Theoretical and Experimental Analysis of Operational Wave Energy Converters

ERIK LEJERSKOG
Abstract

This thesis studies wave energy converters developed at Uppsala University. The wave energy converters are of point absorbing type with direct driven linear generators. The aim has been to study generator design with closed stator slots as well as offshore experimental studies. By closing the stator slots, the harmonic content in the magnetic flux density is reduced and as a result the cogging forces in the generator are reduced as well. By reducing these forces, the noise and vibrations from the generator can be lowered. The studies have shown a significant reduction in the cogging forces in the generator. Moreover, by closing the slots, the magnetic flux finds a short-cut through the closed slots and will lower the magnetic flux linking the windings.

The experimental studies have focused on the motion of the translator. The weight of the translator has a significant impact on the power absorption, especially in the downward motion. Two different experiments have been studied with two different translator weights. The results show that with a higher translator weight the power absorption is more evenly produced between the upward and downward motion as was expected from the simulation models. Furthermore, studies on the influence of the changing active area have been conducted which show some benefits with a changing active area during the downward motion. The experimental results also indicate snatch-loads for the wave energy converter with a lower translator weight.

Within this thesis results from a comparative study between two WECs with almost identical properties have been presented. The generators electrical properties and the buoy volumes are the same, but with different buoy heights and diameters. Moreover, experimental studies including the conversion from AC to DC have been achieved.

The work in this thesis is part of a larger wave power project at Uppsala University. The project studies the whole process from the energy absorption from the waves to the connection to the electrical grid. The project has a test-site at the west coast of Sweden near the town of Lysekil, where wave energy systems have been studied since 2004.

Keywords: ocean wave energy, WEC, permanent magnet, linear generator, closed stator slots, offshore experiments

Erik Lejerskog, Department of Engineering Sciences, Electricity, Box 534, Uppsala University, SE-75121 Uppsala, Sweden.

© Erik Lejerskog 2016

ISSN 1651-6214
urn:nbn:se:uu:diva-274635 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-274635)
Dedicated to Cecilia, Ebba and Julia
List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


Other contributions of the author, not included in the thesis.


Reprints were made with permission from the publishers.
1 Introduction .................................................................................................................. 13
  1.1 Wave energy technology ......................................................................................... 14
  1.2 The Uppsala University wave energy concept ..................................................... 15
  1.3 The Lysekil research site ......................................................................................... 17
  1.4 The Hammarudda test site ...................................................................................... 19
  1.5 Aim of the thesis ..................................................................................................... 20
  1.6 Previous work done on wave energy at Uppsala University ................................. 20

2 Theory .......................................................................................................................... 23
  2.1 Ocean waves ............................................................................................................ 23
  2.2 Field model ............................................................................................................. 24
  2.3 Linear generator .................................................................................................... 24
    2.3.1 Magnetic material .......................................................................................... 25
    2.3.2 Losses ........................................................................................................... 26
    2.3.3 Electromotive force ....................................................................................... 27
    2.3.4 Armature reaction ......................................................................................... 28
    2.3.5 Inductance ..................................................................................................... 29
    2.3.6 Electric equivalent circuit ............................................................................... 29
    2.3.7 Reluctance network model ............................................................................ 30

3 Method .......................................................................................................................... 32
  3.1 FE-simulations ....................................................................................................... 32
  3.2 Closed stator slots ............................................................................................... 33
  3.3 Static model for power absorption limits ............................................................. 35
  3.4 Analytic model for the motion of the translator .................................................... 36
  3.5 Offshore experiment ............................................................................................. 37
    3.5.1 Experiments on the WESA generator ......................................................... 37
    3.5.2 Experiments on the L9 ............................................................................... 38
    3.5.3 Experiments on the L2 and the L3 ............................................................... 38
    3.5.4 Experiments on the L1 connected to a rectifier and a capacitor bank .......... 39
    3.5.5 Experimental error analysis ....................................................................... 40

4 Summary of results and discussion ........................................................................... 42
  4.1 Closed stator slots ............................................................................................... 42
  4.2 Study of the L9 ..................................................................................................... 44
  4.3 Study of the WESA generator .............................................................................. 47
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>Study of the L2 and the L3</td>
<td>50</td>
</tr>
<tr>
<td>4.5</td>
<td>L1 connected to a rectifier</td>
<td>52</td>
</tr>
<tr>
<td>5</td>
<td>Conclusions</td>
<td>54</td>
</tr>
<tr>
<td>6</td>
<td>Future Work</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>Summary of Papers</td>
<td>56</td>
</tr>
<tr>
<td>8</td>
<td>Svensk Sammanfattning</td>
<td>60</td>
</tr>
<tr>
<td>9</td>
<td>Acknowledgments</td>
<td>62</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>63</td>
</tr>
</tbody>
</table>
# Nomenclature and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>SI unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Tm</td>
<td>Magnetic vector potential</td>
</tr>
<tr>
<td>B</td>
<td>T</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>D</td>
<td>C/m²</td>
<td>Displacement field</td>
</tr>
<tr>
<td>E</td>
<td>V/m</td>
<td>Electric field</td>
</tr>
<tr>
<td>H</td>
<td>A/m</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>J</td>
<td>A/m²</td>
<td>Current density</td>
</tr>
<tr>
<td>M</td>
<td>A/m</td>
<td>Magnetization field</td>
</tr>
<tr>
<td>A</td>
<td>m²</td>
<td>Area</td>
</tr>
<tr>
<td>a</td>
<td>m/s²</td>
<td>Acceleration</td>
</tr>
<tr>
<td>Bₘₜ</td>
<td>T</td>
<td>Peak flux density</td>
</tr>
<tr>
<td>Bᵣ</td>
<td>T</td>
<td>Remanent magnetic flux density</td>
</tr>
<tr>
<td>E</td>
<td>V</td>
<td>Electromotive force effective value</td>
</tr>
<tr>
<td>e</td>
<td>V</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>Fₖ</td>
<td>N</td>
<td>Cogging force</td>
</tr>
<tr>
<td>Fₜb</td>
<td>N</td>
<td>Buoyancy force</td>
</tr>
<tr>
<td>Fₑₘ</td>
<td>N</td>
<td>Electromagnetic force</td>
</tr>
<tr>
<td>f</td>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>g</td>
<td>m/s²</td>
<td>Acceleration of gravity</td>
</tr>
<tr>
<td>Hₑₙ</td>
<td>A/m</td>
<td>Coercive field strength</td>
</tr>
<tr>
<td>Hₘ₀</td>
<td>m</td>
<td>Significant wave height</td>
</tr>
<tr>
<td>I</td>
<td>A</td>
<td>Current</td>
</tr>
<tr>
<td>Iₐ</td>
<td>A</td>
<td>Armature current</td>
</tr>
<tr>
<td>J</td>
<td>W/m</td>
<td>Energy transport</td>
</tr>
<tr>
<td>kₑₙ</td>
<td>J/s¹/²/(m³T³/²)</td>
<td>Material constant excess loss</td>
</tr>
<tr>
<td>kₑₑ</td>
<td>Sm⁴/kg</td>
<td>Material constant eddy current loss</td>
</tr>
<tr>
<td>kₑₕ</td>
<td>J/(m³T²)</td>
<td>Material constant hysteresis loss</td>
</tr>
<tr>
<td>kₑₖ</td>
<td>–</td>
<td>Winding factor</td>
</tr>
<tr>
<td>L</td>
<td>m</td>
<td>Wave length</td>
</tr>
<tr>
<td>Lₐₐ</td>
<td>H</td>
<td>Self inductance</td>
</tr>
<tr>
<td>Lₛₐₗ</td>
<td>H</td>
<td>Mutual inductance</td>
</tr>
<tr>
<td>lₛₐₗ</td>
<td>m</td>
<td>Stack length</td>
</tr>
<tr>
<td>Lₙ</td>
<td>H</td>
<td>Leakage inductance</td>
</tr>
<tr>
<td>Lₘₚ</td>
<td>H</td>
<td>Main inductance</td>
</tr>
<tr>
<td>Lₛₗ</td>
<td>H</td>
<td>Synchronous inductance</td>
</tr>
<tr>
<td>lₛₗ</td>
<td>m</td>
<td>Free stroke length</td>
</tr>
<tr>
<td>lₛₜ</td>
<td>m</td>
<td>Stator vertical length</td>
</tr>
<tr>
<td>mᵦ</td>
<td>kg</td>
<td>Buoy weight</td>
</tr>
<tr>
<td>mₙ</td>
<td>m²Hzⁿ</td>
<td>Spectral moment number, n</td>
</tr>
<tr>
<td>mᵣ</td>
<td>Kg</td>
<td>Translator weight</td>
</tr>
<tr>
<td>Symbol</td>
<td>SI unit</td>
<td>Quantity</td>
</tr>
<tr>
<td>--------</td>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>(N)</td>
<td>—</td>
<td>Number of coil turns</td>
</tr>
<tr>
<td>(P)</td>
<td>W</td>
<td>Active power</td>
</tr>
<tr>
<td>(P_{in})</td>
<td>W</td>
<td>Absorbed active power</td>
</tr>
<tr>
<td>(P_{out})</td>
<td>W</td>
<td>Power at load</td>
</tr>
<tr>
<td>(P_{iron})</td>
<td>W/m(^3)</td>
<td>Iron losses</td>
</tr>
<tr>
<td>(P_{cu})</td>
<td>W</td>
<td>Copper losses</td>
</tr>
<tr>
<td>(R)</td>
<td>(\Omega)</td>
<td>Resistance</td>
</tr>
<tr>
<td>(R_g)</td>
<td>(\Omega)</td>
<td>Winding resistance</td>
</tr>
<tr>
<td>(R_l)</td>
<td>(\Omega)</td>
<td>Load resistance</td>
</tr>
<tr>
<td>(S(f))</td>
<td>m(^2)Hz</td>
<td>Variance spectral density</td>
</tr>
<tr>
<td>(t)</td>
<td>s</td>
<td>Time</td>
</tr>
<tr>
<td>(T_e)</td>
<td>s</td>
<td>Energy period</td>
</tr>
<tr>
<td>(U)</td>
<td>A−turns</td>
<td>Magnetic potential difference</td>
</tr>
<tr>
<td>(V)</td>
<td>m(^3)</td>
<td>Volume</td>
</tr>
<tr>
<td>(V_e)</td>
<td>V</td>
<td>Electric potential</td>
</tr>
<tr>
<td>(v)</td>
<td>m/s</td>
<td>Speed</td>
</tr>
<tr>
<td>(W_{el})</td>
<td>J</td>
<td>Electric energy</td>
</tr>
<tr>
<td>(W_{loss})</td>
<td>J</td>
<td>Energy losses</td>
</tr>
<tr>
<td>(W_{mag})</td>
<td>J</td>
<td>Magnetic field energy</td>
</tr>
<tr>
<td>(W_{mec})</td>
<td>J</td>
<td>Mechanical energy</td>
</tr>
<tr>
<td>(w_p)</td>
<td>m</td>
<td>Pole pair width</td>
</tr>
<tr>
<td>(\delta)</td>
<td>rad</td>
<td>Load angle</td>
</tr>
<tr>
<td>(\phi)</td>
<td>Wb</td>
<td>Magnetic flux</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Wb−turns</td>
<td>Flux angle</td>
</tr>
<tr>
<td>(\mu_0)</td>
<td>Vs/Am</td>
<td>Permeability of vacuum</td>
</tr>
<tr>
<td>(\mu_r)</td>
<td>—</td>
<td>Relative permeability</td>
</tr>
<tr>
<td>(\rho)</td>
<td>kg/m(^3)</td>
<td>Density</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>A/Vm</td>
<td>Conductivity</td>
</tr>
<tr>
<td>(\omega)</td>
<td>rad/s</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>(\mathfrak{R})</td>
<td>1/H</td>
<td>Reluctance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>emf</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>L1–L10</td>
<td>Wave energy converters at Lysekil</td>
</tr>
<tr>
<td>LVMS</td>
<td>Low voltage marine substation</td>
</tr>
<tr>
<td>MVMS</td>
<td>Medium voltage marine substation</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Neodymium iron boron</td>
</tr>
<tr>
<td>PM</td>
<td>Permanent magnets</td>
</tr>
<tr>
<td>OWC</td>
<td>Oscillating water column</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave energy converter</td>
</tr>
</tbody>
</table>
1. Introduction

