Full Scale Applications of Permanent Magnet Electromagnetic Energy Converters

From $\text{Nd}_2\text{Fe}_{14}\text{B}$ to Ferrite

BOEL EKERGÅRD
Abstract

This thesis presents research regarding a full scale linear ferrite permanent magnet generator, installed in a wave energy conversion system. The ferrite based magnetic circuit, supplementing the previous utilized Nd$_2$Fe$_{14}$B-magnet design, is designed with an electromagnetic numerical simulation tool, where the model is derived from Maxwell’s equations. The full scale design is, known to the author, the first developed linear ferrite based machine. The material change in the magnetic circuit required different mechanical solutions of the generator. The fundamental, primary theory and reasoning behind the new mechanical design is here presented, where sustainability, economy and production have been in focus and affected the final design. Two versions of the generator have been assembled and deployed at the projects experimental site on the Swedish west coast, and three more are under construction, planned to be installed during the autumn of 2013.

Further, the thesis presents an electric conversion circuit based on the electric resonance phenomena. Full scale experimental results present a successfully achieved electric resonance between the linear wave energy generator and external circuit.

Finally, research regarding a two pole permanent magnet motor for an electrical vehicle is presented. Detailed analytical and numerical calculations are utilized to investigate the losses in the machine over a wide frequency interval. The results indicate the possibility of an increased efficiency of electrical motors in electrical vehicle system and argue for elimination of the gearbox. The system total efficiency and mechanical stability can thereby be increased.

The work concerning the wave energy converter is a part of a larger project, the Lysekil Wave Power Project, developed by a research group at Uppsala University, whereas the work concerning the electric motor so far has been carried out as an individual project. However, a future goal is to integrate the research on the electric motor for electric vehicles with ongoing research regarding a flywheel based electric driveline for an All Electric Propulsion System.

Boel Ekergård, Uppsala University, Department of Engineering Sciences, Electricity, Box 534, SE-751 21 Uppsala, Sweden.

© Boel Ekergård 2013

ISSN 1651-6214
urn:nbn:se:uu:diva-207280 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-207280)
Till min kära familj
List of Papers

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


**Patent pending, not official**

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


Abbreviations and nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CVW</td>
<td>Coulomb’s Virtual Work</td>
</tr>
<tr>
<td>D1</td>
<td>Diode 1</td>
</tr>
<tr>
<td>D2</td>
<td>Diode 2</td>
</tr>
<tr>
<td>D3</td>
<td>Diode 3</td>
</tr>
<tr>
<td>D4</td>
<td>Diode 4</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IM</td>
<td>Induction Motor</td>
</tr>
<tr>
<td>MST</td>
<td>Maxwell’s Stress Tensor</td>
</tr>
<tr>
<td>PhD</td>
<td>Doctor of Philosophy</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>RM</td>
<td>Reluctance Motor</td>
</tr>
<tr>
<td>rpm</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>SBM</td>
<td>Synchronous Brushed Motor</td>
</tr>
<tr>
<td>SPM</td>
<td>Synchronous Permanent Magnet Motor</td>
</tr>
<tr>
<td>TW</td>
<td>Terawatt</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave Energy Converter</td>
</tr>
</tbody>
</table>

