached to a floater anchored to the sea bed in areas with depths between 40 and 50 meters. This makes the converter less prone to destruction and potentially harness more energy as it can oscillate freely. There are three known types of floating OWCs: the Backward Bent Duct Buoy (BBDB), the Sloped Buoy and Spar Buoy [4]. Examples are the Mighty Whale and the Oceanlinx, prototypes with 110 and 300 kW installed in Gokasho (1998, Japan) and Port Kembala (2010, Australia), respectively.

![Examples of floating-structure OWC prototypes](image)

Figure 1.10: Examples of floating-structure OWC prototypes. Adapted from [13]

### 1.3.2 Oscillating Bodies

Oscillating Bodies (or third generation devices) are designed to take advantage directly of the wave’s motion to produce energy. Installed offshore, they are intended to harvest greater amounts of energy available in deep waters (typically depths superior to 40 meters) and can either be floating or fully submerged. Although generally simpler in appearance, these devices have to withstand harsher conditions and are therefore more complex to construct and maintain due to difficult access[15].

\(^6\)Land Installed Marine Power Energy Transmitter
Single or two-body heaving buoy

Heaving buoy systems take direct advantage from the vertical translational motion of the sea surface. These devices are generally conceived as point absorbers, i.e., devices of small dimensions relative to the wavelength and are, therefore, indifferent to wave direction.

The single-body system relies on a buoy connected to a fixed frame of reference, a structure fixed to seabed or the seabed itself [4]. An early single-body prototype, the Norwegian buoy, was developed and tested in the Trondheim Fjord (Norway, 1983). The device consisted of a spherical buoy (about 1 meter diameter) oscillating along a metallic strut anchored by an universal joint to the seabed. The power take-off (PTO) mechanism\(^7\) was an air turbine activated by the hull's movement to produce energy [16].

![Norwegian heaving buoy](image1) ![Swedish heaving buoy](image2)

Figure 1.11: Examples of single-body heaving systems [16][4][17].

Other version of the same topology started to be developed in 2002 by the Swedish Uppsala University, culminating in a prototype installed in the proximity of Lysekil at a depth of 25m. This WEC uses a taut-moored buoy connected to a linear electric generator (bottom fixed) by a tensioned cable (see Figure 1.11).

Two-body systems, on the other hand, aim to overcome the difficulties experienced in single-body devices: the high distances between surface and the sea bottom (even amplified by the tide-cycle). These employ multiple oscillating bodies in which energy is converted from their relative motion. Several multiple-body examples are the IPS, the Aquabuoy, the Wavebob and the Powerbuoy.

\(^7\) The mechanism that transforms the energy absorbed by the primary interface into electricity
Pitching devices

Contrary to heaving buoys, pitching devices harness energy over relative pitch oscillation caused by the income waves rather than heaving. One prime example of this WEC technology is the Duck, created in the University of Edinburgh by Stephen Salter in the 1980s [18]. Salter understood the troublesome of having a device with moving parts that, though unavoidable, could be vastly reduced. The solution comprised an array of cam-like floaters (Ducks) connected together parallel to the wave front (a terminator) with a hydraulic-electric PTO system. Despite the several iterations, the design never reached the full-scale prototype [4].

The Pelamis, developed in the United Kingdom, is a 750 kW 180 meter long slack-moored articulated structure with several semi-submerged cylindrical sections (floaters) linked by hinged joints. The structure, disposed perpendicularly to the wave front (an attenuator), is conceived to allow movement of adjacent cylindrical sections relative to each other across two degree of freedom (vertical and horizontal movements) whereas the PTO consists on sets of hydraulic cylinders feeding high-pressure fluid to
hydraulic motors which are then coupled to electric generators [4][19] (see Figure 1.14). In 2005, three Pelamis devices were bought and installed in the Portuguese northern coast (near Pôvoa de Varzim) which would later be destroyed by the ocean itself [11].

![Image](image_url)

(a) Physical layout  
(b) Wave farm in northern Portugal

Figure 1.14: Pelamis WEC. Adapted from [19] and [13], respectively.

Other examples of pitching devices are the Raft (by Sir Christopher Cockerell), the McCabe Wave Pump (by Peter McCabe, 1980), the PS Frog Mk5 (developed at Lancaster University, 1985) and the Searev (developed at Ecole Centrale de Nantes) [4].

**Fully submerged heaving system**

Fully submerged heaving systems’ design is vastly similar to single-body heaving buoys in all aspects except the fact that the first completely submerged in order to be less vulnerable to storm derived rough seas. The best example of this topology is the Archimedes Wave Swing (AWS), developed by the Teamwork Technology BV company in Zijdewind, Netherlands. The AWS embraces an air filled chamber moored to the seabed (silo) closed by another cylinder (floater) [20]. Mechanical to electrical conversion happens as the incoming wave pressurizes the heaving floater and the PTO system, a linear electrical generator, is activated 8.

![Image](image_url)

Figure 1.15: AWS schematic representation [4].

---

8Chronologically, the AWS was the first device to employ this PTO system
Portugal was selected as the desired location for the full-scale testing due to the combination of its high wave potential and the proximity between the shore and electrical grid [20]. In 2004, after several failed attempts, a 2MW prototype was submerged offshore the Portuguese coast.

Figure 1.16: AWS docked in Leixões harbour, Portugal [20].

**Bottom-hinged system**

Bottom-hinged devices are projected based on the inverted pendulum phenomena in order to avail the elliptical movement of water particles observed in the deepness as waves are formed. The Oyster and WaveRoller are two main examples of this system. Both are intended to be deployed nearshore and share the same design concept: a fully submerged flap which rotates around an horizontal base anchored at the seabed [4]. The Oyster uses a water pump to feed a Pelton turbine whereas the WaveRoller employs a hydraulic PTO.

Figure 1.17: Examples of bottom-hinged devices. Adapted from [11].
1.3.3 Overtopping

Unlike OWC and Oscillating Bodies, the operation of overtopping WECs is considerably different as these don’t use wave oscillations to produce work but rather gather energy passively by the overtopping principle [20]. The working principle evolves the capture of water that is close to the wave’s crest by forwarding it to a reservoir positioned higher than surrounding sea level. The originated head (potential energy differential) is then converted into electrical energy through several hydraulic turbines [4].

The Wave Dragon, developed in Denmark [21], is one of the major projects employing this concept. It’s design comprises a 300m wide (in its full-scale 7MW model) offshore floating structure featuring a ramp and a pair of reflectors to concentrate increase wave heigh (see Figure 1.19). The fluctuation is ensured by an air chamber system which is also responsible to regulate its height. Since the hydraulic head range typically varies between 1 and 4m, which is on the lower bounds of water turbines, the PTO is composed of 16 to 32 individually controlled low head Kaplan turbines connected to rotary electrical generators [11][20].

![Wave Dragon prototype](image)

Figure 1.18: Wave Dragon prototype [22].

![Wave Dragon overtopping device](image)

(a) Schematic  (b) Overtopping principle

Figure 1.19: Wave Dragon overtopping device. Adapted from [11] and [22], respectively.

The Tapchan - Tapered Channel Wave Power Device - and the Seawave Slot-Cone Generator (SSG) are other examples that conceptualize the overtopping concept but with fixed-type structures. Similar to the Wave Dragon, both used several Kaplan turbines.

1.4 The role of the linear electrical generator

The viability of a wave energy converter largely depends on its PTO system as it not only affects the overall efficiency of the converter but also has great influence over its complexity, control and cost [23].
From the WECs introduced in section 1.3, the great majority relies on complex pneumatic and hydraulic systems to convert the basic oscillatory wave movement (mostly heaving) in rotary movement for post electrical conversion.

![Diagram of wave energy conversion systems](image)

Figure 1.20: Alternative PTO for wave energy to electricity conversion [24]

Naturally, the greater the complexity of the interfaces, the greater the power absorbed by these and the less efficient they will be. This effect was analysed for several WEC in [23] and is summed up by table 1.2.

Table 1.2: Overview of the indicative efficiency for different wave PTO system. Adapted from [23]

<table>
<thead>
<tr>
<th>PTO System</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic</td>
<td>65</td>
</tr>
<tr>
<td>Water</td>
<td>85</td>
</tr>
<tr>
<td>Air</td>
<td>55</td>
</tr>
<tr>
<td>Mechanical</td>
<td>90</td>
</tr>
<tr>
<td>Direct Drive</td>
<td>95</td>
</tr>
</tbody>
</table>

The linear generator comes here as an opportunity to simplify the overall process. The implementation of this technology allows to reduce the complexity of the mechanical apparatus to a direct connection between the primary hydrodynamic interface and the generator, consequently contributing to minimize reliability and maintenance issues, much important in offshore environments [19].

Although the utilization of direct electrical drive systems has been investigated for several decades, its development was somewhat overdue by the lack of light materials and complex excitation systems, resulting in heavy, inefficient (low power density) and expensive machines [15]. Yet, the recent interest
on new magnetic materials and reduced costs of AC/DC and DC/AC electronics opened a new era for electrical linear machine technology (as seen in several floating and submerged heaving devices like the AWS).

Nevertheless, linear machines still face several challenges to their full success. Since there is a direct connection with the waves, these have to be prepared for high peaks of torque (characteristics of the sea environment) and must be capable to handle overload situations. Also, the high forces of attraction verified between the static and moving parts (stator and translator) cause a high burden on the translator bearings and consequently hinder the use of small air-gaps [25].

1.5 Goals and Outline

This work focuses on a permanent magnet linear generator (PMLG) power take of system previously built from a linear induction machine in the master dissertation of Paulo Cordovil. The prototyped generator suffered from high magnetic dispersion and high cogging forces, hindering its operation under sea conditions. Having established the stator pieces would remain untouched geometry wise, the opportunity and main goal of this work relies on revise the translator components and study different approaches to improve, if possible, the identified problems.

Other specific goals evolve to:

- Analyze the base design magnetic circuit and establish its performance regarding useful flux, flux density, magnetic flux dispersion, attraction and cogging forces;
- Evaluate the feasibility between 2D and 3D FEM/FEA approaches;
- Validate the base design FEM model experimentally;
- Study parametrically different translator topologies within:
  - Air-gap length variation;
  - Basic volume geometry variation;
  - Different magnet shapes;
  - Different magnetization directions;
- Conclude on the best approach for this generator;

The content of this work is outlined over five main chapters.

The chapter where we're now found, the introduction, introduces the reader to the context of wave energy as an alternative renewable source and details the main wave energy conversions systems studied and employed over the origins to the recent days.

In second chapter, the basic permanent magnet linear generator concepts are covered with the main topologies and the state-of-the-art generators being raised.

The third chapter occupies the base linear generator design analysis and introduces the contents of chapter 4 in which the parametric studies are performed, analyzed and discussed on.