The total electricity production in 2012 was 22,752 TWh [1] and the consumption in the world increases rapidly. The IEA 2015 report [2] indicates a 70% increase in the electricity demand between 2013 and 2040. A large part of the increase will come from the non-OECD\(^1\) countries, which have a strong economic growth and a growing population. To manage such an increase in energy demand without increasing CO2-emissions, alternative sources of clean energy need to be investigated.

Finding a way to deliver clean energy to the world has been on the agenda for quite some time. However, a large part of the world’s total energy still comes from fossil fuels and will do so for the considerable future, as predicted in Fig. 1.1.

![Fig. 1.1. Primary inputs to electricity production between 1965 to 2035 in percentage. [1]](image)

One of the reasons for this is that in the renewable sector is hard to get a stable power flow, i.e. wind power only works when it is windy, solar power needs sunlight etc. The notable exception is hydropower. The problem could be solved to some extent by using different sources of renewable energy, e.g. when there is no wind the sun might shine. Another solution would be to use different storage devices where the energy from a windy or sunny day could be stored and used when needed.

Wave energy is a source of renewable energy that is relatively unexploited. Only in recent years have power plants begun to deliver electricity to shore [3, 4, 5, 6]. This is due to problems with keeping the devices operational at sea and on the shore. In 2012,\(^1\)

\(^1\)OECD stands for The Organization for Economic Cooperation and Development it includes 34 democracies with market economies.
the installed ocean power capacity was about 6 MW [7]. In Europe alone this number is estimated to rise to around 26 MW in 2018 [8]. The global wave energy potential is estimated to be 3.7 TW [9]. In Sweden, the wave energy potential is estimated to be 5–10 TWh annually [10]. Wave energy has one of the highest energy densities of all renewable energy sources [10]. In Sweden this is a factor of 10 higher than wind power and a factor of 100 higher than solar power. Including wave energy in the renewable energy sector, would mean a large increase in capacity.

1.1 Wave energy technology

Wave energy has been tested on a larger scale since the 1970s and the first patent on converting wave energy into usable energy can be found as early as 1799 [10]. According to [11] there were 147 different WECs in various stages of development in 2013 and according to [8] in 2015 this number had increased to 170.

Harvesting the energy of ocean waves poses many challenges. The device needs to be reliable and able to withstand extreme forces during storms at the same time as it needs to be economically viable. Moreover, the converters need to transfer the energy to where it is usable which is usually quite far from where the wave energy is extracted. Most devices are converting the wave energy into electricity and thus transfer the energy to the electric grid. Many different types of wave energy devices have been tested and a good review can be found in [12, 13]. The devices are usually divided into three different groups: oscillating water columns (OWCs), overtopping devices and oscillating bodies. Fig. 1.2 illustrates the working principle for the different concepts.
Oscillating water columns

OWCs can be divided into two subsections: (a) fixed structures which are usually placed on the shore or near the shore and (b) floating structures placed offshore. The main idea behind the energy conversion is to press air through an air turbine using ocean waves. When an ocean wave is moving towards the device, the water level inside the chamber rises and the air is pressed out through an air turbine. When the water is retracting, air comes back into the chamber through the air turbine see Fig. 1.2a. At the largest island of Azores, Pico, an OWC called the Pico Power Plant has been tested for a long time².

Overtopping devices

Overtopping devices can be compared to a hydropower unit that is close to the shoreline or is floating offshore. Overtopping devices use the principle of a water reservoir which can be floating or fixed. The ocean waves spill over into the reservoir when hitting the structure. The reservoir is filled to a greater level than the sea and the water is then flushed back into the sea through hydro turbines driving a generator which converts the potential energy into electricity. Fig. 1.2b presents a floating overtopping device. An off-shore overtopping device called the Wave Dragon has been tested and developed in Denmark³.

Oscillating bodies

Oscillating bodies can be divided into three subsections: (a) fixed structure on the shoreline, (b) floating structures and (c) submerged structures or a combination of these. The main idea behind these concepts is that they use the wave motion to convert energy. A further classification of the oscillating body devices and how they extract energy from the waves is made by defining the motion. The bodies can move in surge, sway, heave, roll, pitch and yaw or a combination of these. Three of these motions are shown in Fig. 1.2c. There are different approaches to converting the energy. This can be done by electric generators, hydraulic motors, piston pumps, turbines etc. An oscillating body system developed by Carnegie Wave Energy, using hydraulics, has recently been connected to the grid⁴.

1.2 The Uppsala University wave energy concept

From the beginning, the wave energy research at Uppsala University has worked with a system approach, studying the whole process from the energy absorbed in the ocean waves to the connection and transfer of the electric energy to the grid. [14, 15]

The wave energy device used to convert the wave energy to electric energy is an oscillating body device. The WEC consists of a linear generator placed at the seabed, and a buoy on the ocean surface, see Fig. 1.3.

²http://www.pico-owc.net/ (accessed 2015-12-09)
³http://www.wavedragon.net/ (accessed 2015-12-09)
⁴http://carnegiewave.com/ (accessed 2015-12-09)
Figure 1.3. Illustration of the WEC developed at Uppsala University.

When the buoy moves with the waves, the motion is transferred through a line to the linear generator. The linear generator consists of a moving part, the translator, with permanent magnets mounted on it, and a static part, the stator. The buoy’s motion makes the translator move in heave and the mechanical and magnetic energy from the permanent magnets are converted into electrical energy in the stator windings.

Using a linear generator as power take-off has become one of the most commonly used strategies in point absorbing WECs [16]. Other wave power research groups using linear generators as power take-off can be found in [17, 18, 19, 20, 21, 22].

Because of the nature of the moving waves and the linear motion of the generator, the voltage and current out of the generator vary both in frequency and amplitude. Moreover, the phases in the generator switch, depending on whether the translator is moving upwards or downwards. This makes it impossible to connect a WEC to the grid directly. Thus, the voltage out from each WEC is rectified and then connected together on a common DC-bus. To be able to connect the system to the grid, the DC is converted to AC using an inverter. To reduce the transmission losses to shore, the voltage is transformed to a higher voltage level. Furthermore, the power output from the WECs can be changed through controlling the speed of the translator by
connecting it to different load controls. The conversion system from the rectifier to the transformer is placed in a water sealed marine substation placed on the seabed. A schematic of a prospective system is presented in Fig. 1.4.

![Schematic of a prospective system](image)

**Figure 1.4.** A schematic description of the conversion system.

1.3 The Lysekil research site

The Lysekil research site has been ongoing since 2004 and is located on the west coast of Sweden see, Fig. 1.5.

![Location of the Lysekil research site](image)

**Figure 1.5.** Location of the Lysekil research site.
A number of WECs and marine substations have been deployed and tested at the site. The site has a water depth of around 25 meter and spans an area of 0.5 km². It is equipped with a wave measuring buoy, an observation tower and sub-sea cables for power, communication and auxiliary power. The cables from the site are connected to a measuring station located on an island about 2 km from the site. The first WEC, the L1, was deployed in 2006 and is still in the water. Since then, 10 more WECs and two marine substations have been deployed. Fig. 1.6, presents an illustration of the sub-sea equipment installed at the research site in 2011.

Figure 1.6. A sub-sea illustration of the equipment installed at the research site in 2011.

The first WECs, the L1-L3, had a cylindrical shaped buoy connected to them. The buoy on the L1 was later exchanged for a torus shaped buoy, because of studies indicating a smaller added mass for this type of buoy [23]. Since then, most WECs installed at the site have had torus shaped buoys connected to them.

The WEC design has gone through many improvements since the L1 was deployed. The L1, the L2 and the L3 used an inner structure to mount the four stator sides. They also used tensile springs which, together with the mass of the translator, acted as the retracting force. The winding was a three phase fractional winding. The L9 used the same type of winding but the inner structure was removed and the eight stator sides were mounted directly on the pressure capsule. Instead of using tensile springs, the mass of the translator was increased and used as the retraction force.

In the L10, the mass of the translator was increased further. Moreover, a new type of piston rod lead-through was developed to reduce the height and thereby the total weight of the WEC. The latest version of the WEC uses ferrite magnets together with pole shoes instead of using surface mounted Ne-Fe-B magnets. The stator sides have been increased to nine sides and are using a distributed one phase winding. It is still

---

5The L6 one of the yellow WECs closest to the L1 in Fig. 1.6 was not installed until 2013
a three phase machine. Three stator sides are connected to each phase and the phases are shifted by the mechanical position of the stator sides inside the pressure capsule. The stroke length has also been increased [24].