Quantity SI Unit Definition

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI Unit</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>m$^2$</td>
<td>Area</td>
</tr>
<tr>
<td>$A_{fe}$</td>
<td>m$^2$</td>
<td>Area of the iron section</td>
</tr>
<tr>
<td>$A_{pm}$</td>
<td>m$^2$</td>
<td>Area of the permanent magnet</td>
</tr>
<tr>
<td>$A_{ag}$</td>
<td>m$^2$</td>
<td>Area of the air gap</td>
</tr>
<tr>
<td>$a$</td>
<td>m</td>
<td>Oscillating amplitude</td>
</tr>
<tr>
<td>$\beta_\phi$</td>
<td></td>
<td>Phase angle</td>
</tr>
<tr>
<td>$\vec{B}$</td>
<td>T</td>
<td>Magnetic flux density</td>
</tr>
<tr>
<td>$B_{ag}$</td>
<td>T</td>
<td>Magnetic flux density in the air gap</td>
</tr>
<tr>
<td>$B_{fe}$</td>
<td>T</td>
<td>The magnetic flux density in the steel</td>
</tr>
<tr>
<td>$B_m$</td>
<td>T</td>
<td>The external magnetic flux</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>T</td>
<td>Maximum value of the magnetic flux density</td>
</tr>
<tr>
<td>$B_{min}$</td>
<td>T</td>
<td>Minimum value of the magnetic flux density</td>
</tr>
<tr>
<td>$B_r$</td>
<td>T</td>
<td>Remanent magnetic flux density</td>
</tr>
<tr>
<td>$B_x$</td>
<td>T</td>
<td>Magnetic flux density in x-direction</td>
</tr>
<tr>
<td>$B_y$</td>
<td>T</td>
<td>Magnetic flux density in y-direction</td>
</tr>
<tr>
<td>$C$</td>
<td>F</td>
<td>Capacitance</td>
</tr>
<tr>
<td>$c$</td>
<td>Nsm$^{-1}$</td>
<td>Linear damping coefficient</td>
</tr>
</tbody>
</table>
\( \vec{d} \) Cm\(^{-2}\) Electrical displacement field
\( d \) m Width of each stator-sheet
\( E \) J Absorbed energy
\( \vec{E} \) Vm\(^{-1}\) Electric field
\( e_i \) V Voltage source
\( f \) Hz Electrical frequency
\( \vec{F} \) N Force
\( F \) N Centripetal force
\( \vec{F}_{y,MST} \) N Force calculated by Maxwell’s stress tensor
\( \vec{F}_{y,CVW} \) N Force calculated by Coulomb’s Virtual Work
\( \vec{F}_{damp} \) N Electric damping
\( f_{res} \) Hz Resonance frequency
\( i \) A Current
\( \vec{i} \) A Current
\( j_f \) Am\(^{-2}\) The free current density
\( k \) Nm\(^{-1}\) Spring constant
\( k_{eddy} \) Sm\(^5\)kg\(^{-1}\) Eddy current loss coefficient
\( k_{exc} \) Am\(^3\)V\(^{-0.5}\)kg\(^{-1}\) Excess loss coefficient
\( k_f \) - Stacking factor
\( k_{hy} \) Am\(^4\)(V/kg\(^{-1}\)) Hysteresis loss coefficient
\( k \) Nm\(^{-1}\) Linear spring constant
\( m \) kg Mass
\( N \) - Number of turns
\( N_c \) - Number of cycles
\( \vec{n} \) - Vector to the normal plane
\( l_{pm} \) m Length of the permanent magnet
\( l_{air} \) m Length of the air gap
\( l_e \) m Length of the stator
\( l_{ps} \) m Length of pole shoe
\( L \) H Inductance
\( L_s \) H Circuit inductance
\( P_C \) W Conductor loss
\( P_{Eddy} \) W Eddy current loss
\( P_{Cu} \) -
\( P_{Fe} \) Wkg\(^{-1}\) Iron loss density
\( P_{Loss} \) Wkg\(^{-1}\) Total core loss density
\( R_{DC} \) Ω Load resistance at DC
\( R_G \) Ω Circuit resistance
\( R_s \) Ω Cable resistance
\( S \) Pa Stress
\( \hat{s} \) Wm\(^{-2}\) Poynting’s vector
\( T \) m Tolerance
\( t_d \) s Delay time
\( \mu_0 \) Vs(Am\(^{-1}\)) Permeability of free space
\( \mu_{fe} \) - Relative permeability in the steel
\( \mu_m \) - Relative permeability in the magnet
\( \mu_r \) - Relative permeability
\( v \) ms\(^{-1}\) Speed
\( \ddot{v} \) ms\(^{-1}\) Velocity
\( U \) V Voltage
\( U_L \) V Voltage over the inductor
\( U_C \) V Voltage over the capacitor
\( W_e \) Ws Energy stored in a capacitor
\( W_{electric} \) Ws Electrical energy
\( W_{field} \) Ws Energy stored in fields
\( W_{mechanical} \) Ws Mechanical energy
\( W_{loss} \) Ws Energy dissipated in losses
\( W_m \) Ws Magnetic energy
\( \dot{x} \) ms\(^{-1}\) Speed
\( \ddot{x} \) ms\(^{-2}\) Acceleration
\( \varepsilon_0 \) As(Vm\(^{-1}\)) Permittivity
\( \delta \) m Skin depth
\( \delta_w \) - Weight factor
\( \sigma \) Sm\(^{-1}\) Electric conductivity
\( \sigma_{maximal} \) m The maximum deviation
\( \sigma_{statistical} \) m The statistical deviation
\( \rho_f \) Cm\(^{-2}\) The free charge density
\( \zeta \) S\(^2\)(mkg\(^{-1}\)) Damping factor
\( \Gamma \) - Degree of rotation
\( \phi \) Wb Magnetic flux
\( \omega_0 \) Rads\(^{-1}\) Critical angular frequency
\( \omega \) Rads\(^{-1}\) Angular frequency
1. Introduction

1.1. Background

More than 83% of the energy conversion in the world is today based on fossil fuels, meanwhile scientist all over the world is debating the topic Peak Oil [1] and the secondary effects of the emissions from the fossil fuels [2,3]. As a future worldwide shortage of useful energy carrier can have devastating consequences on the political and economical stability of the world, most of us agree that the world needs to switch into a more sustainable energy system. The focus and requirement for clean and cheap renewable energy conversion techniques has therefore increased.