Lastly, the fifth chapter concludes on the studies and overall findings of this work.
Chapter 2

Permanent Magnet Linear Generator

Linear electrical generators have prove advantageous for wave energy conversion as they enable the possibility of direct conversion of mechanical energy into electrical energy that, contrasting with hydraulic and turbine driven rotating generators, allows to reduce the number of mechanical components and implicitly contributes to reducing maintenance issues [15]. The interest in this type of PTO mostly comes from the Oscillating Body converters (introduced in the previous chapter) where point absorbers are responsible for primary wave interaction.

2.1 Basic Concepts

The structure of a linear generator mostly as its origin on a classic rotating machine. The parallelism can be made by abstractively cutting and unrolling the machine with linear dimensions and displacements replacing angular ones and forces replacing torques (see Figure 2.1) [26].

![Figure 2.1: From rotary to linear concept [27.](image-url)](image-url)

On its simplest form, a linear generator comprises one or more stationary stator pieces (the primary, containing the windings) and a moving translator (the secondary, equivalent to a rotor on rotating machines) with permanent magnets mounted in alternating polarities for excitation purposes. The translator, physical separated from the stator by an air gap, moves linearly in relation to it in order to induce a voltage (or electromotive force) $E_w$ at the armature windings’ terminals.
Figure 2.2: Basic morphology of a linear generator. Adapted from [27].

Under the Faraday law of induction, $E_w$ is determined by

$$\oint_C E \cdot ds = - \frac{d}{dt} \int_S B \cdot da$$  \hspace{1cm} (2.1)

where $E$ is the electric field intensity around a closed contour and $B$ the magnetic flux density. Knowing that the equation’s right-hand side is dominated by the magnetic flux $\phi$ crossing a surface $S$ given by

$$\phi = \int_S B \cdot da$$  \hspace{1cm} (2.2)

and that $E$ field on the wire is neglectable (low impedance), the Eq. 2.1 can be simplified to

$$E_w = -N \frac{d\phi}{dt} = -\frac{d\lambda}{dt}$$  \hspace{1cm} (2.3)

where $E_w$ is the electromotive force (emf) and $\lambda$ denotes the flux linkage of the armature winding through $N$ number of turns. The equation can finally be rewritten in function of the translator position

$$E_w = \omega \lambda_{pm} = 2\pi \frac{v}{w_p} \lambda_{pm}$$  \hspace{1cm} (2.4)

where $\lambda_{pm}$ is the permanent magnet induced flux per pole for $N$ number of turns and $\omega$ the angular frequency given by the translator speed $v$ and the pole pitch (distance between poles) $w_p$ [27][26].

2.2 State of the art

Multiple permanent magnet linear generators were developed over the years to serve several different purposes such as transportation, robotics and, the main topic of this work, wave energy conversion. Due to the particulars of WECs not all linear machines are suitable for the application, having to fulfill the prerequisites of handling high peak force, low speed (around 1 m/s), irregular motion and be low cost [28]. Today, these span around three main topologies: the longitudinal flux permanent magnet generator, the variable reluctance permanent magnet generator and transverse flux permanent magnet
Longitudinal flux permanent magnet generator (LFPM)

Longitudinal flux permanent magnet generators (LFPM), also known as synchronous permanent magnet generators, are linear machines which flux path is parallel to the translator movement. As illustrated by the Figure 2.3, the magnetic flux produced by one magnet follows the path with less magnetic reluctance\(^1\) through the air gap and into the ferromagnetic stator teeth (encircled by the armature coils). The path then divides and closes in the translator trough an adjacent teeth and magnet (with opposing direction) [27].

Figure 2.3: Cross-section of a LFPM generator [27].

LFPM generators usually comprise one or more flat type stator pieces as the manufacturing process of these is simpler and allows low fabrication costs with some choosing to employ a multiple-side design in order to distribute and overcome the high forces experienced between the primary and secondary parts [29].

Another characteristics of LFPMs are the small synchronous reactance and the low power rating per air gap area as their geometry is a limiting factor for the stator tooth width and thus the emf. Choosing to increase the former in order to increase the magnetic flux demands a larger pole pitch (distance between consecutive poles) which consequently reduces the angular frequency of the flux [27].

The most notorious examples that incorporate this topology are the AWS and Uppsala University project (introduced in Section 1.3.2) with both reaching sea-based tests.

AWS

The AWS converter, jointly developed in Netherlands by the Teamwork Technology BV company and Delft University of Technology, employs a three-phase (full pitch winding with one slot per pole per

\(^1\) or magnetic resistance
phase) permanent magnet system with the ferromagnetic primary surrounded by an external double-translator to balance the attractive forces. In its 1MW version, the structure reached 8 meters of length which later caused problems on the bearings [25][28].

Figure 2.4: AWS permanent magnet linear generator [28]

Uppsala University project

Swedish Uppsala University, on the other hand, developed a generator that assumes a more classical design with the internal translator engaging a central position and being surrounded by four stator pieces. The translator accommodates several NdFeB (Neodymium Iron Boron) magnets and the winding distribution is made with 6/5 slots per pole per phase in order to reduce the cogging forces [25][30]. The 10kW generators were later the basis for a partnership with Seabased AB company which, after further development, used several of these converters to form a wave park.

Figure 2.5: Uppsala University permanent magnet linear generator. (a) Photograph detailing the four stator arrangement (b) armature winding configuration. Adapted from [25].
2.2.2 Variable reluctance permanent magnet generator (VRPM)

Variable reluctance machines operate on a different level from LFPM generators, both geometrically and flux wise. Here the geometry related emf limitation seen in LFPMs is avoided through the use of a small pitch iron teeth to allow alternate return flux paths [27][31]. The magnets (placed sequentially in alternating directions) in combination with the short pole pitch arrangement enables the formation of a high intensity and high frequency magnetic flux as a single pole movement reverses the direction of the magnetic flux (see Figure 2.6). As the less positive aspect, these machines tend to have high synchronous reactances [31].

![Figure 2.6: Basic principles of VRPM [27].](image)

Presently, there are several topologies developed under this working principle of which the transverse flux permanent magnet machine and the Vernier Hybrid Machine stand out.

**Vernier Hybrid Machine**

The linear Vernier Hybrid Machine (or VHM) developed in the British Durham University is a variant of a VRPM machine. The design comprises three single-phase stators in which both permanent magnets and windings are installed in order to reduce the cogging forces. Each of these stators is composed by two front-faced C-shaped cores with the PMs installed on the surface of each pole whereas the translator is a ferromagnetic toothed structure that extends along the machine length. The alternating magnetic flux has its direction defined by the magnetization direction of the PMs that are aligned with the translated tooth. The frequency over which it occurs is significantly higher than the mover mechanical frequency due to the magnetic gearing effect [29].

![Figure 2.7: Vernier Hybrid Machine. (a) Photograph of a 3kW prototype [32], (b) working principle [31].](image)
All along, the machine is able to offer a 143.9 kN/m² force density making it suitable for the low-speed high-torque characteristics of wave energy conversion [29]. The major drawbacks of this design are the high forces between the translator and stator pieces, low power factor and very small air-gaps (less than 1mm) [29][31][33].

Transverse flux permanent magnet generator (TFPM)

In a transverse flux permanent magnet machine the main magnetic flux path is perpendicular to the direction of the translator movement. The primary of these machines normally consists of sets of ferromagnetic C-shaped pieces that allow the flux to circulate around the armature coils. The same C cores are enclosed by the translator permanent magnets whose displacement forces the flux to vary three-dimensionally in both transverse and axial directions through adjacent cores [31]. Figure 2.8 depicts the working principle of a double sided version of a TFPM machine. By employing the base characteristics of VRPM with such layout, TFPM machines are able to produce high amounts of power in the air gap region with the drawbacks of high cogging forces and a low power factor (needing reactive power compensation) [31].

![TFPM diagram](image)

Figure 2.8: TFPM working principle. On the left, 3D-view of a double sided with two sets of C-Cores and, on the right, cross-section view of the flux paths of two consecutive poles [27].

The C-Gen is a double sided modular TFPM machine developed and manufactured at the Edinburgh University [34] with the design aim of annulling attraction forces between the stator and the permanent magnets. For this an internal air-cored winding primary was used with the translator being composed by sets of two front-faced C-cores (hence the modularity) with built-in permanent magnets. This configuration allows for a mainly transverse flux path that also can travel longitudinally through adjacent cores.

2The concept and effects are detailed in section 3.1.
The generator was developed as an alternative PTO for the AWS WEC (subsection 2.2.1) whose original design had several performance and structural problems [34].

2.2.3 Tubular air-cored permanent magnet generator (TAPM)

Tubular air-cored permanent magnet machines were developed to counter the drawbacks of iron-cored machines identified in the previous topologies forming a new type of geometry not present in rotating machines [27]. The concept was investigated for wave energy conversion by Baker and Mueller (from the University of Durham and Edinburgh) [35] and consists of a tubular translator surrounded by stationary copper coils (stator), materialized in a 3kW prototype.

The translator has axial NdFeB magnets disposed in opposing directions separated by steel spacers (here also as flux concentrators) although radial magnets could also be used. The air-supported coils in combination with the translator tubular geometry eliminates the attractive forces experienced

---

21
between the two, allowing for a less complex supporting structure and less burden on bearings [32]. The least positive aspects are the low inductance (high power factor) and less shear stress than the other topologies due to the infinite air-gap [15].

Other prototypes of TAPM generators were also developed in the University of Stellenbosch [36] and University of Oregon [37] along with several iron-cored versions [38] with better shear stress performance than the first at the expense of characteristic high attraction forces.

Commercially, TAPM generators are available by the hand of Trident Energy Ltd. The PowerPod, developed with the support of the University of Edinburgh and Cambridge [39] is a modular, two-phase, slotless air-cored linear generator. The translator consists of stacks of axial NdFeB permanent magnets separated by steel spacers with the armature containing two-phased coil winding connected in parallel (detailed in Figures 2.11 and 2.12). Depending on the number of modules the generator’s power can range from 60kW for two modules to 360kW for six modules therefore being compatible with several WEC designs.

![Figure 2.11: Trident Energy TAPM. (a) Top view of two generators [39] (b) coil winding detail [40].](image)

![Figure 2.12: Trident Energy TE5 module schematic [39].](image)
The tables below characterize and summarize the state-of-the-art topologies and respective permanent magnet linear generators (table 2.1) from which the pros and cons were equally gathered and compared in 2.2.

Table 2.1: Permanent magnet linear generator state of the art synthesis. Adapted from [25].