The first substation was designed to connect three WECs, the L1, the L2 and the L3. In the substation, each WEC output was first rectified and then connected together on a common DC-bus. Placing the WECs so they did not produce peak power at the same time, achieved a more evenly distributed power on the DC-bus [25, 26, 27]. Finally, the DC was converted back to AC and connected to resistive loads at the measuring station at Hermanö [28].

The seabed at the site is flat and consists mainly of sand silts. Placing a structure in this kind of environment could make an artificial reef. Environmental studies are ongoing on everything from biofouling and colonization of species on the structure to how sounds and vibrations from the structure affect different species [29, 30]. Studies using a sonar system to monitor the environmental effect of the deployment and maintenance of the sub-sea system are also carried out.

To study the motion of the buoys and for observation and weather data, a 12 m high tower equipped with a camera was installed at the site. Studies done on the buoy motion and further details about the observation tower can be found in [31].

The measuring station was first equipped with resistive loads and a measuring system to be able to evaluate the first WEC. Later, the station was equipped with a rectifier and a capacitor bank, see Paper II-Paper V. Since then, the station has been upgraded with a DC/DC-converter [32], a resonance circuit [33] and a grid connection point for future connection of a wave energy plant. The station is also equipped with a control and communication system to be able to control the station remotely. More information about this can be found in [34]. A more detailed description of the expansion of the Lysekil research site from 2006 to 2015 can be found in Paper VI, Paper XIII, Paper XIV and [35].

1.4 The Hammarudda test site

The WESA (Wave Energy for a Sustainable Archipelago) project was developed to investigate the performance of a WEC system designed to operate in an archipelago environment with ice conditions during winter. The site is located 15 km west of Mariehamn on Åland. The test site was a part of the WESA project that started in 2011. In January 2012 a WEC together with a subsea power cable was deployed at the site. The water depth at the site is about 25 m and a 1.4 km long subsea cable was deployed from the site to a measuring station placed onshore. The site was also equipped with a wave measuring buoy and an observation tower to study the buoy motion especially during ice conditions.

Fig. 1.7a presents a picture of the measuring station placed 100 m inland from the shore. On the wall of the station a number of resistive loads were mounted for different conditions of damping of the WEC. Inside the station a measuring system, a control system, and a logging system were installed which could be accessed remotely from Uppsala University. Fig. 1.7b shows the deployment of the WEC at the site. The WEC consisted of a four sided linear generator with surface mounted permanent magnets.
The stator was wound with a three phase integral slot winding. [36] gives a thorough description of the project and the site.

![Equipment WESA project](image)

Figure 1.7. Equipment WESA project a) measuring station b) WEC.

1.5 Aim of the thesis

The aim of this thesis has been to study the performance of the linear permanent magnet generators developed to convert wave energy into electricity. It includes studies of the behaviour of different weights on the translator and on how the active area and buoy volume affect the power absorption. Moreover, a new design using closed stator slots has been evaluated. The study has been done by using numerical and analytical simulations and by studying experimental data.

1.6 Previous work done on wave energy at Uppsala University

In the wave power group, 18 PhDs and 3 Licentiates have graduated.

Mrs Ivanova did her licentiate thesis, *Simulation of a Linear Permanent Magnet Octagonal Generator for Sea Wave Energy Conversion* in 2004 [37]. This thesis presents theoretical and numerical simulations on an octagonal WEC.


---

6 The pictures are a part of the WESA project. The WESA project has been financed to 75% by the European Regional Development Found (ERDF) under the Central Baltic INTEREG IV Programme 2007-2013.

Dr Eriksson did his doctoral thesis, *Modelling and Experimental Verification of a Wave Energy Converter* in 2007 [40]. The main focus in this thesis is the modelling of a WEC in operation using linear potential wave theory.

Doc Waters did his doctoral thesis, *Energy from Ocean Waves: Full Scale Experimental Verification of a Wave Energy Converter* in 2008 [41]. The thesis centres on offshore experimental results from the first WEC installed at the Lysekil research site. It also presents a comprehensive study on the wave climate at the Swedish west coast.

Dr Langhamer did her doctoral thesis, *Wave energy conversion and marine environment: Colonization patterns and habitat dynamics* in 2009 [42]. This thesis presents environmental studies at the Lysekil research site including colonization of species, biofouling and sediment testing.

Dr Rahm did his doctoral thesis, *Ocean Wave Energy: Underwater Substation System for Wave Energy Converters* in 2010 [43]. The focus in this thesis is the design of a marine substation for WECs including studies on power smoothing by WEC arrays.

Doc Boström did her doctoral thesis, *Electrical Systems for Wave Energy Conversion* in 2011 [44]. This thesis described an electrical system for wave power with the main focus on the electrical damping of the generator connected to different loads.


Dr Lindroth did his doctoral thesis, *Buoy and Generator Interaction with Ocean Waves: Studies of a Wave Energy Conversion System* in 2011 [46]. The thesis is about an observation system to study movement on the buoy connected to a WEC.

Dr Savin did his doctoral thesis, *Experimental Measurements of Lateral Force in a Submerged Single Heaving Buoy Wave Energy Converter* in 2012 [47]. This thesis focus on lateral forces on the hull of the WECs and on the inclination angle between the buoy and the WECs.

Dr Strömstedt did his doctoral thesis, *Submerged Transmission in Wave Energy Converters: Full Scale In Situ Experimental Measurements* in 2012 [48]. This thesis presents measurements on piston rod movements and on the piston rod mechanical lead-through transmission for the WECs.

Dr Svensson did his doctoral thesis, *Experimental results from the Lysekil Wave Power Research Site* in 2012 [49]. The major part of this thesis is about the control and sensor system used during experiments at the Lysekil research site.

Dr Ekergård did her doctoral thesis, *Full Scale Applications of Permanent Magnet Electromagnetic Energy Converters: From NdFe14B to Ferrite in 2013* [24]. The thesis primarily describes the design and testing of a linear permanent magnet generator using ferrite magnets.

Mrs Sjökvist did her licentiate thesis, *Hydromechanical Simulations of Wave Energy Conversion: Linear aspects* in 2014 [50]. This thesis focuses on comparing the hydromechanical parameters between two commercial simulation programs.

Dr Krishna did her doctoral thesis, *Grid Connected Three-Level Converters: Studies for Wave Energy Conversion* in 2014 [51]. The major part of the thesis is describing a multilevel inverter for a wave energy conversion system.
Mr Baudoin did his licentiate thesis, *Thermal study of a sub-merged substation for wave power* in 2014 [52]. The thesis studies the thermal effect from power devices placed in a submerged substation used for wave power.

Dr Gravråkmo did his doctoral thesis, *Buoy geometry, size and hydrodynamics for power take off device for point absorber linear wave energy converter* in 2014 [53]. This thesis presents hydrodynamic studies on torus shaped buoys for WECs with special attention on added mass.

Dr Haikonen did his doctoral thesis, *Underwater radiated noise from point absorbing wave energy converter: Noise characteristics and possible environmental effects* in 2014 [54]. The thesis concerns the environmental studies at the Lysekil research site, with the main focus on sub-sea emitted noise from the WECs.


Dr Hai did her doctoral thesis, *Modelling wave power by equivalent circuit theory* in 2015 [56]. In this thesis linear and non-linear electric equivalent circuits were developed for studies of a WEC system.
2. Theory

2.1 Ocean waves

Ocean waves are created by wind and as long as the waves are traveling in deep water almost no energy is lost. Because of this, waves can be created far from where they are studied. When the water depth is small, the wave will feel friction against the seabed and lose its energy. The energy in an ocean wave at deep water is distributed as seen in Fig. 2.1. 95% of the energy is located between the water surface and one fourth of the wave length, L [57].

![Figure 2.1. Basic of an ocean wave in deep water.](image)

This thesis is only involves deep water, so a good approximation for deep waters is when \( \frac{h}{L} \geq \frac{1}{2} \) [58].

Real ocean waves are irregular and are composed of more than one frequency. To be able to distinguish between the frequencies, a fast Fourier transform can be used on the surface elevations to create a wave power spectral density \( S(f) \). The wave power density can be calculated as follows assuming linear wave theory and a deep water condition:

\[
J = \frac{\rho g^2}{64\pi} T_e (H_{m0})^2 \quad (2.1)
\]

where \( \rho \) is the seawater density and energy period and significant wave height is calculated as follows:

\[
T_e = \frac{m_{-1}}{m_0} \quad (2.2)
\]
and

\[ H_{m0} = 4\sqrt{m_0} \]  \hspace{1cm} (2.3)

where \( m_{-1} \) and \( m_0 \) are spectral moments calculated through:

\[ m_n = \int_0^\infty f^n S(f) \, df \]  \hspace{1cm} (2.4)

where \( f \) is the frequency.

### 2.2 Field model

The electromagnetic fields in an electric machine can be described by using the following set of equations, i.e. Maxwell’s equations relating to different field quantities:

\[ \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \]  \hspace{1cm} (2.5)

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]  \hspace{1cm} (2.6)

\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (2.7)

\[ \nabla \cdot \mathbf{D} = \rho_f \]  \hspace{1cm} (2.8)

where \( \mathbf{E} \) is the electrical field, \( \mathbf{B} \) is the magnetic flux density, \( \mathbf{H} \) is the magnetic field intensity, \( \mathbf{J} \) is the surface current density, \( \mathbf{D} \) is the displacement field and \( \rho_f \) refers to the free charge density.

Eq. 2.5 is known as Faraday’s law, which states that a time varying flux in a closed circuit induces an electromagnetic force, and is usually presented in the following form:

\[ E = -\frac{d\phi}{dt} \]  \hspace{1cm} (2.9)

where \( \phi \) is the magnetic flux enclosed by the coil. By neglecting the displacement field due to low frequencies, Eq. 2.6 can be written as Ampere’s law which gives the relation between the magnetic field intensity, \( \mathbf{H} \), and the current, \( I \), enclosed by a closed path of integration.

\[ \oint_c \mathbf{H} \cdot dl = I \]  \hspace{1cm} (2.10)

Gauss’s law for magnetic fields, Eq. 4.3 simply states that the divergence of the magnetic field in any point is equal to zero. Gauss’s law for electric fields, eq. 4.4 states that the divergence of the displacement field is the free electric charge density.