However, energy carrier shortage can be prevented by development of renewable energy converters as well as with increase of the energy efficiency in our society. Almost 27% of the world’s total energy conversion during 2011 occurred in the transport sector where the combustion engine represented close to 100% of the propulsion system. By replacing the fossil fuel dependent combustion engine with a high efficiency electric motor in an All Electric Propulsion System, the conditions to decrease the energy demand and increase the sustainability in the transport sector is huge [4].

1.2. Wave Power

Ocean waves are clearly carriers of great amount of energy, and over the years large efforts have been spent both by academia and industry to find and improve ways to convert electrical energy from the source. The correct amount of power available in the ocean waves close to a coastline is not possible to state, but estimations present a potential about 1 TW over the globe [5], representing 41% of the total electric power production in the world 2011.

A challenge with this energy source lies within the engineering solutions of the conversion devices. The device shall convert the wave energy into

---

1. http://www.eia.doe.gov/oiaf/ieo/highlights.html 2013-08-09
electrical energy in an economic and safe way. Numerous research groups have tried and a series of concepts have been developed over the years. Fundamental differences of the absorption are utilized, where each project and technique has to handle different questions and challenges. One of the best known is the Pelamis\textsuperscript{4}. Other projects more or less active in the recent years are The Archimedes Wave Swing\textsuperscript{5}, The WaveRoller\textsuperscript{6} and The Pico Plant\textsuperscript{7}. Historically, most projects and techniques have failed to develop a system which can withstand the ocean’s harsh climate or to find the technology cost effective. In comparison with wind- and solar-power, the development of wave power-technologies has therefore progressed slower and only recently full scale wave energy experimental sites have been up running.

1.3. Lysekil Wave Power Project

For over a decade, a research group at the Division of Electricity at Uppsala University, has developed a wave energy conversion system. The wave energy converter, WEC, consists of a direct driven linear generator installed at the seabed, connected by a line to a point absorbing buoy, illustrated in Fig. 1.1. The direct driven magnetic part of the generator, the translator, follows the motion of the heaving ocean waves. Intermediate energy storages and gearboxes are removed, believed to increase the lifetime of the system [6].

The output voltage from the linear direct driven generator varies both in amplitude and frequency. To connect the wave energy converters to the grid, an electrical conversion system is required. A marine substation, located on the ocean floor, is thereby integrated in the system [7].

\textsuperscript{4} www.pelamiswave.com 2013-08-12
\textsuperscript{5} AWS Ocean Energy, www.awsocean.com 2013-08-12
\textsuperscript{7} http://pico-owc.net 2013-08-12
The project has an experimental research site on the Swedish west coast, presented in Fig. 1.2.

The first full-scale wave energy converter was installed in March 2006 and the site has since then been continuously updated. Until the autumn of 2013, eleven different WECs and two marine substations have been deployed, where the latest wave energy converter, L12, was installed in July 2013. With the deployed units, experiments on a WEC array of three generators connected to the marine substation have been performed. The power output from each WEC was separately rectified by a passive diode rectifier and connected in parallel to a common DC-bus in the substation. After DC/AC-conversion and transformation, the electrical power was transmitted to a nearby island, Härmanö, and converted into heat in resistive dump loads [7].

In connection to the development of the WECs and the electrical system, research regarding environmental impact [8], hydrodynamics [9,10], wave resource description [11,12] measurement and control systems [11,12,13] has been carried out.

A further detailed description of the experimental work and main progress within the Lysekil Wave Power Project at the Lysekil Research Site is presented in [14].
1.4. Electric Motors in Vehicular Technology

During several years car manufacturers have developed hybrid and electric solutions for propulsion systems [15,16,17] and a detailed review of the different topologies in electric vehicles is presented in Paper X. More than 100 different electric motors topologies are utilized, resulting in a wide market of induction motors, reluctance motors, DC motors, synchronous permanent magnet motors and synchronous brushed motors. Table 1.1 presents a brief overview, most frequently utilized are motors with efficiency below 95% [18-30].

<table>
<thead>
<tr>
<th>Motor</th>
<th>Electronics</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPM</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>SBM</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>RM</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>IM</td>
<td>3.5</td>
<td>4</td>
</tr>
<tr>
<td>DC-motors</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1.1.
Relative efficiency figures of electric motors and drives, rated from 1 to 5.
Published in Paper X.