<table>
<thead>
<tr>
<th>Main topology</th>
<th>Generator &amp;/or Developer</th>
<th>Core Type</th>
<th>Translator</th>
<th>PM installation</th>
<th>Nominal Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFPM</td>
<td>AWS [28]</td>
<td>Iron</td>
<td>External</td>
<td>Secondary</td>
<td>2MW</td>
</tr>
<tr>
<td></td>
<td>Uppsala/Seabased [30]</td>
<td>Iron</td>
<td>Internal</td>
<td>Secondary</td>
<td>10kW</td>
</tr>
<tr>
<td>VRPM-TFPL</td>
<td>C-Gen [34]</td>
<td>Air</td>
<td>External</td>
<td>Secondary</td>
<td>25kW</td>
</tr>
<tr>
<td>VRPM-VHM</td>
<td>U.Durham VHM [31]</td>
<td>Iron</td>
<td>Internal</td>
<td>Primary</td>
<td>3kW</td>
</tr>
<tr>
<td>TAPM</td>
<td>U.Durham TAPM [32]</td>
<td>Air</td>
<td>Internal</td>
<td>Secondary</td>
<td>1.6kW</td>
</tr>
<tr>
<td></td>
<td>Trident Energy PowerPod [40]</td>
<td>Air</td>
<td>Internal</td>
<td>Secondary</td>
<td>60-360kW</td>
</tr>
<tr>
<td></td>
<td>U.Stellenbosch [36]</td>
<td>Air</td>
<td>Internal</td>
<td>Secondary</td>
<td>1kW</td>
</tr>
</tbody>
</table>

Table 2.2: Linear generator topology comparison. Table adapted from [27]. Information relative to VHM topology obtained from [33].

<table>
<thead>
<tr>
<th>Topology</th>
<th>Power per air gap area ([\text{kW/m}^2])</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFPM</td>
<td>25</td>
<td>Low synchronous reactance. Simple and robust stator.</td>
<td>Low power rating per air gap area.</td>
</tr>
<tr>
<td>VRPM-TFPL</td>
<td>50</td>
<td>High power per air gap area.</td>
<td>High synchronous reactance. Complex Stator.</td>
</tr>
<tr>
<td>VRPM-VHM</td>
<td>-</td>
<td>Simple Translator. High power per air gap.</td>
<td>High attraction and cogging forces. Very high synchronous reactance.</td>
</tr>
<tr>
<td>TAPM</td>
<td>&gt;12.8</td>
<td>No normal forces in the air gap area.</td>
<td>Very low power rating per air gap area.</td>
</tr>
</tbody>
</table>
2.3 Initial design

2.3.1 Prototype Specifications

The generator within the scope of this work is a three-phase longitudinal flux permanent magnet (LFPM) comprising a flat ferromagnetic two-sided armature (laminated iron stator pieces) and one planar translator prototyped by Paulo Cordovil in its master thesis [25]. The translator itself is mainly made of acrylic and contains twenty surface mounted NdFeB magnets arranged in alternated polarities.

![Prototype 3D view](image1)

Figure 2.13: Prototype 3D view.

Stator and Winding

The linear generator comprises a toothed double stator developed by Prof. Cabrita in its PhD thesis [41] were both stator and windings’ configuration derived from an induction motor. Each stator piece is 438mm long, 65mm high and 77mm deep (from top view) and has eight poles distributed by 24 slots, resulting in a relation of 3 slots per pole and 1 slot per pole per phase (q=1). The core is made of laminated iron, modelled with M-15 steel B-H curve.

![Stator section top view with tooth detail](image2)

Figure 2.14: Stator section top view with tooth detail.
\[
q = \frac{24}{3 \times 8} = 1
\]  

(2.5)

Figure 2.15: Top and isometric view of stator pieces.

Regarding winding configuration, this generator has star terminated concentrated windings connected in series between the two stators in which each regular coil is distributed over 3 slots (Figure 2.15). End-windings, also known by compensation windings, are also displaced at both ends of each stator in order to diminish the longitudinal effects [25]. Stator and coil specifications are summarized on Table 2.3.

Table 2.3: Stator and coil specifications. Adapted from [25].

<table>
<thead>
<tr>
<th>Stator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stators</td>
<td>2</td>
</tr>
<tr>
<td>Teeth width</td>
<td>6mm</td>
</tr>
<tr>
<td>Stator length</td>
<td>438mm</td>
</tr>
<tr>
<td>Number of slots</td>
<td>24</td>
</tr>
<tr>
<td>Stator height</td>
<td>65mm</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>25</td>
</tr>
<tr>
<td>Stator depth</td>
<td>77mm</td>
</tr>
<tr>
<td>Pole pitch</td>
<td>54.75mm</td>
</tr>
<tr>
<td>Stator weight</td>
<td>16kg</td>
</tr>
<tr>
<td>Number of poles</td>
<td>8</td>
</tr>
<tr>
<td>Stator iron losses at 50Hz and 1.5T</td>
<td>0.8 W/kg</td>
</tr>
<tr>
<td>Number of slots per pole</td>
<td>3</td>
</tr>
<tr>
<td>Slot height</td>
<td>36mm</td>
</tr>
<tr>
<td>Number of slots per pole per phase</td>
<td>1</td>
</tr>
<tr>
<td>Slot width</td>
<td>12mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coils</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Isolation class (NEMA Class)</td>
<td>H(180°C)</td>
</tr>
<tr>
<td>Number of coils</td>
<td>27</td>
</tr>
<tr>
<td>Winding resistance per phase per stator</td>
<td>6.8ohm</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>100</td>
</tr>
<tr>
<td>Nominal current (as induction motor)</td>
<td>3.3A</td>
</tr>
<tr>
<td>Winding wire diameter</td>
<td>1mm</td>
</tr>
<tr>
<td>Nominal voltage (as induction motor)</td>
<td>400V</td>
</tr>
<tr>
<td>Slot fill factor</td>
<td>37%</td>
</tr>
</tbody>
</table>

**Translator**

The flat translator designed for the generator is centrally mounted between the stators with an air-gap of 6mm and has sixteen 25x24x77mm³ (WxHxD) Neodymium Iron Boron (NdFeB) permanent magnets
built into it (see Figure 2.16). The employed NdFeB magnets belong to the N35EH variance (designed to withstand working temperatures up to 200°C) and are surface mounted and arranged in alternate polarities in order to create an uniform longitudinal flux along the stators length. The demagnetization curve and main magnetic properties of such are shown in Figure 2.17.

![Figure 2.16: Translator top view with measures (the arrows represent the magnetization direction).](image)

![Figure 2.17: NdFeb demagnetization curve at 20°C. Remanence $B_r = 1.25T$, coercivity $H_c = -970kA/m$.](image)

Due to the lack of material availability, the translator was prototyped with only two 25x24x25mm depth magnets per pole instead of the projected 25x24x77mm single one (see Figure 2.18) [25]. It is important to note that the translator is naturally longer than the stator (about double length) to accommodate the oscillating wave movement amplitude.
Figure 2.18: On the left, magnets designed for the translator, on the right, magnets used in the physical prototype.
Chapter 3

Base Design Analysis

3.1 Problem framing

The linear generator layout proposed and prototyped by Cordovil [25] (detailed in section 2.3) and focus of this work was concluded to have several drawbacks affecting its overall performance. The first and foremost is the low magnetic efficiency consequence of the high magnetic dispersion or leakage flux present in the air-gap region as a large part of the magnetic flux produced by the permanent magnets ends up closing through the air (path wise) instead of going through the stator iron teeth and surrounding coils (dubbed the linkage or useful flux).

![Leakage flux path exemplification.](image)

The relation is given by

\[ \phi_{PM} = \phi_{useful} + \phi_{leakage} \]  

(3.1)

where \( \phi_{PM} \) represents the total magnetic flux produced by one permanent magnet and \( \phi_{useful} \) the flux that crosses the coils of one pole.

The phenomenon above occurs mainly due to the high mechanical air-gap setting (6mm) chosen...
in order to overcome which is the other major issue with the proposed design: the high attraction and movement detent forces, experienced between the translator and stators.

The first component actuates perpendicularly to the translator movement and results from the natural tendency to reduce the magnetic reluctance between the magnets and ferromagnetic stator pieces therefore attracting each other. The presence of such imposes a burden in the fixation and bearing systems that must be robust enough to handle these forces. Here, the opposing double stator configuration helps to attenuate the effect as long as both pieces are vertically aligned.

Detent force is also a magnetic reluctance force whose main component actuates along the translator movement axis. At a given time frame, if the translator is moving into a lower reluctance position (from a tooth to a slot), the detent force contributes to the movement and do the opposite if it is moving into a high reluctance one. M. Salman further investigated the behaviour in [42] and identified the total movement resistant forces the generator is subjected as the composition of cogging and end-effect forces.

\[ F_{\text{detent}} = F_{\text{cogging}} + F_{\text{end\text{-}effect}} \]  

The end-effect forces result from the interaction of outer stator teeth with the entering or leaving permanent magnets and can be reduced or eliminated by adopting a short secondary design instead of a short primary setting [43]. Cogging forces, on the other hand, do not depend on the stator-translator topology since they are due to the inner teeth-slots interaction and require a different approach to minimize them [42].

The presence of both introduces an undesired ripple in this generator that overlaps the thrust force provided by the waves and has a considerable effect on performance with the vibrations becoming more significant specially at the low speed that the generator operates.

With regard to iron losses, the same low speed operation in combination with the large pole pitch on the primary, results on an considerable low electrical frequency at the coils terminals. As consequence, the inherent iron losses weren’t found impactful enough to degrade the generator performance [25].

The development of this work has its objective and focus in exploring the translator component and permanent magnets properties and geometry to evaluate and minimize the drawbacks identified while keeping the same stator design. Prototyping a new translator with the post obtained results was evaluated but put aside due to the high costs evolved in the fabrication of new permanent magnets. Given
this, finite element analysis (FEA) was chosen to endorse the study of the factors of interest of this work: the "magnetic efficiency" (leakage-useful flux relation), flux harmonic distortion, magnetic forces and amount of material used.

3.2 Finite-element Analysis

Finite Element Method (FEM) is a powerful mathematical tool in electrical machine design since it allows to obtain precise results for complex electromagnetic problems and machine geometries without the simplifications made on analytic analysis, as studied in [44]. As result, it is possible to precisely map flux density distribution, calculate parameters like winding inductances and induced voltage as well as analyse mechanical phenomena.

To address the studies on the linear generator a choice had to be made between two or three-dimensional finite element analysis (2D or 3D FEM). The first option usually offers acceptable results for simple non varying geometries with reasonable computation time for the simulations. On the other hand, 3D FEM can offer an higher degree of precision on any geometry at the expense of and higher human and computational effort. As investigated in [42], the later also allows to precisely represent end-effect forces not possible in 2D FEM.