### 2.3 Linear generator

The theory for linear generators is similar to the one for rotating generators. There are some obvious differences, e.g. the stator moves in a linear motion, which means that there are turning points where the translator needs to stop and pick up speed again.
This is not an issue with the rotor in a rotating machine. Also, the linear generator will get a phase shift between the phases in the generator at these turning points.

Another difference is the longitudinal end-effects that only occur with a linear machine. The end-effects have an influence on the magnetic flux in the generator and give rise to large forces when the magnets slip in and out of the stator. Longitudinal end-effects are studied in detail in [59, 39].

The linear generator and the rotating generator convert mechanical energy into electrical energy through a magnetic coupling in the air-gap. In this process there will be losses in each conversion stage. By the first law of thermodynamics, the relation between the different energies in the generator can be written as:

\[
\Delta W_{mec} = \Delta W_{mag} + \Delta W_{el} + \Delta W_{loss}
\]  

Where \(\Delta W_{mec}\) is the mechanical energy, \(\Delta W_{mag}\) is the magnetic field energy, \(\Delta W_{el}\) is the electric energy, and \(\Delta W_{loss}\) describes all the losses in the system.

2.3.1 Magnetic material

The linear generator mainly consists of two parts: (a) the stator, the static part; and (b) the translator, the moving part, see Fig. 2.2.

![Figure 2.2. Linear PM generator.](image)

The material and the behaviour of the magnetic fields in these parts are of high importance when designing a generator. The general relation between the magnetic field intensity and the magnetic flux density in a material are written as:

\[
B = \mu_0 (H + M)
\]  

where \(\mu_0\) is the magnetic permeability of free space and \(M\) is the magnetization representing how much a material is magnetized. Assuming the magnetization is proportional to the applied magnetic field, Eq. 2.12 can be written as:

\[
B = \mu_r \mu_0 H
\]  

where \(\mu_r\) is the relative permeability of the material.

The material used for the stator is made up of thin electric steel sheets where the winding pattern is punched through each sheet. By using thin sheets instead of a solid core the eddy current losses can be kept down to a minimum. The material used for the stator sheets in the machines is a soft ferro-magnetic non-oriented type with
a high permeability, \( \mu \), and a low coercive field strength, \( H_c \). This means that if a small external field is applied to the material, it results in a high magnetic flux in one direction and in the reverse direction when the applied field is reversed. When the crystal structure has such a response to a small applied field, the material is called a soft material. A material with this crystal structure is usually also mechanically soft. [60] The BH-curve for a soft magnetic material is presented in Fig. 2.3b.

The translator is made of surface mounted permanent magnets mounted on a ferromagnetic steel plate. The permanent magnets can be described as a magnetic potential source. When placed close to a good magnetic conductor i.e. a low reluctance circuit, the magnetic flux from the magnets will take the easiest path. Using this knowledge, the electric steel in the stator can be designed in such a way that the magnetic flux flows in a path that surrounds the cables wound in the stator. In contrast to the crystal structure in soft ferromagnetic material, the permanent magnets attached to the translator cannot have these properties, but instead have a permanent direction. This means that the crystal structure in the material needs to be subjected to a high externally applied field in order to get magnetized and that it will stay magnetized after the field is removed. [60] A material with these properties is called hard and the BH-curve is presented in Fig. 2.3a.

During a normal load condition the permanent magnet is affected by a changing magnetic field and will therefore move along the recoil line in the second quadrant see in Fig. 2.3a. If the magnet is subject to a magnetic field larger than the coercive field strength \( H_c \) the magnets could be permanently damaged. Moreover, the magnets are temperature dependent. A high temperature will decrease the remanent magnetic induction and the coercive field strength, making them easier to demagnetize. [61]

### 2.3.2 Losses

The losses can be divided into three classes: winding losses, iron losses and mechanical losses. The winding losses are related to the resistive losses of the conductor and the eddy current losses. The resistive losses are calculated by:

\[
P_{cu} = \frac{1}{\sigma} \int_{vol} J^2 dV
\] (2.14)
where $\sigma$ is the conductivity and $J$ is the current density integrated over the volume of the coil.

Losses in the iron are divided into hysteresis losses, eddy current losses and excess losses.

Hysteresis losses arise from the magnetic domain, discussed in section (2.3.1), not aligning with an external applied field in soft ferromagnetic material. When an external field is applied to the material and then reversed, parts of the domain will not return to the initial state. This is partly due to impurities in the material. In Fig. 2.3b the area enclosed by the loop is the hysteresis loss per cycle.

Eddy currents are due to the changing magnetic fields which are the very nature of electric machines. When a time varying magnetic field is applied through the stator, a voltage and current will be induced in the conductor. Since the ferromagnetic material is also conductive, current loops will be created in the stator. The magnitude of these currents depends on the area, the resistivity of the material, and on how fast the magnetic field is changing. To reduce the eddy currents, the resistance of the material could be increased. Another method would be to reduce the area. This is done by using insulated lamination’s of electrical steel sheets. Eddy current losses will make the BH-curve in Fig. 2.3b thicker.

Excess losses are due to the fact that eddy currents are generally higher than predicted. The local flux density fluctuation in the domain walls will induce eddy currents adding to the total eddy current losses.

The total losses in the iron assuming a sinusoidal flux density can be expressed as [62]:

$$P_{\text{iron}} = K_h f B_m^2 + K_e f^2 B_m^2 + K_c f^{1.5} B_m^{1.5}$$  \hspace{1cm} (2.15)

where $K_h$, $K_e$ and $K_c$ are material dependent coefficients for hysteresis, eddy currents and excessive losses respectively. $B_m$ is the peak magnetic flux density and $f$ is the frequency.

Mechanical losses are related to friction losses in different parts of the generator. In the linear generator, it is mainly the large number of wheels that will add to the friction loss. Besides, considering the WEC, friction will occur when the piston rod moves through the sealing and when the buoy line moves against the funnel.

### 2.3.3 Electromotive force

The induced electromotive force, $emf$, in the linear generator is dependent on the vertical speed, $v$, the pole pair width, $w_p$, and the permanent magnet magnetic flux per pole, $\phi_{pm}$. When the translator moves relative to the stator, the stator will be subjected to a varying flux wave. By using equation 4.5 and assuming an ideally wound stator at no-load and a sinusoidal motion, the $emf$ per phase can be described as:

$$e = \frac{2\pi v N_k \phi_{pm}}{w_p} \sin\left(\frac{2\pi v}{w_p} t\right)$$  \hspace{1cm} (2.16)

where, $N$, is the total number of winding turns per phase in the stator, $k_w$ is the winding factor and $v/w_p$ is the electric frequency $f$. Using Eq. 2.14, the effective value of the $emf$ can be written as:
\[ E = 4.44 f N k_w \phi_{pm} \]  

(2.17)

The amplitude of the permanent magnet flux can be calculated by knowing the flux through the yoke when the winding is placed in-between one north and one south magnet. Some of the flux will take a shortcut through the air between two stator teeth and this will also contribute to the linkage flux as long as it surrounds some of the cable windings. Magnetic flux between two magnets and at the edge of the magnets will, however, not contribute to the linkage flux. The total linkage flux for one phase is:

\[ \lambda = N \phi \]  

(2.18)

### 2.3.4 Armature reaction

A 3-phase synchronous generator at no-load will only create a flux wave dependent on the permanent magnets. But during a load condition, a current will run through each phase in the stator. Each phase is shifted \(2\pi/3\). These currents will together create an armature flux wave called the armature reaction. The armature flux wave, together with the magnetic flux from the permanent magnets, creates the resulting magnetic flux wave [63] see Fig. 2.4.

![Figure 2.4. Flux waves in a permanent magnet generator together with a phasor diagram.](image)

The resulting flux wave is the flux seen in the machine during normal working conditions. A force will act to align the PM flux wave with the armature flux wave. This force is called the electromagnetic force, \(F_{em}\), similar to the electromagnetic torque in rotating machines. In the generator mode, the electromagnetic force will counteract the motion of the translator. When the current in the windings is increased or the angle between the flux wave is decreased, the electromagnetic force will increase. In the
generator mode, the permanent magnet flux will lead the armature flux wave by $\pi/2 + \delta$, where $\delta$ is the load angle.

2.3.5 Inductance

The steady state inductance i.e. the synchronous inductance in a 3-phase generator is given by:

$$L_s = \frac{3}{2}L_m + L_l$$  \hspace{1cm} (2.19)

where $L_m$ is the main inductance and $L_l$ is the armature leakage inductance. The $\frac{3}{2}$ term for the main inductance arises from the moving magnetic flux wave in the air-gap. For a three phase armature winding, the currents create a moving flux wave with a magnitude $\frac{3}{2}$ times the magnitude of one phase only. The self-inductance of phase a can be written as:

$$L_{aa} = L_m + L_l$$  \hspace{1cm} (2.20)

where the leakage inductance can be described by the self-inductance and the mutual inductance as:

$$L_l = L_{aa} + 2L_{ab}$$  \hspace{1cm} (2.21)

where $L_{ab}$ is the mutual inductance between phase a and phase b. Combining equations 2.19, 2.20 and 2.21 gives us the synchronous inductance described by the self-inductance and the mutual inductance.

$$L_s = L_{aa} - L_{ab}$$  \hspace{1cm} (2.22)

2.3.6 Electric equivalent circuit

By assuming an ideal three phase generator under balanced three phase conditions where all the armature quantities of the synchronous generator vary sinusoidally in time, an equivalent circuit for one phase can be used to study the generator [64]. Fig. 2.5 presents an equivalent circuit for a generator connected to a resistive load $R_l$. $E$ is the effective value of the emf, $R_g$ is the winding resistance of one phase and $L_s$ is the synchronous inductance.