This thesis presents, together with Paper XI and Paper XII, a two pole permanent magnet motor, designed to be implemented in an All Electric Propulsion System. The geometry of the rotor is shown in Fig. 1.3, where the embedded Nd$_2$Fe$_{14}$B-magnet is located in the middle of the rotor.

![Pole-shoe](Figure 1.3. A three-dimensional view of the rotor.)
1.5. Aims of the Thesis
The introduction of this thesis stresses the requirement of finding economical renewable energy conversion techniques. Presented references ensure the potential power in the ocean waves, arguing for research regarding wave energy conversion systems. The technology developed at Uppsala University has proven the ability to convert the energy in the ocean waves and transmit the electrical energy onshore [6,7,12-14]. As the complete system evolves, the significance of the economical perspective increases, i.e. the reduction of both the material and the production cost shall have a major impact on the system’s final design. The aim of this thesis is to present a constructed linear generator developed with the above demands, further presented on a number of papers. Paper I and Paper II focuses in the developed magnetic circuit, where the Nd$_2$Fe$_{14}$B magnet is supplemented with the cheaper material, ferrite magnet. The changed magnetic circuit required a different geometrical and mechanical solution for the machine, i.e. the author has put major focus on the revised mechanical design. The aim of section 3 is to further present the scientific reasoning behind these mechanical calculations and parts of this work are summarized in Paper VI and Paper VII. The full scale design is, known to the author, the first developed linear ferrite based machine. Additionally, section 3 aims to presents the novel resonance circuit, highlighting its positive impact on the energy conversion. The first initial results are here presented and discussed, whereas a more detailed description can be found in Paper III, Paper IV and Paper V.

The introduction further argues for research regarding a high efficiency electric motor, for an all electric propulsion system. The aim of the author’s work within this area is to design and to present an electric two pole motor with a high efficiency over a wide frequency interval, presented in Paper XI and Paper XII.

1.6. Structure of the Thesis
The thesis is divided in different sections. This first chapter gives a short introduction to the wave energy and electrical motor concept studied in this thesis. The second chapter gives a theoretical background to the work, whereas the third chapter presents the analytical and numerical calculation methods as well as a deeper presentation of the experimental setups designed and used during the author’s work. Chapter four is dedicated to present a summary of the results and chapter five discusses the research. The conclusions and the future work are presented in chapter six and chapter seven, respectively. Chapter eight presents a summary of the included papers
whereas the final chapter, chapter nine, gives the reader a Swedish summary of the thesis.

The presented papers are categorized in five different groups. Paper I and Paper II focus on the ferrite based magnetic circuit, whereas Paper III, Paper IV and Paper V presents results within the resonance circuit. Paper VI and Paper VII are dedicated to the mechanical design of the developed linear generator, Paper VIII and Paper IX discuss a generator with a Nd$_2$Fe$_{14}$B magnet design whereas Paper X, Paper XI and Paper XII conclude the work within the electrical motor.

1.7. Previous Work within the Project

At the present time, The Lysekil Wave Power-project has educated twelve PhDs. A short summary of each of the twelve theses are given below, listed in order of publication.

Dr Karin Thorburn became the first doctor within the area as she defended *Electric Energy Conversion System: Wave Energy and Hydropower*, in 2006. The thesis present designs of transmission systems where electrical converters and transformers are utilized to connect a wave power farm to the electrical grid. Further, an analytical model of the induced voltage in the linear machine is derived [31].

Dr Oskar Danielsson provides the reader the design of the magnetic circuit in both the experimental generator and the first full scale offshore linear generator with the thesis *Wave Energy Converters, Linear Synchronous Permanent Magnet Generator*. An analytical model of the longitudinal end effects in a linear generator is derived, and the first verification of the numerical model is provided [32].

Dr Mikael Eriksson, became the third doctor with the thesis *Modelling and Experimental Verification of Direct Drive Wave Energy Conversion. Bouy-Generator Dynamics*. The thesis focus on the wave-buoy-generator interaction, and the first modelling of a wave energy converter in operation is presented and verified with experimental data [33].

Dr Rafael Waters investigates and presents the results from the first full scale offshore linear generator in *Energy from Ocean Waves. Full Scale Experimental Verification of a Wave Energy Converter*. Further a wave climate study on the Swedish west coast is presented [34].
Dr Olivia Langhamer focuses on the main biological impact from a wave power farm in her thesis *Wave Energy Conversion and the Marine Environment: Colonization patterns and habitat dynamics* [8].