To obtain an order of magnitude on how these two approaches influenced the results of this specific design, a comparison magnetostatic study was performed on 2D and 3D FEM software over the respective 2D and 3D CAD designs of the generator. The permanent magnets shared the same specifications for both simulations, i.e., NdFeB with remanence $B_r = 1.25T$ and coercivity $H_c = -970kA/m$, as well as the stator ferromagnetic material, with the BH curve parametrized from M-15 steel (see Figure 3.3).

The simulated translator was centrally aligned with the stators and consisted of twenty permanent magnets with 24mm height, 77mm deep and of variable width (to the maximum width of a polar pitch), arranged to produce longitudinal magnetic flux in the stator (see Figure 2.18).
The useful flux was then measured on the fourth polar step at the center of the teeth (see Figure 3.4 and compiled as in the table 3.1.

Table 3.1: Difference between 2D and 3D FEA simulation

<table>
<thead>
<tr>
<th>PM width (mm)</th>
<th>$\phi_u$ (mWb)</th>
<th>2D</th>
<th>3D</th>
<th>Diff. to 3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.915</td>
<td>0.764</td>
<td>19.8%</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1.436</td>
<td>1.279</td>
<td>12.3%</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>1.756</td>
<td>1.621</td>
<td>8.3%</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>1.910</td>
<td>1.811</td>
<td>5.5%</td>
<td></td>
</tr>
<tr>
<td>54.75</td>
<td>1.950</td>
<td>1.854</td>
<td>5.2%</td>
<td></td>
</tr>
</tbody>
</table>

The maximum difference between 2D and 3D FEM estimated useful flux is 19.8% for the 15mm wide magnets with 2D simulation over estimating it. Missing the extra deepness dimension, the 2D study is unable to consider the dispersion of magnetic field verified near top and bottom borders of the generator, therefore possible in 3D. As the magnet width is increased until reaching polar pitch, the difference between 2D and 3D becomes less significant as the iron in the stator begins to saturate.

Despite being more time consuming than 2D, the verified error margin between 2D and 3D FEM analysis and the precision intended to this work lead us to use 3D FEM for the following studies as the geometry simplification inherent to the former could lead to imprecise and incorrect conclusions.
later gains special importance when trying to analyze the flux paths along the Z axis (deepness). The end-effect force component, one of the main problems and object of study of this dissertation, couldn’t also be effectively represented in two-dimensional analysis as 2D FEM neglects the influence of magnet ends as verified in [42] and [45].

3.2.1 Base design performance analysis

The base design and starting point of this work, presented in detail in section 2.3, comprises series of 25x24x77mm (WxHxD) surface mounted magnets with alternating polarities, fulfilling about 46% of the pole pitch. The magnetic flux originated by these 25mm wide magnets finds its lowest reluctance\(^1\) path, i.e., the lower magnetic resistance path, mostly through the mechanical air-gap into one pair of stator teeth to the stator back.

The stator to magnet return path is made through the closest teeth and magnet (with opposing polarity) which then re-conducts the flux to the second stator piece, with the same flux path being shared by both stator pieces. Given this, a translation between two polar steps (109.5mm) is necessary to generate a complete wave period of induced EMF (360 electrical degrees), per phase.

![Figure 3.5: Main magnetic flux paths with a surface mounted magnet translator. The magnet support structure was omitted for better visualization.](image)

The generator was found to suffer from high flux dispersion in the air-gap region consequence of both large mechanical air-gap length as well as the small stator teeth pitch configuration [25]. In order to understand such behaviour a steady-state simulation was performed and the magnetic field density distribution measured in the middle of the magnets, at the air-gap region and at the stator teeth. The results were then plotted in Figure 3.6.

\(^1\)The reluctance of a magnetic circuit can be calculated as \( R = \frac{l}{\mu A} \)
Figure 3.6: Magnetic flux density distribution in the translator (a), air-gap (b) and teeth (c), along the
generator length (438mm).
By observing the first plot, it is possible to identify and distinguish the magnetic flux contribution of each of the eight magnets, each with its alternating polarity. Isolating the analysis to a single pole pitch (and therefore to a single magnet), the variation of the flux density $B_m$ from the center to the sides of the magnet becomes evident with a difference of roughly 0.4 Tesla. The spikes present in the magnet sides are a consequence of two main factors: the magnet edge discontinuance effect and the field interaction with the stator teeth (with the depression corresponding to the slotting effect), resulting in a field density value that nearly reaches, in modulus, the 1.25 remanent flux ($B_r$) characteristic of the NdFeB magnets employed.

This interaction becomes even more apparent in the second plot as we move our measuring line to the air-gap towards the stator. Here the spikes previously observed are attenuated as the field begins to be guided according to the teeth-slot shape resulting in a distribution with a larger sinusoidal component. The number and shape of the slots largely affects the distribution and intensity of air-gap flux density. This effect, dubbed the Carter effect, was firstly studied by F.W.Cater and later investigated in the permanent magnet context by H. Vu Xuan et al. in [45]. Since changing the shape of the stator is beyond the scope of this work, this point will not be analyzed as a possibility of improvement.

Lastly, as the flux reaches the stator (third plot) it is guided through the teeth as this represents the path of lower magnetic reluctance. The sinusoidal shape of the electromotive force has its origin in the sinusoidal variation of the field in the teeth as the translator is moved along its axis. Depending on the magnet width and translator position, one up to three stator teeth may be simultaneously magnetized. The set of these flux density variations results in the global flux density distribution depicted in Figure 3.7.

Figure 3.7: Close up view of the magnetic flux density distribution (norm) at the center of the generator.

One aspect that becomes evident as soon as we analyze the obtained data is the large amount of
flux concentrated in each tooth with values around 1.5T. For values above 1.3T the iron on the stator operates in the nonlinear region (as in Figure 3.3). A possible solution to reduce the flux density would be, once again, enlarging the teeth width.

With the computed flux distribution it is also possible to validate the main flux path previewed in Figure 3.5, here evidenced by the black arrow lines, with the path following the same magnet1-stator1-magnet2-stator2-magnet1 path. Highlighted in white is the zoomed view of the region between magnets. In an ideal scenario there would be no flux lines between magnets. The presence of flux arrow lines perpendicularly to the magnet flux normal hints that an amount of flux is dispersed through adjacent magnets. This situation corroborates the analysis made by Cordovil in [25] with the large air-gap length of 6mm being one of the factors contributing to the phenomenon.

The extra physical dimension of the 3D FEM model also allows to inspect the field behaviour on the top of the generator (see Figure 3.8). In addition to the flow that disperses laterally between magnets there is also a portion of the magnetic flux that is dispersed vertically (along Z axis) to the magnet itself and to the adjacent magnets. The use of a translator with magnets of slightly smaller depth than the stationary parts could be one way of attenuating the vertical dispersion.

Figure 3.8: Flux lines between magnets at the top of the generator.

To quantify the flux dispersion is necessary to measure the flux produced by on one magnet and the useful flux\(^2\) of the respective polar step (highlighted in red). Through the relation of the quantities of the equation (3.1):

\[
\Phi_R\% = 100\% \times \frac{\Phi_u}{\Phi_m}
\]

(3.3)

where \(\Phi_R\%\) can be perceived as the "magnetic flux efficiency" of one polar step. The flux dispersion

\(^2\)The flux that reaches the coils
can then calculated as:

\[ \text{Disp}\Phi\% = 1 - \Phi_R\% \quad (3.4) \]

In this configuration each magnet produces a magnetic flux \( \Phi_m \) of 1.81mWb. From that value, 1.26mWb (\( \Phi_u \)) reach the stator coils of one phase which results in a flux dispersion \( \text{Disp}\Phi\% \) of 30%.

To conclude the performance analysis of the reference design, attraction and detent forces between the translator and the stators were addressed. The double stator configuration present in this generator was intended to cancel the attraction force produced by a single stator piece. Experimentally \(^3\), as soon as the translator is set in motion, the attraction forces caused the translator to wobble considerably, demonstrating that these can not be disregarded.

Recurring to the electromagnetic force expression (for Y axis component) and the data of the same FEM model and by isolating the translator to a single stator piece, the attraction force \( \text{Force}_Y \) felt by the translator was determined to be 2298N. This force was demonstrated in \[46\] to be inversely proportional to the air-gap length whereas the choice of a large air-gap length of 6mm for the base prototyped model was therefore largely influenced by its influence on attraction and cogging forces.

Regarding detent force influence (force along X axis), the same translator was displaced by two pole pitch lengths (109.5mm) to the right in order to capture the evolution over 360 electric degrees.

![Figure 3.9: Detent force evolution over 360 electrical degrees (or two pole pitch).](image)

The detent force experienced over 360 degrees varies between +/- 200 N with a characteristic odd symmetry centered on 180 electrical degrees. The high frequency components visible along the displacement, overlap a fundamental sinusoidal wave with a RMS value of 108 N, introducing an undesirable ripple. Depending on the overall mass of the translator and thrust force imposed by the buoy, these high-frequency components can be more or less cancelled, being the lower-frequency components the predominant ones.

\(^3\)As in the work of Cordovil \[25\]
The base performance of the reference design is then summed by the following table.

<table>
<thead>
<tr>
<th>PM dim. (mm³)</th>
<th>$\Phi_m$ (mWb)</th>
<th>$\Phi_u$ (mWb)</th>
<th>Disp %</th>
<th>Force Y (N)</th>
<th>Force XPeak (N)</th>
<th>Force X RMS (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25x24x77 (WxHxD)</td>
<td>1.81</td>
<td>1.26</td>
<td>31</td>
<td>2298</td>
<td>202</td>
<td>107.7</td>
</tr>
</tbody>
</table>

### 3.2.2 3D FE Model Experimental Validation

In order to validate the materials, mesh size and BH curves chosen to figure in the FE models, an experimental validation was performed recurring to a HIRST GM08 Gaussmeter hall-probe available in the electrical department laboratory.

The objective was to measure the magnetic flux density in the air-gap region on the physical prototype along a pole pitch length (54.75mm) and contrast the results with the ones obtained through the FE model. As the physical prototype comprised sets of 25x24x25mm (WxHxD) magnets, the respective model was adjusted. The physical measurements took place in the air-gap region between the center-left top magnet (red) and the stator teeth by sliding the probe in a straight line (see Figure 3.11).

![Figure 3.10: The HIRST GM08 Gaussmeter model and respective probe being placed between in the air-gap region.](image)

![Figure 3.11: Top and perspective views of the chosen measuring line position.](image)
Finally, the experimental points were overlapped to the flux density evolution obtained through the 3D FE model (blue line) in Figure 3.12 and respective points detailed in table 3.3.