![Figure 2.5. Equivalent circuit.](image_url)
By using the simplified equivalent circuit and knowing some of the parameters of the generator, the current can be calculated as:

\[ I_a = \frac{E}{R_g + R_l + j\omega L_s} \]  \hspace{1cm} (2.23)

And by knowing the armature current, the input active power and the output power over \( R_l \) are calculated as:

\[ P_{\text{in}} = \frac{E^2(R_g + R_l)}{(R_g + R_l)^2 + (\omega L_s)^2} \]  \hspace{1cm} (2.24)

\[ P_{\text{out}} = \frac{E^2R_l}{(R_g + R_l)^2 + (\omega L_s)^2} \]  \hspace{1cm} (2.25)

By using Fig. 2.4, knowing that the emf will lag the PM flux by \( \pi/2 \) and the armature current will be in phase with the armature flux, a vector diagram is presented in Fig. 2.6. The resulting flux will be in phase with the air-gap voltage which is the voltage over the leakage inductance, the winding and the load resistance.

Figure 2.6. Phasor diagram.

The load angle, \( \delta \) in Fig. 2.6 is the same as in Fig. 2.4. And can be calculated as:

\[ \delta = \arctan \left( \frac{\omega L_s}{R_g + R_l} \right) \]  \hspace{1cm} (2.26)

2.3.7 Reluctance network model

A magnetic circuit can be used to model the PM generator. The basis of the magnetic circuit theory is the generalized form of Ampere’s law, the flux conservation law and the constitutive relation \( B(H) \) [65]. The magnetic potential difference can be written, using Eq. 2.10, as:

\[ U = NI = \oint_c \mathbf{H} \cdot d\mathbf{l} \]  \hspace{1cm} (2.27)

where \( N \) is the number of winding turns. Hopkinson’s law states that the magnetic potential difference is equal to the magnetic flux in the circuit times the magnetic resistance (Reluctance) in the circuit as:

\[ U = \phi \mathcal{R} \]  \hspace{1cm} (2.28)

The reluctance in different parts of the generator is calculated as:
\[ R = \frac{l}{\mu_0 \mu_r A} \quad (2.29) \]

where \( l \) is the length and \( A \) is the area of each segment. By calculating the reluctance in each segment, an expression for the total reluctance can be found. By knowing the sources of the magnetic flux in the generator i.e. the PM and the armature current, the magnetic flux and the magnetic potential difference can be calculated in the different segments of the circuit.
3. Method

This chapter presents a description of the different studies carried out in the thesis and how they have been performed.

3.1 FE-simulations

The numerical simulations in this thesis are done with Ansys Maxwell. The FEM is used to solve the field equations numerically [66] where the first step to solve a problem is to create the geometry and to define the material in 2D or 3D. Then mesh operations are applied to the geometry. The accuracy of the results depends mainly on the number of mesh elements used. But the number of mesh elements is directly related to the computer speed. The challenge is to have a high number of elements in the parts of the geometry where the accuracy needs to be high and a smaller number at areas of less interest. In transient problems, the moving band method is used where only the band area surrounding the moving objects is re-meshed each time-step. The stationary objects outside of the band and the object inside the band are not re-meshed. Next, the boundary conditions need to be defined. Depending on static or transient FEsimulation the boundary conditions could be different. In this thesis both transient and magnetostatic simulations have been performed. To lower the computational domain in transient simulations in some cases, the symmetries in the geometry have been reduced by using a periodic boundary. Fig. 3.1 presents the geometry, the mesh and the boundary conditions for a transient simulation where the mesh is applied through adaptive meshing.

A time-dependent magnetic field equation can be written as [67]:

\[
\nabla \times \left( \frac{1}{\mu_r \mu_0} \nabla \times A \right) + \sigma \frac{dA}{dt} = J_s + \nabla \times \mathbf{H}_c - \sigma \nabla V_e
\]

(3.1)

where \( A \) is the magnetic vector potential, \( \sigma \) is the conductivity and \( V_e \) is the electric potential. The moving and stationary parts in the model have their own reference frames so that the velocity can be put to zero in each coordinate system.

By numerically solving for the vector potential, the magnetic flux density is calculated as:

\[
\mathbf{B} = \nabla \times \mathbf{A}
\]

(3.2)

In 2D problems the model is assumed to be symmetrical in the \( z \)-axis, thus the magnetic vector potential becomes a scalar, \( A \rightarrow A_z \). Moreover, the displacement current is neglected due to the low frequency, usually \( f < 20\, \text{Hz} \), in simulations. End winding resistance and inductance need to be calculated and added to the simulation.
3.2 Closed stator slots

To study the magnetic flux in the generator when closing the stator slots, an analytical model was derived and compared with FE-simulations. Fig. 3.2 shows the difference between a closed slot and an open slot in a generator. The point of using closed slots is that the permanent magnet flux has a larger area to flow through, increasing the total flux entering the stator. Parts of this flux will go through the closed slots but as the flux going through the closed slots increases, the steel will be less magnetically conductive with a reluctance close to that of air. Furthermore, by closing the slots, the cogging force related to the fact that the magnets tend to cling against the teeth in the stator will be reduced.

By changing the thickness of the slot, the electromagnetic performance was investigated. A permanent magnet can be described as a magnetic potential source where the magnetic flux from the source is dependent on the reluctance in the magnetic circuit. An equivalent circuit can be used to solve the magnetic flux [68, 69]. The equivalent circuit is presented in Fig. 3.3, where the armature current is zero, i.e. the generator has no load connected to it, and only the permanent magnets contribute to the magnetic flux in the circuit.

The magnetic flux sources in the circuit have a reluctance path in parallel connected to it. These are related to the reluctance of the PM and the individual leakage flux of the magnets. Reluctance parts marked with a thicker black line at the edges in Fig. 3.3 are related to non-linear parts in the magnetic circuit, i.e. the magnetic material. With a starting point from the magnetic circuit, the flux through the closed slot can be derived as:
\[
\phi_{cs} = \frac{2H_i l_{pm} \mu_0 L_i}{a \beta + \frac{l_1}{\mu_1 w_1}} \tag{3.3}
\]

where \(\alpha\), \(\beta\) and \(\gamma\) are given by

\[
\alpha = \frac{2l_{pm}}{\mu_{rec} w_{pm}} + \frac{2l_g}{w_g} + \frac{l_4}{\mu_4 w_4} \tag{3.4}
\]

\[
\beta = \frac{2l_2}{\mu_2 w_2} + \frac{l_3}{\mu_3 w_3} + \frac{l_1}{\mu_1 w_1} \tag{3.5}
\]

\[
\gamma = \frac{2l_2}{\mu_2 w_2} + \frac{l_3}{\mu_3 w_3} \tag{3.6}
\]

where \(L_i\) is the stack length, \(l\) and \(w\), are parameters related to the geometry in different parts and \(\mu\), is the relative permeability in different parts. The non-linear behaviour is related to the BH-curve. Because of the thin width of the closed slot, the magnetic flux density will be high through the material and will easily become saturated. A modified Langevin expression has been used to model the non-linear parts [68].

\[
B_i(H_i) = \mu_0 (H_i + M_s (\coth(\frac{H_i}{a} - \frac{a}{H_i}))) \tag{3.7}
\]

where \(M_s\) is the saturation magnetization and \(a\) is a material dependent parameter. In each part of the iron, the magnetic field is iterated and by using Eq. 2.13, the relative permeability for each part can be calculated.

34
3.3 Static model for power absorption limits

The WEC basically consists of a point absorbing buoy on the surface connected to a linear generator on the seabed as mentioned in the introduction. By assuming a constant active area of the generator and ignoring friction and cogging forces, roughly, for an upward motion on the translator, the lifting force of the buoy must be larger than the electromagnetic force and the mass of the buoy and translator as:

\[ F_b > F_{em} + (m_b + m_t)g \]  \hspace{1cm} (3.8)

where \( m_b \) and \( m_t \) are the weight of the buoy and the translator respectively.

The absorbed power can be described by the electromagnetic force and the speed of the translator as follows:

\[ P_{abs} = F_{em}v \]  \hspace{1cm} (3.9)

The limit in absorbed power for an upward motion of the translator, ignoring hydrodynamic forces, occurring when the buoy is totally submerged, can be written as:
\[ P_{abs} = (F_{tot} - (m_b + m_t)g)v \]  

(3.10)

The buoyancy force, \( F_{tot} \), for a totally submerged buoy is described by Archimedes force as:

\[ F_{tot} = \rho gV \]  

(3.11)

where \( \rho \) is the density of the sea water and \( V \) is the total volume of the buoy.

For a downward motion, the gravity force of the translator needs to be greater than the electromagnetic force as:

\[ m_t g > F_{em} \]  

(3.12)

The limit in power absorption when the translator moves downwards only depends on the mass of the translator, the gravitational force and the speed of the translator as:

\[ P_{abs} = m_t g v \]  

(3.13)

### 3.4 Analytic model for the motion of the translator

The model was derived to study the peak speed of the translator moving in the downward direction assuming a slack buoy line. In the model, the active area is changing with the position of the translator and the cogging forces are included. Likewise, it can be used to study the influence of the translator weight and the buoy volume. It has been used to study the upward motion but the model does not include the hydrodynamic forces. Fig. 3.4 illustrate different positions of the translator used as boundary conditions in equation 3.15.

![Figure 3.4. Illustration of different positions of the translator.](image)

The electromagnetic force is calculated by using the linkage flux \( \lambda \) and the inductance \( L \) of the generator. These parameters can be calculated analytically by using
the reluctance circuit mentioned in section (2.3.7) or they can be extracted from an FE-simulation. Hence, the electromagnetic force can be calculated as:

\[ F_{em} = \frac{12\pi^2 \lambda^2 v R}{(Rw_p)^2 + (2\pi v L)^2} \]  

where \( v \) is the speed of the translator, \( R \) is the total resistance per phase and \( w_p \) is the pole pair width.

If the friction force is ignored, analytical equations for the downward motion of the translator can be written using Newton’s second law as:

\[
\begin{aligned}
\frac{dv}{dx} + \left( \frac{h_1 + x}{l_{st}} \right)^2 \cdot \frac{F_{em}(v)}{v_{m_t}} + \frac{F_c(x)}{v_{m_t}} - \frac{g}{v} &= 0, \quad x_0 \leq x \leq x_1 \\
\frac{dv}{dx} + \frac{F_{em}(v)}{v_{m_t}} + \frac{F_c(x)}{v_{m_t}} - \frac{g}{v} &= 0, \quad x_1 \leq x \leq x_2 \\
\frac{dv}{dx} + \left( \frac{h_2 - x}{l_{st}} \right)^2 \cdot \frac{F_{em}(v)}{v_{m_t}} + \frac{F_c(x)}{v_{m_t}} - \frac{g}{v} &= 0, \quad x_2 \leq x \leq l_s
\end{aligned}
\]  

(3.15)

where \( x \) is the position of the translator, \( h_1 \) and \( h_2 \) are the vertical length of the activated area when the translator is positioned at the top or the bottom of the generator respectively, \( l_{st} \) is the length of the stator, \( l_s \) is the free stroke length and \( F_c \) is the cogging force. The boundary \( x_0 \leq x \leq x_1 \) is valid when the translator is moving into the stator, increasing the active area. \( x_1 \leq x \leq x_2 \) is valid for a full active area and \( x_2 \leq x \leq l_s \) is valid when the translator moves out of the stator, decreasing the active area.