Dr Magnus Rahm defended his thesis *Ocean Wave Energy: Underwater Substation System for Wave Energy Converters* in the spring of 2010, where the design of a marine substation is presented. Results from offshore experiments with three linear generators connected to the marine substation are provided [35].

Dr Cecilia Boström focuses on the electrical conversion of the output voltage in her thesis *Electrical systems for wave energy conversion*. The aims of the presented studies are to investigate the output power at different linear and non-linear electrical damping strategies [36].

Dr Jens Engström studies the energy transport of ocean waves and develops the wave-buoy-generator interaction models, presented in [33], in his thesis *Hydrodynamic Modelling for a Point Absorbing Wave Energy Converter*. Dr Engström further presents the theory behind a two-body system and the first results from a simulation model [9].

Dr Simon Lindroth presented *Buoy and Generator Interaction with Ocean Waves* in the late autumn of 2011. An optical measuring instrument is utilized to investigate the motion of the buoy relative the generator and the ocean surface [37].

Dr Andrej Savin defended his thesis *Experimental measurement of lateral force in a submerged single heaving buoy wave energy converter* in the winter of 2012. The thesis presents offshore measurements of the external forces acting on the hull as well as a detailed study of the inclination angle between the buoy and the linear generator. The results are used both for verifications of analytical and numerical models and provides important information during the design process of upcoming generators [38].

Dr Erland Strömstedt became the eleventh doctor within wave energy as he defended his thesis *Submerged Transmission in Wave Energy Converters* in the autumn of 2012. The thesis focuses on a measurement system, implemented in a linear wave energy converter to measure small relative displacements within the machine [39].

Dr Olle Svensson’s focus lies in on- and offshore measurement system. The presented results in the thesis *Experimental results from the Lysekil Wave Power Research Site* highlight the difference between the peak and average force amplitude in the system [40].
2. Theory

The aim of this chapter is to give the theoretical background to the different areas presented in the thesis. The three first sections concern electric machine theory, where energy conversion, losses and material parameters are discussed. The fourth section presents electric resonance and finally, the fifth section provides theory within the research area solid mechanic.

2.1. The Electromechanical Energy Conversion

The principle of an electric generator is to convert mechanical energy, fed from an external system, to electrical energy. The two most important components of a generator are the stationary part, the stator, and the moving magnetic part, the rotor or, alternatively, the translator. The stator consists of thin silicon steel sheets, assembled in an external frame, and holds the generator’s winding. The rotor, respectively the translator, is connected to the rotating/linear shaft, supplying the mechanical energy. The stator is separated from the magnetic part by a well-defined distance, the air gap. Figure 2.1 illustrates a cross-section of both a linear and rotating generator as well as defines the different components and directions.

Figure 2.1. A rotating and a linear electric machine. Notice the introduced notations and directions.
2.1.1. Maxwell’s Equations
As written previously, the operation principle of an electric generator is to convert mechanical energy, fed from an external system, to electrical energy. If the losses in the machine are neglected, the energy conversion is reversible and the electrical energy can be converted back into mechanical energy. The primary equation for the electromechanical energy conversion in generator mode is defined as:

\[ \Delta W_{\text{mechanical}} = \Delta W_{\text{electric}} + \Delta W_{\text{field}} + \Delta W_{\text{loss}} \]  \[ \text{[Ws]} \]  (2.1)

\( W_{\text{mechanical}} \) represents the mechanical energy, \( W_{\text{electric}} \) is the electrical energy, \( W_{\text{field}} \) is the energy stored in the electromagnetic field and \( W_{\text{loss}} \) presents the energy dissipated in losses. The term \( W_{\text{field}} \) plays a central and important role in the electromechanical energy conversion process as the magnetic field acts as a coupling phase between the mechanical and the electrical energy.

The theory of the electric and magnetic field behavior and the energy conversion is stated in well-known Maxwell’s equations:

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  \[ \text{[Ts}^{-1}] \]  (2.2)

\[ \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \]  \[ \text{[Am}^{-2}] \]  (2.3)

\[ \nabla \cdot \vec{D} = \rho_f \]  \[ \text{[Cm}^{-2}] \]  (2.4)

\[ \nabla \cdot \vec{B} = 0 \]  \[ \text{[-]} \]  (2.5)

Equation 2.2 presents Faraday’s law of induction, described for the first time the relationship between the magnetic flux density, \( \vec{B} \), and the electric field, \( \vec{E} \), in year 1840. By rewriting the equation with Stoke’s theorem, analytical calculations of the induced voltage in an electric circuit can be performed, presented as Eq. 2.6.

\[ U = -N \frac{d\Phi}{dt} \]  \[ \text{[V]} \]  (2.6)

where \( U \) represents the induced voltage, \( N \) is number of turns and \( \frac{d\Phi}{dt} \) presents the time-dependent magnetic flux. Equation 2.3, Ampere’s law, states the curl of the magnetic field strength, \( \vec{H} \), is equal to the sum of the
time derivative of the displacement field, $\ddot{\rho}$, and the free current density, $\dot{J}_f$, and Eq. 2.4, *Gauss’s Electric law* relates the free charge distribution, $\rho_f$, with the electric displacement field. Equation 2.5, *Gauss’s Magnetic law*, states that the divergence of the magnetic flux density, $\vec{B}$, is zero [41].