![Magnetic flux density distribution in the air-gap. In blue, the values from the 3D FE model and in green, the experimental points.](image)

**Table 3.3: Experimental flux density points.**

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>x=0</th>
<th>x=5</th>
<th>x=10</th>
<th>x=15</th>
<th>x=20</th>
<th>x=25</th>
<th>x=30</th>
<th>x=35</th>
<th>x=40</th>
<th>x=45</th>
<th>x=50</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.Density (T)</td>
<td>0.073</td>
<td>0.082</td>
<td>0.137</td>
<td>0.264</td>
<td>0.622</td>
<td>0.417</td>
<td>0.441</td>
<td>0.582</td>
<td>0.408</td>
<td>0.152</td>
<td>0.092</td>
</tr>
</tbody>
</table>

The experiment was found to validate not only the flux density distribution curve but also the range of flux density values with the experimental points closely following the ones obtained in the FE model. Around the 35mm mark is possible to identify the presence of the second stator tooth, however, with a higher experimental flux density measure, not so expressive in the FE model. The difference, despite residual, was possibly due to the mesh geometry chosen for the simulation, not having a considerable impact on the rest of the FE parameters here validated.
3.2.3 Parametric Study Approach

The main objective of this work is to study and understand the magnetic strands of this permanent magnet linear translator in order to improve, if possible, the major drawbacks verified theoretically and experimentally by Cordovil while maintaining the stators geometry and volumetry. For this, it is important to acknowledge that the magnetic useful flux (and consequently the EMF) and electromagnetic forces of a linear generator are affected by several properties [42] of which the most relevant are:

- Air-gap length;
- Magnet volume (in this case width, height and depth);
- Magnet shape;
- Magnetization direction;
- Stator length;
- Stator slot number, shape and width;

Having established the baseline within the initial study analysis in the previous section (3.2.1), a set of studies was developed comprising variations of the properties listed above (with the exception of the ones that are stator related). These parametric studies that intend to explore the influence and shortcomings of varying such parameters on both useful flux and detent forces were subdivided in three major groups, presented in chapter 4:

1. Air-gap length and volume variation
2. Magnet shape variation
   
   (a) Slotted magnet geometry
   
   (b) Hexagonal magnet geometry
3. Magnetization direction and magnet arrangement variation
   
   (a) Axial magnetization
   
   (b) Axial magnetization with iron spacers;
   
   (c) Quasi-Halbach magnetization;

Each of the three studies groups is outlined with objective explanation, results analysis and intermediate conclusions. In the end, overall conclusions address the pros and cons of each parameter choice and which of the translator topologies is most suitable to maximize useful magnetic flux and minimize electromagnetic forces.
Chapter 4

Parametric FEM Studies

4.1 Air-gap length and volume variation

The first set of studies has two main objectives while still maintaining the original translator topology. The first is to understand the effects that altering the air-gap length, the magnet height and magnet width (see Figure 4.1) have on the performance of useful flux at the stator, magnetic dispersion and attraction and detent forces. With the added dimension brought by 3D FEM analysis in relation to the 2D models used by Cordovil there is also the opportunity to verify the validity of Cordovil’s approach that, for the study demonstrated on section 3.2, can produce considerable differences under some geometric conditions.

Figure 4.1: Parametric geometry variations.

4.1.1 Air-gap length

In electric machinery the air-gap length plays an important design aspect in what concerns overall efficiency. In linear machines and contrasting with rotating machinery for the case, the attraction forces between translator and stator cannot be easily annulled as between the stator and a rotor (except in linear tubular topologies). The trade-off on play is that the bigger the air-gap is, the lowest the attraction
forces will be. On the other hand, dispersion will generally increase, reducing the overall magnetic flux and power efficiency. A balance is therefore important to achieve.

Following the same approach presented in the base design analysis (subsection 3.2.1) of only one stator piece arrangement, the useful flux, dispersion and attraction forces were measured with the air-gap length varying from to 2 to 7mm (increments of 1mm) and with the translator centrally positioned. Magnet geometric characteristics remained the unaltered. The results were then plotted in the Figures below with respective data gathered in the table 4.1.

![PM magnetic flux variation with increasing air-gap length.](image)

**Figure 4.2:** PM magnetic flux variation with increasing air-gap length.

![Attraction force between the translator and one stator piece](image)

**Figure 4.3:** Attraction force between the translator and one stator piece.
Table 4.1: Air-gap length variation performance data.

| Air-gap (mm) | $\Phi_m$ (mWb) | $\Phi_u$ (mWb) | $Disp_{\Phi}$ (%) | Attraction force (|N|) |
|--------------|----------------|----------------|-------------------|------------------------|
| 2            | 2.03           | 1.77           | 12.8              | 4810                   |
| 3            | 1.96           | 1.65           | 16.2              | 3803                   |
| 4            | 1.90           | 1.51           | 20.6              | 3122                   |
| 5            | 1.85           | 1.39           | 24.9              | 2564                   |
| 6*           | 1.81           | 1.28           | 29.2              | 2298                   |
| 7            | 1.77           | 1.18           | 33.0              | 1904                   |

The obtained results corroborate, as expected, the inversely proportional evolution of the useful flux and attraction force as the air-gap is enlarged. If physical possible for the support structure and bearings to support the forces while maintaining an air-gap length of 2mm would drastically reduce the dispersion verified in the base design from 30% to 13% and increase the useful flux in 38%. This phenomenon is also visible in Figure 4.4 where is possible to verify that by shortening the air-gap, the flux between magnets becomes absent (left image) being mostly guided to the teeth of both stators instead of closing through adjacent magnets.

![Figure 4.4: Magnetic flux density (B) in the air-gap region for an air-gap length of 2mm (a), 4mm (b) and 6mm (c).](image)

In theory, the double stator configuration present in the prototype would cancel the attraction forces. Experimentally this is not verified since the translator isn’t completely rigid and flexes with the linear movement. As consequence, the mechanical air-gap doesn’t remain constant along the machine length and the attraction forces are amplified. A possible solution approach would be adding pairs of stator pieces into a multi-sided generator. This would allow to distribute more evenly the forces along the generator therefore the reduction of the air-gap length.
4.1.2 Magnet height and width

While maintaining the air-gap length fixed in the 6mm of the initial design, magnet height and width were varied with the translator fixed in center position. The objective is to understand and quantify the impact that a change in magnet volume has in useful flux and dispersion. It is expected that the larger the amount of magnetic material, the larger the field produced by it, and the greater the amount of field in both the air gap and the stator teeth. As seen in [25] and studied in [42], a translator with overly dimensioned magnets can cause a situation of iron saturation.

The degree of freedom was given separately to the height and width properties with magnet depth being fixed at 77mm in order to avail the useful area of the stators. More specifically, magnet height was varied from 8 to 32mm with increments of 4mm (width fixed in 25mm) and the width varied from 15 to 54.75mm (pole pitch) with increments of 10mm (height fixed in 24mm). The respective magnetic flux evolutions were depicted in Figures 4.5 4.7 and respective data compiled in tables 4.2 4.3.

Complementarily, within magnet width variation, the translator was also displaced of 360 electrical degrees to study and compare its detent force component.

Magnet height results

![Graph showing magnetic flux for different height magnets.](image)

**Figure 4.5:** Magnetic flux for different height magnets.

<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Vol. (cm³)</th>
<th>Φₘ (mWb)</th>
<th>Φₜ (mWb)</th>
<th>Disp (%)</th>
<th>Height (mm)</th>
<th>Vol. (cm³)</th>
<th>Φₘ (mWb)</th>
<th>Φₜ (mWb)</th>
<th>Disp (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>15.4</td>
<td>1.10</td>
<td>0.78</td>
<td>29.8</td>
<td>24*</td>
<td>46.2</td>
<td>1.80</td>
<td>1.28</td>
<td>29.2</td>
</tr>
<tr>
<td>12</td>
<td>23.1</td>
<td>1.37</td>
<td>0.97</td>
<td>29.1</td>
<td>28</td>
<td>53.9</td>
<td>1.89</td>
<td>1.34</td>
<td>29.3</td>
</tr>
<tr>
<td>16</td>
<td>30.8</td>
<td>1.56</td>
<td>1.11</td>
<td>28.8</td>
<td>32</td>
<td>61.6</td>
<td>1.97</td>
<td>1.38</td>
<td>29.7</td>
</tr>
<tr>
<td>20</td>
<td>38.5</td>
<td>1.69</td>
<td>1.21</td>
<td>28.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.2:** Height variation data.
A positive variation in height results in a greater useful flux as expected. The evolution of magnetic flux produced by the magnets closely follows the resulting useful flux in the stators, meaning that the dispersion remains unaltered independently of the magnet height (or volume). This is also demonstrated in the flux distribution mapping depicted in Figure 4.6 where is possible to verify the existence of a constant field in inner magnet region.

![Magnetic flux density (B) distribution in the air-gap region for a magnet height of 8mm (a), 16mm (b), 24mm (c) and 32mm (d).](image)

Figure 4.6: Magnetic flux density (B) distribution in the air-gap region for a magnet height of 8mm (a), 16mm (b), 24mm (c) and 32mm (d).

**Magnet width results**

![Magnetic flux for different width magnets.](image)

Figure 4.7: Magnetic flux for different width magnets.
When evaluating the results obtained for magnet width variation, it becomes evident that the evolution of the magnetic flux produced in the larger magnets does not follow the same behaviour as in volume trough height variation. Here, the increasing proximity of the magnets as their width evolves into occupying the entire polar pitch causes the produced flux to close sideways through neighbouring magnets (see Figure 4.8).

![Magnetic flux density (B) distribution in the air-gap region for a magnet weight of 15mm (a), 25mm (b), 35mm (c), 45mm (d) and 54.75mm (e).](image)

This magnetic short circuit verified for larger magnets impacts the flux dispersion as less flux is availed by the stator coils. The optimal width is, from this point of view, the 25mm as this is the lowest
dispersion point (see Figure 4.9). The behaviour correlates with Cordovil conclusions although with dispersion values being underestimated by it.

**Magnet height vs. width variation**

![Figure 4.9: Flux dispersion evaluation for magnet height and width volume variation. Base design volume is pointed at red.](image)

To compare the two approaches regarding flux dispersion and useful flux in relation to magnet volume, a value extrapolation was made from each set of data in order to establish a common window for volume values. Through Figure 4.9 is possible to verify that increasing magnet volume through height than through width is a better choice when the objective is to increase useful flux (and EMF), as the first presents a lower dispersion curve.

![Figure 4.10: Useful flux evaluation for magnet height and width volume variation.](image)
Also plotted in Figure 4.10 is the useful flux evolution within volume variation. Here, increasing magnet height shows up to be a better choice to get a greater useful flux up to the break-even point of reference volume point (46.2cm³). Above that, increasing width produces a better flux per volume relation than increasing height despite being less "magnetic efficient" due to bigger dispersion.