3.5 Offshore experiment

In this thesis, the experimental data have been gathered from two offshore test sites. The Lysekil research site is located on the west coast of Sweden near the city of Lysekil. The Hammarudda test site is located on the east coast of Sweden close to the island Åland.

3.5.1 Experiments on the WESA generator

The WESA generator is a four sided generator with surface mounted permanent magnets. The stator sides are mounted on an inner framework and are wound with a three phase integral slot winding. Compared to the WECs that were deployed earlier, the weight of the translator has been increased significantly. Moreover, the pole width has been decreased, thus increasing the electric frequency. The buoy attached to the WEC during the experiment was a hexagonal circular shaped torus. The buoy was connected through a steel wire with the piston rod in the generator placed at the seabed. The power from the WEC was transferred to the measuring station via a 1.4 km sub-sea power cable.

The WESA generator is presented in Fig. 3.5 before deployment.

The experiments on the WESA generator were conducted for two load cases with a similar wave climate. The resistive loads in the measuring station were Y-connected, where each resistor in the connection was 1.67 \( \Omega \) or 6.67 \( \Omega \). This is equivalent to a delta connection of respective 5 \( \Omega \) or 20 \( \Omega \).
Inside the measuring station, the current on each phase and the voltage over the load were measured with a sampling frequency of 100 Hz.

3.5.2 Experiments on the L9
The L9 is the second generation of WECs developed at Uppsala University. The main difference between the L1-L3 and the L9 is that the inner framework was taken away and the stator sides were mounted directly on the inside of the hull of the WEC. This was to save space and material. The earlier design had four stator sides mounted on the inner framework whereas the L9 has eight stator sides which slightly increases the active area of the generator. Fig. 3.6, shows a picture of the L9 during deployment.

During the experiments conducted with the L9, three different delta connected resistive loads placed at the measuring station were used: 4.9, 11 and 20 Ω. When the generator is connected to a 4.9 Ω load, one of the resistors in the delta connection is 4.9 Ω. The absorbed power is calculated from the voltage and the current measurements on each phase in the measuring station.

3.5.3 Experiments on the L2 and the L3
Comparative studies have been carried out on the L2 and the L3 when they were connected to resistive dump-loads, see Paper VI and Paper IV.

The L2 and the L3 have identical linear generators inside the pressurized capsule see Fig. 3.7. The WECs had small differences in their structure, with the L3 having a slightly higher superstructure to fit a new piston rod mechanical lead-through. They were also equipped with different types of sensors [47, 48].
The buoys connected to the L2 and the L3 where of a cylindrical shape with the same volume, but the buoy connected to the L2 had a smaller diameter and was higher compared to the L3 buoy which had a larger diameter with a smaller height.

The purpose of dump-loads is to keep the WEC loaded during deployment and when it is disconnected from the marine substation. If the WEC is not connected to a load, the translator in the generator would not be electrically damped and could move quite easily. If this would happen during a powerful wave climate, the WEC could be destroyed because of the high speed and the high force when hitting the end-stops. The dump-load consisted basically of three resistive loads connected in a delta-connection where each resistor had a resistance of $4 \, \Omega$. It can be turned on and off by a switch controlled by the substation. When the dump-loads are turned on, the voltage is measured in the substation, and by knowing the resistance of the dump-load, the current and the power can be calculated.

**3.5.4 Experiments on the L1 connected to a rectifier and a capacitor bank**

The experiments done on the L1 include rectification and smoothening of the voltage with capacitors presented in Paper II, Paper III and Paper IV.

To be able to connect a WEC to the grid, the first step is to rectify the voltage out from the WEC. To verify this step, a rectifier circuit was built and installed at the research site in the measuring station. The circuit was then connected to the L1.
The experiments were carried out to study how the WEC would behave when rectified and when having a large capacitor bank connected to it. In Fig. 3.8 a), an equivalent circuit of the system is shown and Fig. 3.8 b) presents the rectifiers and the capacitor bank.

3.5.5 Experimental error analysis

During the experiments and the handling of the data some errors will be present. The load resistors and the resistance of the cables are temperature dependent, i.e. the resistivity of the material will change $\pm 1.5\%$. Furthermore, the current and the voltage measurement sensors have an accuracy of $\pm 0.5\%$ and $\pm 1.5\%$ respectively. During the data handling, especially for the L9 experiments, the noise was induced in the voltage measuring signal close to zero crossings, when the translator was at its top or bottom position. They are presented as peaks in the speed due to the small $\Delta t$ of the noise at almost zero power. A filter has been used to reduce these peaks, but some of these speed peaks with no power are still visible in the results.

Figure 3.7. Picture before deployment of L2 and L3 and one of the dump-loads.
Figure 3.8. Rectifier and capacitor bank installed at the measuring station. a) Presents an equivalent circuit for the system and b) presents a picture of the experimental setup.
4. Summary of results and discussion

A short summary of the results from the papers included in the thesis are presented in this chapter. It is divided into five parts to give an easy overview.

4.1 Closed stator slots

This part presents some of the results from the study on closed stator slots from Paper VII and Paper X. The results include both magnetostatic, transient FEM simulations and analytical calculations. Fig. 4.1, presents the magnetic flux density in the air gap for three different cases: open slots, closed slots 1 mm thick and closed slots 2 mm thick.

![Figure 4.1. Magnetic flux density in the air-gap for open slot (blue), closed slot 1 mm (green) and closed slot 2 mm (red). Results from Paper VII.](image)

The cogging force calculated over one pole pair for open slots and for closed slots 1 mm and 2 mm thick are presented in Fig. 4.2.

The results from Paper VII and Paper X, indicate that there is improvement of the magnetic flux density in the air-gap with closed stator slots. Moreover, a lower cogging force for the closed slots case is visible, see Fig. 4.1, and Fig. 4.2.

In Fig. 4.3, the analytically calculated peak magnetic flux through one closed slot with the thickness of the closed slot between 0.1 mm to 4 mm is compared with FEM simulations for a 0.5 mm, a 1 mm and a 2 mm thickness of the closed slot.
The analytical model derived for solving the magnetic flux through the closed slots shows good agreement with the FEM simulations, which indicates that the model could be used to further study the generator.

However, as expected, the leakage flux increased in the generator due to the shortcut for the magnetic flux through the closed slots. The benefit of an increasing area of stator steel for the flux gave a 2.4% increase in the flux entering the stator when comparing open slots to closed slots of 2 mm thickness.

When the linkage flux for the open and the closed slots cases are compared, a decrease in the linkage flux is visible for an increasing thickness of the closed slots. This gives a direct impact on the induced voltage of the generator. This can be solved by increasing the size of the permanent magnets.

For the generator studied in Paper X, with 1 mm thick closed slots, the synchronous inductance is increased by 8% and the linkage flux is decreased by 5% at nominal speed. Additionally, the cogging force is decreased by 3.6 times compared to the open slots reference generator. These parameters will affect the damping of the generator with a lower damping for the closed slots. This effects the speed of the translator and this in turn changes the power. Assuming a slack buoy line, studying the translator in the downward motion, the increase in the speed at the same load will increase the absorbed power for the closed slots case in the majority of the stroke-lengths, although the power at the same speed is higher for the open slots. In reality, the motion of the ocean waves is more or less controlling the speed of the translator. Fig. 4.4 and Fig. 4.5 present the result for the translator speed and the absorbed power versus the translator position for red closed slots and green open slots during a full stroke-length and assuming a slack buoy line at the same resistive value of the load. When the speed of the two cases is equal or almost equal, the power for the open slots case will be higher. However, as the differences in speed increase, the power for the closed slot case will be higher. There is also a visible difference between damping at a full active

Figure 4.2. Cogging force over one pole pair during 360 electrical degree for open slot (dot), closed slot 1 mm thick (diamond) and closed slot 2 mm thick (cross). Results from Paper VII.
Figure 4.3. The analytical model compared with the FEM simulations for the peak magnetic flux through the closed slot versus the thickness of the closed slot. The black line is the analytical calculations, 0.5 mm (green), 1 mm (blue) and 2mm (red) are the FEM-simulated values. Results from Paper VII.

area starting at a position of 0.5 m, where the speed and the power will drop much faster for the open slots case.

The different damping will in this case, because of the lower linkage flux and the higher inductance for the two generators, lead to higher currents in the windings for the closed slots case at equal power. Hence, higher copper losses will be induced.

Figure 4.4. Speed of the translator versus position for closed slots (red) and open slots (green) during one stroke-length in downward direction assuming a slack buoy line at same load. Results from Paper X.

4.2 Study of the L9

The main focus in Paper VIII was to study the influence of the buoy size and the translator weight on the power production during different load cases and sea states for the
WEC L9. To model this, a simplified model studying the limit in the absorbed power assuming a constant active area was derived. The model is valid for calculations on the limit during a constant active area. The model is only dependent on the translator mass and the buoy volume, making the model independent of numerical simulations to calculate parameters such as inductance, $emf$ and hydrodynamic parameters.

Three different cases of experimental results are compared to an analytical model for power absorption versus the speed of the translator and presented when connected to different resistive loads, 4.9 $\Omega$, 11 $\Omega$ and 20 $\Omega$ respectively. In Fig. 4.6- Fig. 4.8, the blue dots present experimental data when the translator moves upwards and the red dots present data when the translator moves downwards. The lower dashed line presents the analytically calculated limit when the translator moves downward. The dashed line in the middle and at the top present the limits when the buoy is submerged 80% and for a totally submerged buoy respectively. The experimental power on the Y-axis is a mean value calculated over one third of a pole width.