### 2.1.2. Magnetic Circuit

The following section is presented using conventional notations for linear electric machines, as defined in Fig. 2.1.

An expression for the magnetic circuit in a permanent magnet electric machine is defined as:

$$\int Hdl = \int \frac{B_m - B_r}{\mu_0 \mu_m} dl_{pm} + \int \frac{B_{fe}}{\mu_0 \mu_{fe}} dl_{fe} + \int \frac{B_{ag}}{\mu_0} dl_{ag} = 0 \ [A] \quad (2.7)$$

where $B_m$, $B_r$, $B_{fe}$ and $B_{ag}$ are the magnets external magnetic flux, the remanence term, the magnetic flux density in the steel and in the airgap respectively, $l_{pm}$, $l_{fe}$ and $l_{ag}$ present the length of the distance in the magnet, in the steel and in the air gap, $\mu_m$ and $\mu_{fe}$ represent the relative permeability of the magnet, respective, the steel and $\mu_0$ is the permeability in vacuum. From Eq. 2.7 and with knowledge of the geometric dimensions and material parameters in the magnetic circuit, the magnetic field density in the air gap, $B_{ag}$, and the magnetic energy density, $W_m$, in the air gap are defined as: [41]

$$B_{ag} = \frac{B_r l_{pm}}{\mu \left( l_{air}^{-1} \left( \frac{l_{air} A_{ag}}{\mu_{air} A_{ag}} \right) + \left( \frac{l_{pm} A_{ag}}{\mu_{pm} A_{pm}} \right) \right)} \quad [T] \quad (2.8)$$

$$W_m = \frac{B_{ag}^2}{2 \mu_0 \mu_r} \quad [\text{Ws m}^{-3}] \quad (2.9)$$

where $A_{ag}$, $A_{fe}$ and $A_{pm}$ represent the different cross-section areas. A variation of the energy density results in a magnetic force. Several methods, for example *Maxwell’s Stress Tensor*, $\vec{F}_{x,MST}$, [42] and *Coulomb’s Virtual Work*, $\vec{F}_{x, CVW}$, [43] can be utilized to determine the amplitude of this force.

$$\vec{F}_{x, MST} = \iint \frac{1}{2 \mu_0} (B_x^2 - B_y^2) \vec{y} dA + \iint \frac{1}{\mu_0} (B_x B_y) \vec{x} dA \quad [N] \quad (2.10)$$
\[ \vec{F}_{y,CW} = \frac{dW_m}{dy} \quad [N] \quad (2.11) \]

where the terms \( b_x \) and \( b_y \) represent the \( x \)-component and \( y \)-component of the magnetic flux density and \( A \) is the investigated area.

2.1.2.1. Differences of a Linear and Rotating Machine

Although the magnetic circuit of a linear and a rotating generator is very similar, there is one fundamental difference – the linear generator is open in both longitudinal ends, causing a non-linear magnetic circuit.

The flux from one magnet in a rotating machine follows the stator teeth and divides into two, more or less equal, flux path in the stator yoke. The magnets are said to be *equally coupled* and an even flux distribution in the stator and the rotor is achieved. However, in a linear machine the outermost magnet has only one return path through the stator, i.e. the two outermost magnets are *pairwise coupled*. As the translator moves and the outmost magnet slips in or out of the stator, the magnets change their coupled partners. A change of the flux component in the translator, not existing in the rotor in a rotating machine, appears. The time-dependent flux component induces eddy currents in the non-laminated translator with the drawbacks of both decreasing efficiency and optionally thermal issues [44].

Studies of the longitudinal ends static impact with both linear [44] and non-linear [45] reluctance models have previously been presented in the literature. In Ref. [46], a dynamic model where the longitudinal ends effects are presented as a second magnetic wave within the air gap is presented, whereas [47,48] include the end effects by introducing an end effect factor during the dynamic calculations. In Ref. [49], the space harmonic analysis is utilized for further studies the secondary effects of the longitudinal ends.
2.2. Losses in an Electric Machine

In the following section all parameter are presented in conventional notations for rotating electric machines, defined in Fig. 2.1.