**Detent force with magnet width variation**

Availing the 15mm to 54.75mm magnet width 3D FEM models, the respective translators were displaced from the central position by two pole pitch lengths (109.5mm) to their right (along the X axis) to complete 360 electrical degrees of useful flux. The affecting detent force was then measured to the translator components and plotted in Figure 4.11 by recurring to the electromagnetic force expression for axis X available in the 3D FEM software.

![Detent force graphs](image)

**Figure 4.11:** Detent force over 360 electrical degrees with different magnet widths. The reference design is marked with *.

The simulation results show that as the volume of the magnet is increased, both peak and RMS\(^1\) (root mean square) values also increase.

\(^1\)RMS value chosen to characterize the force profile as an arithmetic mean would be null over a complete translation.
mean square) force values as well as the predominance of a low frequency component also increases. The greater force amplitude is a natural consequence of having a larger quantity of magnetic flux present on the large air-gap region which, in turn, causes more abrupt differences in magnetic reluctance as the transition from the teeth to the slots occurs.

Once again, the impact of lower-frequency components is, in WEC systems, harder to absorb than the high frequency ripples as the inherent mechanical properties are usually of low frequency as well.
4.2 Magnet shape variation

In this group of studies, while keeping the dimensions and magnetization direction of base design magnets, two different magnet shapes were explored with two distinct objectives in mind. The first, the slotted geometry, was explored in order to reduce the magnetic flux dispersion in the air-gap by slotting the magnet such that the extremities, of width similar to stator teeth, would effectively guide the flux to teeth reducing dispersion.

The second designed geometry, a hexagonal shaped magnet, was explored, on the other hand, to reduce the detent forces identified in previous section by smoothing/cutting the magnet edges to reduce the abrupt variation of magnetic reluctance as the magnets are entering or leaving the stator teeth pairing.

4.2.1 Slotted Magnet Geometry

The short width of the stator teeth (6mm) has proven to be, as in the base design analysis, one of the major reasons for the high dispersion of magnetic flux in the air-gap region. This problem becomes even more predominant as the distance between adjacent teeth (the stator slots) is bigger than the teeth width itself (12mm), leaving a considerable portion of the magnet surface without any ferromagnetic material coverage as the translator moves linearly.

![Figure 4.12: Top and perspective views of 3mm and 6mm slotted magnet models. The 3mm slot variation is on the top and left and 6mm on the bottom and right. Arrows represent magnetization direction.](image)

To understand whether it would be possible to route the magnetic flux produced by the magnets more effectively to the stator teeth, two translators comprising 20 surface-mounted magnets with its top and bottom surfaces slotted by 3 and 6mm (trimmed from the original 25x24x77mm magnets), were designed. With this geometry, the magnet extremities now become aligned with pairs of stator teeth allowing. The effects, evaluated recurring to two steady-state studies with the 6mm air-gap length maintained from the base design and the translator fixed in the center position were then registered on the table 4.4 and plotted in Figure 4.13.
Table 4.4: Slotted magnet topology performance data.

<table>
<thead>
<tr>
<th>Slot height (mm)</th>
<th>M. Volume (cm$^3$)</th>
<th>$\Phi_u$ (mWb)</th>
<th>$\Phi_m$ (mWb)</th>
<th>$Disp_\Phi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0* (slotless)</td>
<td>46.2</td>
<td>1.80</td>
<td>1.25</td>
<td>29.2</td>
</tr>
<tr>
<td>3</td>
<td>40.7</td>
<td>1.60</td>
<td>1.07</td>
<td>33.3</td>
</tr>
<tr>
<td>6</td>
<td>35.1</td>
<td>1.42</td>
<td>0.91</td>
<td>36.0</td>
</tr>
</tbody>
</table>

Since the slotted magnets have now less volume than the original slot-less magnet, the produced magnetic flux of 1.60mWb and 1.42mWb is, as expected, also lower. The magnetic dispersion, on the other hand, calculated through the relation of the useful flux over the produced flux (equation 3.3 and 3.4), is independent to magnet volume. Within the results of flux dispersion, the translator with 6mm slotted magnets causes, contrary to the intended effect, 6.8% larger dispersion than the base magnet.

Figure 4.13: Magnetic flux density distribution results from base magnet geometry (a), 3mm slotted geometry (b) and 6mm slotted geometry (c).

Analyzing Figure 4.13 visually confirms the larger dispersion verified in the 6mm slotted magnet. By sweeping the sub-figures (b) and (c), it is possible identify the presence of magnetic flux between magnets (highlighted by the presence of bigger arrow lines), not so present in the base design. Also in the 6mm magnet sub-figure, the slotting of the magnet’s top and bottom surfaces induce a large flux density at the ends of the magnet (highlighted by the presence of red color). Facing these results it is therefore concluded that slotting a surface mounted magnet has no positive effect on reducing flux dispersion.
4.2.2 Hexagonal Magnet Geometry

The hexagonal magnet shape was designed with the intention of reducing the cogging and end-effect forces experienced by the generator. These electromagnetic forces are essentially magnetic reluctance forces that actuate in the translator magnets whenever it leaves a position of low reluctance. When the translator is left freely in an high reluctance position, i.e., with the 8 pole magnets misaligned with stator teeth, the resistive cogging forces will enforce it to move into a lower reluctance position. This effect becomes problematic during regular operation as it ends up introducing multi-frequency ripples that, depending on the inertial of the machine, may or may not be cancelled.

Figure 4.14: CAD design views of different hexagonal magnet geometries. On the left, from left to right and top to bottom, magnets with 2, 4, 6, 8 and 10mm edge cuts (a). On the right perspective view of 6mm and 10mm cuts (b) and (c).

The shape modification from the base squared magnet design into the hexagonal-type geometry was done with successive cuts on the magnet edges as demonstrated in Figure 4.14 with the aim of evaluating the respective effects on the detent force component. A total of five translator models were built with the projected hexagonal shaped magnets with edge cuts of 2, 4, 6, 8 and 10mm, measured from the lateral faces to the center. The respective translator were then displaced by 109.5mm (or 360 electrical degrees) in five respective FEM studies.

Since the study of these forces could not be disaggregated from the study of magnetic field behaviour, the dispersion was firstly measured as a function of the volume and shape of the magnet and the results gathered in the table 4.5.
While analyzing the magnetic flux data retrieved from the 3D FEM studies it possible to verify that the magnetic flux dispersion in the air-gap region is increased in consequence of smoothing the magnet edges. The dispersion is more prominent as a larger bit of the magnet is cut off, increasing linearly into a 12% difference between the base square shaped magnet and the 10mm edge-cut magnet. In this, the almost diamond shape it forms, causes the flux produced by it to be directed diagonally for both the stator teeth and adjacent magnets (see Figure 4.15), increasing the overall reluctance of the flux path thus also increasing dispersion.

![Figure 4.15](https://via.placeholder.com/150)

**Figure 4.15:** Magnetic flux density distribution with 2mm hexagonal geometry (a), 4mm hexagonal geometry (b) and 6mm hexagonal geometry (c) and 10mm hexagonal geometry (d).

The study of electromagnetic forces has proven to be quite mesh sensitive. A finer mesh was necessary (shown in Figure 4.16) in order to capture in detail the small variations along the stator displacement when comparing with the more coarser mesh used to compute the magnetic field density distributions and flux quantities. By using a mesh of lower density, the detent force profile would present higher than reality peaks and leave out the higher frequency ripples verified experimentally.
Given this, the detent force evolution along was measured for each translator variation and compared with the base design performance, analyzed in the chapter 3. The results were plotted in Figure 4.17 and table 4.6.

![Figure 4.17: Detent force over a translator displacement of 360 electrical degrees for different magnets.](image)

<table>
<thead>
<tr>
<th>Edge cut (mm)</th>
<th>Force_{X\text{Peak}} (N)</th>
<th>Force_{X\text{RMS}} (N)</th>
<th>Edge cut (mm)</th>
<th>Force_{X\text{Peak}} (N)</th>
<th>Force_{X\text{RMS}} (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° (cutless)</td>
<td>202</td>
<td>107.7</td>
<td>6</td>
<td>316</td>
<td>182.4</td>
</tr>
<tr>
<td>2</td>
<td>286</td>
<td>133.5</td>
<td>10</td>
<td>487</td>
<td>279.6</td>
</tr>
<tr>
<td>4</td>
<td>293</td>
<td>130.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The obtained results first show that cutting the magnet edges does increase the detent force amplitude, contrary to what is desired. Comparing the base magnet force profile with the 10mm hexagonal
magnet, there is a 258% increase verified in the RMS value. To compare both cases frequency wise, a Fast Fourier Transform (FFT) was applied with a displacement velocity of 2 pole pitch lengths per second ($v_t = 109.5 mm/s$) or an electrical frequency of $f_e = 1 Hz$. The results were plotted in Figure 4.18.

![Graph showing detent force FFT for base geometry and 10mm hexagonal magnet geometry translator.](image)

Figure 4.18: Detent force FFT for base geometry (top) translator and 10mm hexagonal magnet geometry translator (bottom).

For the base magnet geometry, the FFT revealed the predominant frequency to be around 1Hz with a force value of 120N followed by a less expressive 6Hz component with 70N.

While frequency domain of base magnet geometry is concentrated in low frequency components, cutting the magnet edges by 10mm causes the detent force frequency profile to shift into a higher frequency plane. Here, most of the frequency distribution is retained in 6Hz with an absolute value of 350N, followed by the 12Hz component with 150N. To understand the mechanical reasons of this frequency shift, the magnetic density distribution was also measured in the air-gap region for the base magnet design, an intermediate 2mm hexagonal (for comparison purposes) and the 10mm hexagonal magnet.
Figure 4.19: Magnetic flux density distribution at the translator for base magnet (top), 2mm (middle) and 10mm (bottom) hexagonal magnet shapes along the generator length (438mm).

Through the set of translator and air-gap flux density distributions on Figure 4.19 is possible to verify
that as the volume of the magnet cut increases, the pairs of spikes previously seen at translator and air-gap region for base design (highlighted by the red boxes) become less pronounced with the 2mm hexagonal magnet translator and completely reduced to a single spike in the 10mm magnet. With this type of geometry, the magnet-teeth coupling along the generator takes a more sinusoidal form that ends up not only amplifying the detent force peak values but also transferring the force profile into higher frequencies with little to no ripples present.

If the generator mechanical constants so permit, these high frequency components are more likely to be cancelled in contrast to the low frequency force components of the base design even with its higher peak values, being the translator with hexagonal magnets more advantageous than the base. The trade-off to be made here is as the bigger magnet edges cuts are, the greater the magnetic flux dispersion will be.