![Figure 4.5](image1.png)

*Figure 4.5.* Absorbed power versus position for closed slots (red) and open slots (green) during one stroke-length in downward direction assuming a slack buoy line at same load. Results from Paper X.

![Figure 4.6](image2.png)

*Figure 4.6.* Power absorption when the L9 is connected to a 4.9 $\Omega$ load on the y-axis versus the speed of the translator on the x-axis at a significant wave height of about 3 m. Results from Paper VIII.
The static model indicated that the lifting force of the buoy was greater than the gravitational force of the translator. The experimental results presented show the same trends as in the static model. The upward lifting force and the power are calculated for a totally submerged buoy to find the limit in the static model. In reality, this does not occur that often. In the downward direction, the limit calculated is close to the experimental data, as expected when only the mass of the translator needs to be considered. The obvious difference between the different load cases is the speed of the translator. When the generator has a lower damping i.e. a higher value of the resistive load connected to it, the translator will move with a higher speed.

Noticeable in the experimental results are the two trends in the downward direction. This is clearest in the results in Fig. 4.8, but it also occurs in Fig. 4.6 and Fig. 4.7. The higher trend is related to when the translator is positioned at the top and starts to move downward to the midpoint. The lower trend is related to the motion from the midpoint down to the lowest position of the translator. These trends are related to the change in the active area of the generator. When the translator is positioned in the highest or the lowest position in the generator, the active area has its lowest value. The active area starts to increase when the translator moves towards the midpoint of the generator where it reaches its maximum. This phenomenon can be understood by studying the analytical results derived in Paper IX compared to the experimental data from the L9 in Fig. 4.9. The analytical calculations are done for a translator positioned at the top of the WEC accelerating from standstill across the free stroke length. The analytical model clearly shows the trends discussed above, though it overestimates the speed and the power at parts of the stroke length. Two main characteristics influencing the result are (a) the fact that the buoyancy force is not included assuming a slack buoy line and (b) the translator is assumed to move a full stroke length although tidal effects and buoy line length could have a large influence on the stroke length. Another part that could influence the results is the end-stop springs attached at the top and bottom of the WEC.
Figure 4.8. Power absorption when the L9 is connected to a 20 Ω load on the y-axis versus the speed of the translator on the x-axis at a significant wave height of about 2 m. Results from Paper VIII.

In Fig. 4.10, the three phase voltage from the L9 is presented during 60 s when it is connected to a 4.9 Ohm resistive load. The highlighted part in the figure shows when the translator moves upwards and downwards. In the beginning of some of the upward motion parts, there are visible high peaks in the voltage.

Also visible in the experiments are the data points displaying particularly high speed and power during all load cases but most frequently in Fig. 4.6, during a 4.9 Ω load. A further investigation of these points indicated that they were the result of so called snatch-loads which have previously been identified in [70, 71]. Fig. 4.10, presents the voltage during 60 s when the L9 was connected to a 4.9 Ω load and highlights a voltage peak. These peaks in voltage seem to occur when the translator is changing direction from the downward to the upward motion. One explanation could be that when the generator has a high damping, the translator falls slower and if it hits the lower end-stop it would move even slower and if the connection line moves downward faster there will be a slack in the line. When the next wave lifts the buoy and the line is stretched then a snatch load would occur. This would explain the more frequent occurrences in the 4.9 Ω load case together with the higher significant wave height during this load case.

4.3 Study of the WESA generator

The results in this section are a part of the experiments conducted at the WESA test site presented in Paper IX. The motivation for the paper was the increased weight of the translator for the WESA generator compared to the L9.

Fig. 4.11 presents the experimental results for the absorbed power and the power dissipated in the load versus the speed of the translator when the WESA generator is connected to (a) a 5 Ω load and (b) a 20 Ω load. The blue and purple dots are the absorbed power and represent the upward and the downward motion of the translator respectively. The red and the cyan dots are the power in the load and represent the
Figure 4.9. Experimental results on the downward motion from the L9 compared with the analytical model. Unpublished result.

Figure 4.10. Three phase voltage during 60 s for the 4.9 Ohm load case. Results from Paper VIII.

upward and the downward motion of the translator respectively. The power on the Y-axis is a calculated mean value for one third of a pole width. The experiments are compared to the numerical simulations presented as black lines. The two load cases were performed during similar sea-states.

The results in Fig. 4.11 show a good correlation between the FE-simulations and the experimental results up to a speed of about 0.7-0.8 m/s. One of the main reasons for this is that the FE-simulations assume a constant active area and the probability for a full active area decreases with the speed. Moreover, the iron losses are not included for the absorbed power in the experimental results.

Comparing the upward and downward power absorption, there is a good correlation between them, though the power absorption for the downward motions hits a limit around 0.9 m/s, although there are a few data reaching as high as 1.2 m/s.

In Fig. 4.12 the experimental results on the translator speed versus the position of the translator when it moves downward are compared to an analytical model. The pur-
Figure 4.11. Experimental data for the absorbed power and the load power compared with the FEM simulations at (a) 5 \( \Omega \) and at (b) 20 \( \Omega \) load. Results from paper IX.

The pose was to study where the peak speed of the translator would occur in the downward direction.

The analytical result in Fig. 4.12 assumes a slack buoy line to find a peak speed which could be true for parts of the stroke length in the downward direction. But at high speed, the buoyancy force is more or less involved. When studying the shape of the speed, they are quite similar and the point between the increasing or the decreasing active area and the constant active area is quite clear.

In Fig. 4.13 the experimental results on power absorption are compared with the static and the analytically derived model during the 5 \( \Omega \) load case. The blue and the black curves present the downward and the upward motion of the translator respectively for the analytical model. The red lines with diamonds and with dots present the downward and the upward motion respectively for the static model.

Fig. 4.13 is a nice presentation of how the static model works and how it could be adjusted to level out the differences in the absorbed power between the upward and the downward motion. By increasing the weight on the translator or the volume of the buoy, the two linear lines will align at a certain point. As explained in the previous section about the L9, the analytical model overestimates the power and the
speed partly because it is developed to study the peak speed of the translator and partly because the translator starts at the top of the generator and moves a full stroke length. It also shows if the power is produced when there is a constant or a changing active area.

### 4.4 Study of the L2 and the L3

In Paper VI, a study on the L2 and the L3 was conducted when they were connected to resistive dump-loads. In Fig. 4.14, the L2 and the L3 are compared on two different dates when the sea states were comparable. The purpose of the plot is to compare two almost identical WECs with buoys that have the same volume but different height and diameter. Each power data point is a 60 s mean value of the power in the load, where the blue dots relate to the L2 and the red dots relate to the L3. The energy period
and significant wave height have been calculated from data gathered from the wave measuring buoy and are calculated mean-values over 30 minutes.

![Figure 4.14](image-url)

*Figure 4.14.* A comparison of power in the load between the L2 and the L3 during two different dates compared with the energy period and the significant wave height. Results from Paper VI.

The two dates in Fig. 4.14, for the comparison between the L2 and the L3 were selected because of the similar sea states. The results show that there is a difference in power dissipated in the dump-load between the two almost identical WECs. The assumption that the WEC connected to the buoy with the larger bottom area against the water should produce more power seems correct when studying the experiments done on the 21st of July. However, the experiments done on the 16th of August present the opposite as during this experiment the buoy with a smaller area produces the highest power.
There are other parts than the buoys that could affect the experimental results and explain these findings. The resistive dump-loads are placed at the seabed and if the resistance of the load is changed for some reason then the damping of the generator will change. The L2 and the L3 had tensile springs attached for the retracting force, and if one of them breaks, the mean power would change. Later studies done on the L2 and the L3 also indicate that the connection lines have different lengths and this together with the tidal variations at the site could be related to the difference in the power dissipated in the load, see Paper IX, [72].

4.5 L1 connected to a rectifier

In Paper II-Paper IV, experimental studies on rectification of the L1 have been carried out. A part of these results from Paper III, can be seen in Fig. 4.15, which explains how the generator behaves when connected to a rectifier, a capacitor bank and a resistive load. The result presents the voltage, the current, the position of the translator, the speed of the translator and the power produced during 30 s. The DC voltage during the experiment was approximately +/- 70 V.

When the voltage output from a WEC is rectified and connected against an almost constant DC voltage, the AC voltage out from the WEC has to reach the DC voltage to be able to produce a current. If the AC voltage is lower than the DC voltage, the generator will be undamped i.e. no current in the stator winding. Because of this, the generator moves more easily and picks up speed, leading to a higher voltage which finally reaches the DC voltage level. In Fig. 4.15, the output AC voltage is flat at the peaks which means that the AC voltage is higher than the DC voltage and therefore is producing current. This is seen on the current in the experiments. The flat parts of the position in the experiments relate to turning points for the translator in the WEC. These are related to a zero speed of the translator and no voltage or current is produced.
Figure 4.15. Experimental results of a WEC connected to a rectifier circuit. Results from Paper III.
The main focus of this thesis has been to present the work done on the closed slots design for the linear generator and the experimental study and analytical models on the buoy volume, the translator mass and the active area of the L9 and the WESA generator.

The results in Paper VII show that the harmonics in the magnetic flux density in the air-gap can be reduced by using closed slots. This is also visible in the cogging force which will be reduced by increasing of thickness of the closed slots. There is also a small increase of the magnetic flux entering the stator compared to the open slots case. Moreover, the leakage flux increases due to the closed slots and consequently the linkage flux decreases. The analytical model for finding the magnetic flux through the closed slots agrees well with the FE-simulations. This indicates that the analytical model could be used to study the linear generator further.

Results from Paper X show a reduction in the cogging force for the closed slots of 3.6 times the open slots case and an increase of the synchronous inductance by 8%. Moreover, the core losses and the third and fifth voltage harmonics are reduced. The analytical model shows an increase in speed for the closed slots compared to the open slots for the same load case.

The experimental results from Paper VIII prove that the WEC L9 produces higher power peaks moving upwards than downwards. This is expected from the simulation model, since the lifting force of the buoy greatly exceeds the downward force of the translator, leading to higher speeds and higher powers.

Two trends in the power have been detected during the downward motion, which seem to be related to the changing active area in the generator. Power peaks during a high speed of the translator have been detected. The peaks seem to be related to higher damping of the generator and sea-state. They occur when the translator is turning from downward to upward motion with a high speed peak in the voltage and the current caused by snatch-loads.