Electric machines suffer from electromagnetic and mechanical losses. In this thesis, the author has chosen to focus only on the electromagnetic losses; i.e. mechanical losses are omitted.

The electromagnetic losses influence the electric machine in primarily four different ways. The first, most obvious is the decreasing efficiency. Second, the thermal problems can damage the machine. Third, the magnetic field from the induced eddy currents can counteract the main magnetic field in the magnetic circuit and the fourth; the force resulting from the interaction of the main and reaction field from the eddy currents can cause mechanical problems. Investigations and high accuracy calculations of the losses are thus of great interest at the design stage of the machine. [50]

2.2.1. Losses in a Conductor

The losses in a conductor, \( P_c \), combines the resistive and the eddy current losses in the conductor, induced by the time depending magnetic flux density inside the conductor, originated from current in the conductor itself, current in nearby conductors and the machine’s main magnetic circuit. In a symmetric three phase machine, the losses can be written as:

\[
P_c = 3R_s I^2 + P_{Cu}^{Eddy} \quad \text{[W]} \quad (2.12)
\]

where \( R_s \) is the cable resistance, \( I \) is the current and \( P_{Cu}^{Eddy} \) denotes the eddy current losses in the conductors [50, 51].

2.2.2. Iron losses

Iron losses in laminated steel-sheets are divided into eddy current losses, hysteresis losses and excess losses and can be calculated as:

\[
P_{Fe} = k_f k_{eddy}(Bf)^2 + k_f k_{hy} B^2 f + k_f k_{exc} (Bf)^{1.5} \quad \text{[Wkg}^{-1}] \quad (2.13)
\]

where \( k_f \) is the stacking factor, \( k_{eddy} \) is the eddy current loss coefficient, \( k_{hy} \) is the hysteresis loss coefficient, \( k_{exc} \) is the excess loss coefficient, \( B \) is the magnetic flux density and \( f \) is the frequency. The hysteresis and excess losses coefficients are specified by the steel manufacturer [51].
2.2.2.1. Eddy Current Losses

In order to reduce the eddy current loss and its induced reaction field, the stator of an electrical machine is laminated, i.e. assembled by thin stator-sheets. Within the laminated design, the eddy currents are constrained by the absent of space and high resistivity and are greatly reduced in magnitude. The current are known as resistance-limited and the eddy current loss coefficient can be calculated as [50]:

\[ k_{\text{eddy}} = \pi^2 \frac{\sigma d^2}{6} \quad [\text{Sm}^4 \text{kg}^{-1}] \quad (2.14) \]

where \( \sigma \) is the conductivity and \( d \) is the steel thickness. To obtain a fulfilled lamination the width of each sheet shall not be thicker than half the skin depth, \( \delta \), of the eddy current, defined as:

\[ \delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}} \quad [\text{m}] \quad (2.15) \]

where \( \omega \) is the angular frequency, \( \sigma \) is the conductivity of the steel, \( \mu_0 \) is the permeability in vacuum and \( \mu_r \) represents the relative permeability of the steel [52].

In a design where the material thickness is larger than the skin depth, the induced eddy current distribution is limited by its own magnetic field rather than by lack of space and high resistivity as in a laminated design. The currents are known as inductance-limited and thereby cannot be calculated by Eq. 2.13 and Eq. 2.14. Different theories have been developed to calculate analytically the size of these losses; for example F. W. Carter, Lawrenson and Gibbs [53-55]. Gibbs’ theorem has been applied in the presented work. The theorem states that the non-sinusoidal flux density wave can be approximated to one dimensional and the reaction field from the induced eddy currents can be ignored [55,56]. For more information about Gibbs’ theory, see [55,56], where the analytical calculations have been verified with both experimental and numerical calculations at different levels of saturation.

2.2.2.2. Correction Term

In the chosen simulation tool, the iron losses are based on parameters from the Epstein Square loss data test. The iron losses estimations, obtained by Eq. 2.13, include therefore only the iron losses from the flux change in the radial direction. However, the flux density wave form in the stator is often partially bidirectional, i.e. the wave form is explained in both a radial and tangential components; presented in Fig. 2.2.
To include the core losses from the tangential component, a correction term, presented in Eq. 2.16 and Eq. 2.17 has been included in the calculations:

\[ P_{\text{Loss}} = (1 + \delta_w \Gamma) \cdot (k_f k_{\text{eddy}} B_f^2 + k_f k_{\text{eddy}} B_f^2 f + k_f k_{\text{exc}} B_f^{1.5}) \] \[ \text{[Wkg}^{-1}\text{]} \] \hspace{1cm} (2.16)

where \( \delta_w \) is the weight factor and \( \Gamma \) represents the degree of rotation, defined as the ratio of the flux density:

\[ \Gamma = \frac{B_{\text{min}}}{B_{\text{max}}} \] \hspace{1cm} [-] \hspace{1cm} (2.17)

The weight factor, \( \delta_w \), can be approximated to the fix value of 0.6 in materials where the magnetic field density is high [57]. The author has applied this constant, partly because data for rotational loss in the material are not available and partly due to high flux density in the investigated parts.