Moreover, if the dual stators present in this generator had teeth structures of greater width (or smaller slots) and a smaller air-gap length, the hexagonal magnet shape would present an even bigger benefit by reducing the detent force peaks within the former.
4.3 Magnetization Direction and Arrangement Variation

In this group of studies, different magnetizations and magnet arrangement topologies are analyzed regarding useful flux and EMF evolution, flux dispersion and detent force with the objective of comparing the effects of these electromagnetic quantities and improve, if possible, the performance of base design.

As both slotted and hexagonal magnet geometries haven’t been found to greatly improve the flux dispersion and detent force effects in the previous study group, the magnets used in the following translators maintained the original squared/rectangular geometry.

Based on literature and state-of-the-art review three magnetization and magnet arrangement topologies have been chosen in complement to the base surface-mounted magnet translator (see Figure 4.20):

- Axial magnetization;
- Axial magnetization with iron spacers between magnets;
- Quasi-Halbach magnetization.

![Figure 4.20](image)

Each magnetization type will be studied and analyzed independently with their respective results being ultimately compared. Both axial with and without iron spacers are studied within a variation of its magnet width while quasi-Halbach configuration magnets, on the other hand, had its width fixed such that there is an upward or downward magnetized magnet per pole pitch to maintain the same useful flux frequency.
4.3.1 Surface Mounted Magnetization

In order to establish the base design performance baseline (in the quantities here studied) for further comparison with axial and quasi-halbach magnetizations, useful flux was measured for the same magnet width variation of section 4.1.2 within the same translator displacement of 360 electrical degrees. From it, the flux linkage per phase $\lambda_u$ was calculated through:

$$
\lambda_u = (\phi_{u1} + \phi_{u2}) \cdot N \cdot P_p = (\phi_{u1} + \phi_{u2}) \cdot 100 \cdot 8
$$

(4.1)

where $\phi_{u1}$ and $\phi_{u2}$ represent the magnetic useful fluxes measured in stator 1 and 2, respectively, $N$, the number of turns per coil per stator and $P_p$ the number of poles. The evolutions for each magnet width was then plotted in Figure 4.21.

![Figure 4.21: Flux linkage per phase evolution within a surface-mounted translator displacement of 360 electrical degrees (2 polar steps).](image)

The flux linkage evolution along the translator displacement produces, as expected, an almost sinusoidal shaped wave form. As seen in the magnet width variation study (4.1.2), the translator with the 54.75mm large magnets, which fully occupying the pole pitch length, is able to produce the most flux linkage per phase ($\lambda_u = 3.02$Wb) although with the expense of also being the least magnetic efficient option with more than 50% of the produced flux dispersed in the air-gap region.

While comparing the different translator flux linkage evolutions, there is an apparent shift of the flux direction reversion point to the left around the 180 degree mark as the magnet volume increases. To quantify this flux linkage’s distortion, the total harmonic distortion (THD), $THD\phi_u$, was calculated and plotted in Figure 4.22.
Despite the deformations observed in Figure 4.21, the THD results show that all magnet formats produce a low harmonic distorted flux linkage with values between -40dBc to -30dBc, corresponding to a distortion factor between 1% to 3% in relation to the real-valued sinusoidal.

As the magnet volume is increased through width variation, the respective useful flux or flux linkage harmonic distortion becomes more centred on the fundamental frequency, i.e., the same frequency of translator movement. With the remaining harmonic having little expressiveness. With this, the 35mm wide magnet translator ends up offering the least harmonic distortion and the 15mm the highest. The overall performance\(^2\) is summarized in Table 4.7.

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>M. Volume (cm(^3))</th>
<th>(\lambda_{\text{umax}}) (Wb)</th>
<th>Disp(_{\Phi}%) (%)</th>
<th>THD(_{\Phi_u}) (dBc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>27.7</td>
<td>1.25</td>
<td>32.8</td>
<td>-30.4</td>
</tr>
<tr>
<td>25(^*)</td>
<td>46.2</td>
<td>2.05</td>
<td>29.2</td>
<td>-37.4</td>
</tr>
<tr>
<td>35</td>
<td>64.7</td>
<td>2.64</td>
<td>32.7</td>
<td>-39.7</td>
</tr>
<tr>
<td>45</td>
<td>83.2</td>
<td>2.96</td>
<td>40.5</td>
<td>-37.7</td>
</tr>
<tr>
<td>54.75</td>
<td>101.2</td>
<td>3.02</td>
<td>51.5</td>
<td>-37.6</td>
</tr>
</tbody>
</table>

### 4.3.2 Axial Magnetization

In an axial magnetization translator, the magnets are assembled horizontally with a magnetization along the movement axis (X axis). The opposing magnetization of adjacent magnets, creates what is called the flux concentration region or flux concentrators [47] between magnets as this arrangement causes

\(^2\)Note that the detent force profile of each magnet width translator combination was previously analyzed in section 4.1 of this same chapter.
the magnetic flux of both to collide and to be directed perpendicular to its magnetization to the stator teeth. The result longitudinal magnetic flux found on the stators is at all similar to the one produced by surface mounted magnets’ but with distinct flux paths (see Figure 4.23).

Figure 4.23: Main magnetic flux path with an axial magnetization translator.

Along this group of parametric 3D FEM studies, the magnet width was varied between 25mm to 54.75mm while the air-gap length and magnet height were fixed in 6mm and 24mm, respectively, similarly to the studies of section 4.1. The translator arrangement was also maintained such that the configuration of one magnet per pole remained. The same was displaced to the right from a central position by 109.5mm (360 electrical degrees) in order to obtain a complete wave period of useful flux. From it, flux linkage evolution, THD and magnetic flux dispersion were measured. The results were then plotted in Figure 4.24 and aggregated in the table 4.8.

Figure 4.24: Magnetic flux linkage per phase evolutions within several axially magnetized translators.
Table 4.8: Axial magnetization magnet width variation results.

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>M. Volume (cm$^3$)</th>
<th>$\lambda_{u,max}$ (Wb)</th>
<th>Disp$\varphi$ (%)</th>
<th>THD$\varphi$ (dBc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25*</td>
<td>46.2</td>
<td>1.60</td>
<td>36.2</td>
<td>-36.0</td>
</tr>
<tr>
<td>35</td>
<td>64.7</td>
<td>2.06</td>
<td>27.5</td>
<td>-38.3</td>
</tr>
<tr>
<td>45</td>
<td>83.2</td>
<td>2.31</td>
<td>23.3</td>
<td>-41.9</td>
</tr>
<tr>
<td>54.75</td>
<td>101.2</td>
<td>2.38</td>
<td>22.2</td>
<td>-36.4</td>
</tr>
</tbody>
</table>

The obtained results evidence not only the expected crescent of flux linkage per phase as the magnet width is increased but also a 90 degree phase difference when compared to the same evolution of surface mounted magnets (Figure 4.21). Here, the flux is null when the translator lays in the initial position and reaches its maximum when in 90 or 270 degrees. This difference is easily explained by comparing both magnetic flux paths where in the first the flux is seen to use the center tooth to reach the stator yoke and teeth to its left in the surface mounted magnet topology.

Regarding magnetic flux dispersion, increasing the magnet width caused the dispersion to decrease with widths over 35mm presenting dispersion values less than 30%. This behaviour is ultimately a consequence of having the magnets faced with opposing polarities where the great majority of magnetic flux is efficiently directed to the upper and lower stators, as demonstrated in Figure 4.25.

![Figure 4.25: Magnetic flux density distribution with 25mm (a), 35mm(b), 45mm (c) and 54.75mm (d) wide axial magnets.](image)

It is while analyzing the same magnetic flux density distribution that this translator topology begins
to present its drawbacks. For magnets larger than 45mm, the magnetic flux produced by the adjacent magnets impose flux density values superior to 2T on some stator teeth, leading the iron to saturate. This behaviour stands out for these wider magnets as the flux tends to be conducted into a single tooth. Despite presenting low a flux dispersion for such high air-gap lengths, this topology may not be suitable for stators with such low teeth width geometry.

Figure 4.26: Detent force over 360 electrical degrees for different magnet widths.

Table 4.9: Detent force performance for the different axial magnetized translators.

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>$F_{\text{Force}_{\text{XPeak}}}$ (N)</th>
<th>$F_{\text{Force}_{\text{XRMS}}}$ (N)</th>
<th>M. Width (mm)</th>
<th>$F_{\text{Force}_{\text{XPeak}}}$ (N)</th>
<th>$F_{\text{Force}_{\text{XRMS}}}$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25*</td>
<td>178</td>
<td>71.1</td>
<td>45</td>
<td>379</td>
<td>182.4</td>
</tr>
<tr>
<td>35</td>
<td>375</td>
<td>195.0</td>
<td>54.75</td>
<td>566</td>
<td>331.5</td>
</tr>
</tbody>
</table>

The obtained force profiles reveal that increasing the axial magnet width generally increases the force amplitude along the translator displacement. Transitioning from a 35mm to 45mm magnet reveals however a lower RMS value of the former (182.4N) and around the same peak values (379N). The phenomenon is due to the 45mm magnets effectively guiding the produced flux into a single tooth while the 35mm ones still use up to three tooth (see sub-figures 4.25 (b) and (c)), causing a more sinusoidal force curve. The larger 54.75mm magnet ended up producing the highest force peaks of 566N.

Axial magnetization with iron spacers

The introduction of iron spacers between magnets was intended to improve dispersion by reducing the global magnetic reluctance. In this, the flux path is, between magnets, guided to stator teeth through iron instead of through the air. Since iron is a classic ferromagnetic material, it is expected a detent force increase.
This set of studies followed the same displacement approach of the axial magnetization topology seen above, having the flux linkage, THD, flux density and detent force evolutions evaluated to three different translators with magnet widths of 25mm, 35mm and 45mm (see Figures 4.27 and 4.28).

![Figure 4.27: Magnetic flux linkage per phase for several axial magnet translators with iron inserts.](image)

![Figure 4.28: Magnetic flux density distribution with 25mm (a), 35mm(b) and 45mm (c) wide axial magnets with iron spacers.](image)
Table 4.10: Axial magnetization with iron spacers variation results.

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>M. Volume (cm³)</th>
<th>λ_u (Wb)</th>
<th>DispΦ (%)</th>
<th>THDφ_u (dBc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25*</td>
<td>46.2</td>
<td>2.11</td>
<td>28.4</td>
<td>-37.2</td>
</tr>
<tr>
<td>35</td>
<td>64.7</td>
<td>2.35</td>
<td>23.8</td>
<td>-42.8</td>
</tr>
<tr>
<td>45</td>
<td>83.2</td>
<td>2.45</td>
<td>22.3</td>
<td>-33.7</td>
</tr>
</tbody>
</table>

While analyzing the results, the introduction of iron spacers revealed a positive impact on flux linkage and dispersion, presenting better performance for the same magnet volumes than without the spacers. For the same 25mm wide magnet, the dispersion was reduced by 7.8% whereas the flux linkage was 24% higher.