The increased weight on the translator for the WESA generator in paper IX shows a more even power absorption between the upward and the downward motion on the translator as expected. Furthermore, for ideal conditions, for the downward motion of the translator, using a changing active area increases the absorbed power from the WEC.
6. Future Work

The work with the wave energy systems is far from finished. One of the plans for the near future involves connecting a WEC in Lysekil to the local grid. There are also plans for experiments on larger arrays of wave energy converters connected to a marine substation to study both the power production and the buoy interference.

From the studies carried out in this thesis a number of topics for future research is suggested.

- Vibration caused by the variations in permeance in the air-gap needs to be further investigated to understand the long-term and short-term impact of these on the WEC system. One way to reduce these is to close the stator slots. Preliminary studies and experimental equipment have been prepared for this study.

- Measurements on the friction force caused by the wheels in the linear generator and by the sealing in the WEC are needed to further develop the analytical models and to develop a WEC with low losses.

- Studies on the harmonics caused by the linear generator and by the electrical system connected to it, are necessary to understand what influence the harmonics have on the magnetic fields in the generator.

- Non-linear damping studies of the generator with closed stator slots.
7. Summary of Papers

Paper I
**Catch the Wave to Electricity - The Conversion of Wave Motion to Electricity Using a Grid-Oriented Approach**

The paper presents the steps taken to turn the idea about a wave energy converter into real offshore experiments. The experimental results presented in the paper agree well with the simulations done on the wave energy converter. The author made a limited contribution in writing the paper.


Paper II
**Experimental results of rectification and filtration from an offshore wave energy converter**

The first results from a WEC connected to a rectifier, a capacitor bank and resistive loads at the Lysekil research site are presented in the paper. The author made a minor contribution in writing the paper and a major contribution on the design of the electrical system and the experimental setup.


Paper III
**Study of a Wave Energy Converter Connected to a Nonlinear Load**

This paper investigates the performance of a wave energy converter when connected to a non-linear load during different sea states. The author made a minor contribution in writing the paper and a major contribution on the design of the electrical system and the experimental setup.

Paper IV

Experimental Results from an Offshore Wave Energy Converter

A detailed description of the Lysekil research site and the equipment installed at the site are presented in this paper. The paper also presents experimental data on the power absorption from a wave energy converter connected to a non-linear load. The author made a minor contribution in writing the paper and a major contribution on the design of the electrical system and the experimental setup.


Paper V

Design proposal of electrical system for linear generator wave power plants

This paper presents the electrical layout for a wave energy plant. A study of a wave energy converter connected to a resistive load and a rectifier and a capacitor bank has been compared. The author has helped on the parts written about the Seabased system and has contributed with the design of the electrical system and the experimental setup.


Paper VI

Lysekil Research Site: A Status Update

A status update about the Lysekil research site is presented in this paper. It also presents experimental data comparing the power output from two almost identical wave energy converters connected to buoys with the same volume but with different radius and height. The author has written most parts of the paper and the results presented in Fig.4.14 in the paper. The author has also contributed to some of the experimental setups at the site.

Published in the proceedings of 8th European Wave and Tidal Energy Conference, EWTEC, Southampton, UK, 2011
Paper VII

**Detailed Study of Closed Stator Slots for a Direct-Driven Synchronous Permanent Magnet Linear Wave Energy Converter**

A study on closed stator slots in a PM linear generator are presented in this paper. The study has been done with FEM simulations and analytical calculation at no-load. The results show that the magnetic flux density in the air-gap is improved and the cogging force is reduced with the thickness of the closed slots. It also shows a decrease in flux linkage. The author has written the paper and done the simulations and calculations.

*Published in Machines, 2(1):73-86, 2014.*

Paper VIII

**Experimental Results on Power Absorption from a Wave Energy Converter at the Lysekil Wave Energy Research Site**

Experimental results from a wave energy converter connected to different resistive loads are presented in this paper. The experimental results have been compared with an analytical model for the power limits in the upward and the downward motions of the translator. The results show that the power output in the upward direction is much higher than in the downward direction. It also presents power peaks which could be related to snatch loads. The author has written the paper, analysed the experimental results and done the simulations.

*Published in Renewable Energy, 77:9-14, 2015.*

Paper IX

**Study of the operation characteristics of a point absorbing direct driven permanent magnet linear generator deployed in the Baltic Sea**

This paper studies the wave energy converter deployed at the Swedish east coast. Experimental results are compared with the analytical results and earlier experimental studies. The WEC deployed in this paper has a translator with an increased weight compared to the L9 WEC. The influence of this is studied in this paper. The results indicate that the power is levelled out between the upward and the downward absorbed power. Moreover, the analytical model shows that by not having a constant active area, it is possible to increase the power compared to a constant active area. The author has written the paper, analysed the experimental data and done the simulations.

*Provisionally accepted, subject to minor revisions, IET Renewable power Generation, January 2016.*
Paper X

Performance study of linear permanent magnet synchronous generator for wave power with closed stator slots

A linear permanent magnet generator with closed stator slots is studied in this paper. The focus has been on the performance during nominal load, studying parameters such as the synchronous inductance, the core losses, the cogging force and damping. Moreover, the absorbed power and the power in the load are compared with a reference generator with open slots. The study has been done with FE-simulations and analytical calculations. The analytical calculations in this paper have been used to compare the downward absorbed power for the generators. The paper shows that there is a small increase of the synchronous inductance for the closed slots and, as expected, the linkage flux is decreasing. The cogging force for the closed slots is greatly reduced and the third and fifth voltage harmonics have been lowered. Studies of the motion of the translator in the downward direction show an increase in the absorbed power for the closed slots due to a higher speed arising partly because of the lower damping and partly because of the lower cogging force. The author has written the paper and done the simulations.

Submitted to IEEE Transaction on Energy Conversion, Feb 2016

paper XI

A Wave Power Unit

Describes the function of a resistive load connected to the generator when the WEC is not connected to a marine substation. It is called a dump-load because if the WECs produces too high a power into the substation, several WECs can be disconnected from the system and instead the power is utilised in the resistors as heat. This to protect both the substation from overloads and the WEC.


Paper XII

A Switchgear

The invention relates to the mechanical and thermal design of the substation. To passively cool the components inside the marine substation the components need to be in contact with the pressurized capsule which in turn are in contact with the seawater. An inner structure inside the substation for the assembly of the components, is preferred when producing them in serial production. To be able to passively cool some of the components, a system that attaches cooling plates from the inner structure is invented.

Vågkraftsforskning har bedrivits runtom i världen under många år och en mängd olika varianter av energiomvandlare för att omvandla vågenergin i vågorna till en användbar energi har föreslagits. Men än idag har ingen teknologi blivit kommersiellt gångbar, men en handfull projekt närmar sig den kommersiella marknaden. Problemen har ofta varit att få dessa omvandlare att klara av det härda klimatet ute till havs och efter kusterna men också få dem kommersiellt gångbara.


Forskningsgruppen har en testanläggning utanför Lysekil där fullskaliga vågkraftverk och marina ställverk kan testas. Det första vågkraftverket sjösattes under 2006 och sedan dess har 11 stycken vågkraftverk och 2 stycken marina ställverk installerats vid testanläggningen.

Huvudsyftet med min forskning har varit att studera de elektromagnetiska egenskaper hos linjärgeneratorn där en studie av slutna spår i statorn har utvärderats. Genom att slutna spåren kan man delvis öka det magnetiska flödet mellan magneterna i translatorn och statorn, och minska krafter mellan magnet och stator spåren. Men det medför också att det magnetiska flödet kan ta en genväg som inte omsluter lindningarna i statorn vilket leder till ett minskat sammanlänkat flöde. Genom att minska de krafter som uppstår från spåren i statorn så kan vibrationer i generatorn reduceras vilket i slutändan kan ge vågkraftverken en ökad livslängd och mindre underhåll. Utöver det så har även experiment bedrivits på olika vågkraftverk installerade vid testanläggningen i Lysekil och vid en testanläggning utanför Åland. Från dessa exper-
iment har studier om hur effektabsorptionen från dessa påverkas av bojstorlek, translatormassa och aktiv area i generatorm. Studierna visar att för att få en jämn effekt produktion mellan translatörrörelsen uppåt och neråt så krävs ett noggrant val av vikt av translatör och volym av boj. Studierna har också visat att en varierad aktiv area kan ge en ökad absorption. En jämförelse studie har också genomförts mellan två identiska vågkraftverk med olika utformning av bojarna. Studien visade att utformningen har betydelse men att mer studier krävs för att kunna dra några slutsatser.
9. Acknowledgments

This work has been supported by the Swedish Research Council under Grant no. 2009-3417, STandUP for Energy, Statkraf AS, Fortum OY, the Swedish Energy Agency, Seabased Industry AB, Draka Cable AB, the Gothenburg Energy Re-search Foundation, Falkenberg Energy AB, Helukabel, Proenviro, ÅF Group, Vinnova, the Foundation for the Memory of J. Gust Richert, the Göran Gustavsson Research Foundation, Vargöns Research Foundation, Swedish Research Council grant no. 621-2009-3417 and the Wallenius Foundation for their support of the project.

First I would like to thank my supervisor Mats Leijon for giving me the opportunity to work within the wave power project.
I also would like to thank my assistant supervisor Rafael Waters for always trying to help when I have questions and for proofreading the thesis.
My roommates, Ling and Antoine thank you for all valuable discussions and fun times at the office and in Lysekil.
My new roommate, Morgan helping me with the last details in latex.
Andrej, for all the fun times we have had at different conferences.
Erland, for the badminton matches although I have received minor injuries and all the discussion about the WESA project.
To all the people working within the Lysekil project both in the past and present for all the fun times and hard work trying to bring wave energy to the world.
All the people working within the division of electricity making it a fun place to work at.
Thanks to Maria, Anna and Gunnel for all the help when it comes to administration questions.
Thanks Thomas for all the help with computer questions and for helping me to upgrade my computer.
To my family and friends thanks for everything and for understanding the effort I have put down the last months on my thesis.
Ebba and Julia for always putting a smile on my face and making me think on other things than my work.
Last but not least I want to thank Cecilia for all the help and support and for being there for better or worse through the thesis and everything else, Thank you.
References


Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1339

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title “Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology”.)

Distribution: publications.uu.se
urn:nbn:se:uu:diva-274635