If the magnetic flux density values were found quite high in the axial translators, the same behaviour is here even more prominent with all width options surpassing flux density values in the stator teeth (see red coloured regions in Figure 4.28) thus requiring even greater care in the dimensioning of the magnets. Total harmonic distortion of flux linkage remained, once again, negligible so will not be took under consideration.

![Figure 4.29: Detent force over 360 electrical degrees for different magnet widths.](image)

Table 4.11: Detent force performance for the different axial magnetized translators with iron spacers between them.

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>ForceX_peak (N)</th>
<th>ForceX_RMS (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25*</td>
<td>162</td>
<td>80.8</td>
</tr>
<tr>
<td>35</td>
<td>349</td>
<td>166.7</td>
</tr>
<tr>
<td>45</td>
<td>507</td>
<td>236.5</td>
</tr>
</tbody>
</table>

Lastly, the detent force component revealed approximately the same profile with larger peak values
but with an induced high-frequency ripple not present without the iron spacers. This ripple is mainly a consequence of the greater amount of magnetic flux in the air-gap region which makes the presence of fine teeth more evident when the translator is entering or exiting positions of minor or greater magnetic reluctance. Other exception case is the 25mm magnet where the frequency and peak force was clearly reduced in relation to the former study.

The challenge of choosing an axial translator design for a permanent magnet linear generator lies ultimately in the robustness of the magnet fixation approach in the translator since maintaining the magnets fixed whose opposing forces tend to be considerably high can be rather difficult.

4.3.3 Quasi-Halbach Magnetization

A quasi-halbach (QH) magnet arrangement involves a combination of surface-mounted and axial magnetized magnets that yield an approximately sinusoidal magnetic field structure [47]. This magnet arrangement is commonly found in slotless tubular actuators with rectangular shaped magnets being the most common despite some approaches choosing to employ trapezoidal shaped permanent magnets as seen in [48].

Since each set of quasi-halbach magnets has its weak and strong field side, the translator designed for this study comprise two individual sets of 27.38x12x77mm(WxHxD) magnets facing top and bottom stators in order to equally magnetize both (see Figure 4.20 (d)). A non-ferromagnetic separator was included between the sets of QH magnets to avoid the magnetic flux path crossing, evidenced by Figure 4.30.

![Figure 4.30: Magnetic Flux Path with axial magnetization translator.](image)

With this multiple magnetization direction arrangement, the main flux path is being constantly directed by the downward magnetized magnets into the left and right magnets and finally to the upward ones. This cyclic directioning is here studied with the intention of understanding its effects on reducing the
dispersion as well as the dentent forces while maximizing the useful flux. From it, the same quantities were measured in a translator displaced of two pole pitch lengths and the results flux linkage and detent force evolutions plotted in Figures 4.31 and 4.33 and summed in table 4.12.

Figure 4.31: Magnetic flux linkage over a Quasi-halbach translator displacement of 360 degrees (2 polar pitch lengths).

The flux linkage per phase $\lambda_u$ produced by this arrangement reaches values of 2.44Wb and is in phase with the one produced by surface-mounted magnets whereas the flux dispersion $^3$ reaches 23%. With the flux density mapping of Figure 4.32, the flux path is also validated, confirming the sinusoidal directioning highlighted in the picture by the black arrow lines. Another positive aspect of this topology is that the iron teeth do not saturate operating in lower flux density values (between 1.5 and 2T).

Table 4.12: Quasi-halbach magnetization results

<table>
<thead>
<tr>
<th>M. Width (mm)</th>
<th>M. Volume (cm$^3$)</th>
<th>$\lambda_u$ (Wb)</th>
<th>Disp$\Phi$ (%)</th>
<th>THD$\phi_u$ (dBc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>54.75 (QH)</td>
<td>101.2</td>
<td>2.44</td>
<td>23.2</td>
<td>-37.3</td>
</tr>
</tbody>
</table>

$^3$measured by the same relation of produced flux and useful flux
Regarding detent force, the QH translator demonstrated an odd symmetrical profile whose main frequency is twelve times the electrical frequency with peaks of 356N and a RMS of 191N. This high frequency, despite its high peak values, has higher probability of being mechanical filtered than the remaining profiles of other translator topologies with predominant frequencies closer to the fundamental.

4.3.4 Results Comparison

In order to compare the four magnetization translator topologies investigated in this section, both flux linkage and flux dispersion were normalized to the magnet volume and the results extrapolated to a common value window in Figures 4.35 and 4.34, respectively.

Overlapping the flux dispersion reveals the better performance of axial magnetization with iron inserts for the great majority of magnet volumes here studied, only being less efficient than surface-mounted magnet topology for volumes less than 38.7cm$^3$. Since in quasi-halbach topology only one magnet width was studied, the respective dispersion was pointed out without extrapolation (marked in blue).
Regarding flux linkage, surface mounted magnets demonstrate higher quantities of flux (and consequently EMF) per cm$^3$ for volumes superior to 46cm$^3$, equivalent to a 25mm width magnet$^4$ (Figure 4.34). This phenomenon is somewhat expected since this is the only studied topology where more teeth are occupied as magnet volume is increased by width variation. This positive aspect doesn’t go, however, without a trade-off in flux dispersion that for such volumes can reach the 50% mark. If the intended flux linkage per phase is to be around 2Wb, the axial with iron demonstrates to be a superior choice.

For the magnetization direction effects on detent force, the 25mm wide magnet translator was chosen over surface-mounted, axial with and without iron topologies with the quasi-halbach arrangement being normalized to the same volume for comparison purposes. From it, detent force evolutions were plotted assuming the same 24mm height and 77mm depth.

---

$^4$assuming the same 24mm height and 77mm depth
along a translator velocity $v_t$ of 109.5 mm/s (or 1 Hz) with the frequency characteristics obtained through FFT.

Figure 4.36: Detent force evolution for different magnetization directions.

Figure 4.37: Detent force comparison for different magnetization directions.
Comparing the topologies in relation to force peak values reveals values around 200N for the surface mounted magnets with the axial with iron inserts topology having the least expressive force pulses. All studied topologies present high frequency ripples superimposed to the main force curve with the axial w/ iron presenting, once again, the lower ripple values. This frequency profile addressing is confirmed while analyzing the FFT results of Figure 4.37 where is possible to see the influence off both low and high frequencies. The ripples reflected by the peaks around 12Hz are absent in the axial w/ iron sub-figure indicating the great majority of its detent force is concentrated in the lower frequency spectrum.

If a translator topology is to be chosen solely for its cogging and end effect force profile the axial magnetization with iron inserts between magnets shows up to be the better choice. This remains true if one conjugates the global results of quantities analyzed in this comparison section with the same offering the lowest magnetic dispersion and highest flux linkage per phase up to 25mm width.
Chapter 5

Conclusions

In this work, a permanent magnet linear generator of LFPM type was studied in its magnetic dimensions recurring to finite element analysis. The same approach was compared in its two and three-dimensional variant, having the 3D FEA being chosen to carry, conceive and validate the different translator topologies due to its extra capacity to study the electromagnetic forces.

Next to it, the base design was analyzed having the reference performance been established with the physical and magnetic properties influencing both the useful flux and detent force. In this point, the stators geometry revealed to be one of the main limiting factors of better performances with the small teeth width profile causing high cogging forces with high frequency force ripples, spoiling the natural linear movement of the translator.

The FEM model built for the base design analysis was validated experimentally within the choice of the materials and BH curves. A detailed comparison of the flux density distribution in the air-gap between the FE model and the values obtained through a gaussmeter was intended. The experiment confirmed both flux density profile and B field values, with the FEM model characteristics being then propagated to the following studies.

The work proceeded with a series of translators being designed to parametrically study the effects of air-gap length variation, magnet volume variation, different magnet shaped translators and finalizing with different magnetization direction translators in order to find the optimal combination.

Increasing the air-gap length has shown to linearly increase the useful flux on both stators while reducing the magnetic flux dispersion to values of 12.8% for an ideal air-gap length of 2mm. Such air-gap length also shown to impose an attraction force between the translator and stator pieces of 4810N, requiring a robust fixation system as well as a completely rigid translator.

Varying the translator’s magnet volume through height was found to be a better choice up to 46.2cm$^3$, with this option offering a lower magnetic dispersion as well as a higher useful flux density. If a larger
magnet is necessary, the wider magnets are able to produce greater useful flux but at the expense of causing higher dispersion.

In the following group of studies, slotted and hexagonal magnet shapes were sought in order to evaluate the effects of both on reducing the magnetic dispersion and the detent force component, respectively. Slotted magnets shown to have no effect on reduction dispersion, even increasing it in some cases. Hexagonal magnets, on the other hand, have proven to shift the low force frequencies to a more likely to be mechanical filtered upper frequency region. The effects of a translator with 10mm hexagonal magnets also revealed higher force peak values for the 6Hz component when moving the translator at a velocity of 109.5mm/s or 1Hz.

In the last group of studies, different magnetization directions and arrangements were analyzed through several surface-mounted, axial with and without iron spacers and quasi-halbach translators. From it, the axial with iron spacers translator proven to be the best choice for intended flux linkages per phase up to 2.25Wb, offering not only the optimum efficient point as the lowest dispersion values per magnet volume and the least cogging forces. If dispersion and forces are dis-considered, the classic surface-mounted topology of base design remains the one that produces greater quantities of EMF per pole pitch.

Ultimately, the longitudinal flux permanent magnet linear generators for wave energy conversion still display a series of problems that could not be effectively eliminated within the set of studies here performed. Detent forces continue to play a large problematic role in stators with toothed geometries and the attraction forces in stator geometries that are not of tubular form. This later topology has been proving successful into distributing attraction forces radially, allowing for smaller air-gap lengths and consequently less magnetic dispersion and EMF at the coil terminals.

Moreover, corrosion problems and high maintenance and operation costs are likely to continue hindering the success of this kind of generators, being necessary to rethink the offshore and submerged positioning usually chosen for their placing.

To conclude, future work should concern a profound study of stator pieces’ geometry, that were shown here on of the main barriers into optimizing this generator. An optimization algorithm in combination with finite element analysis should also be considered as it would allow to study the machine and therefore optimize it as a whole, within the constraints imposed by its real offshore environment.
Bibliography


## Appendix A

### Scatter table

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Figure A.1: Portuguese coast power scatter table in function of $H_s$ and $T_s$. Adapted from [49].