2.3. Energy Flow in the Machine

It is possible to obtain and calculate many different quantities from Maxwell’s equations. As presented in Section 2.1 the magnetic force, magnetic energy and the conversion between electric and magnetic energy, can be found. Field theory can further provide expressions to derive the converted power. Poynting’s vector, \( \vec{S} \), describes the power flowing through a surface, into a volume in terms of the electric, \( \vec{E} \), and the magnetic field \( \vec{H} \) [58].

\[ \vec{S} = \vec{E} \times \vec{H} \] \hspace{1cm} [Wm\text{-}^{-2}] \hspace{1cm} (2.18)

The vector gives an important and valuable picture of the power flow inside the machine.
2.4. Electric Resonance

Electric resonance is a phenomenon occurring in an electrical circuit as the magnetic energy in an inductor, $W_M$, and the electrical energy in a capacitor, $W_C$, are equal in magnitude. The energy storage in the circuit shall then be maximal, with the energy flowing back and forth, converted between magnetic energy in the inductor and electrical energy in the capacitor. Figure 2.3 presents an electrical circuit during electric series resonance, where $e_i$ is the voltage-source, $R_G$ represents the circuit resistance, $L_s$ is the circuit inductance and $C$ is the total value of the capacitance.

$U_L$ and $U_C$ are equal in magnitude, with a phase shift of 180° electrical degrees. The circuit reactance term converges to zero, i.e. the current $i$ becomes purely resistive. If the resistive part of the circuit impedance is small, the current becomes many times greater during the resonance scenario, resulting in a high voltage over the inductor [59]:

$$U_L = \frac{d\Phi}{dt} = L_s \frac{di}{dt} \quad \text{[V]} \quad (2.19)$$
2.5. Solid Mechanics
The behavior and deformation of materials during action of forces, stresses related to temperature changes and other external and internal scenarios are defined within solid mechanics research. This section gives a brief summary of the theory used during the author’s work.

2.5.1. Fatigue
The structural damage which can occur when a material is subjected to cyclic loading is known as fatigue. General dimension methods have been developed and a well-known theory, utilized by the author, focuses on the nominal stress required to cause a fatigue failure of the material after a number of cycles. This test result is presented as the S-N curve, that plots the stress, $S$, versus the number of cycles to failure, $N$ [60].

2.5.2. Reaction and Delay Time
The solution for a driven damped harmonic oscillation is written as:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t)$$

where $x$ is the amplitude of the oscillation, $F$ is the external force, $m$ is the mass, $k$ is the linear spring constant and $c$ defines the linear damping coefficient respectively.

As an incoming body meets a harmonic oscillator, the incoming body mechanical energy is partly absorbed by the oscillator. During this energy absorption, the motion of the oscillation is equal to zero, i.e. the motion has a delay-time, illustrated in Fig. 2.4.

![Figure 2.4. The oscillation and the introduced delay-time.](image-url)
To calculate the delay time, material parameters and the system parameters has to be known. A short summary of the calculations follows below.

The linear damping coefficient, $c$, is calculated via the energy-absorption, $E$, the oscillations amplitude $x$ and the system’s angular frequency $\omega$.

$$c = \frac{E}{\pi x^2 \omega} \quad [\text{Nsm}^{-1}] \quad (2.21)$$

The damping factor, $\zeta$, is defined as:

$$\zeta = \frac{c}{2\sqrt{km}} \quad [s^2(\text{mkg})^{-1}] \quad (2.22)$$

where $m$ is the system mass and $k$ is the spring constant. The phase angle $\beta$ is found with the oscillation’s angular frequency, $\omega$, and the system’s critical angular frequency, $\omega_0$:

$$\tan \beta = \frac{2\zeta \omega / \omega_0}{1-(\omega / \omega_0)^2} \quad [^\circ] \quad (2.23)$$

The time delay for the oscillating system is then obtained with the formula

$$t_d = \frac{\beta}{2\pi} t \quad [\text{s}] \quad (2.24)$$

where $t$ presents the oscillation’s time period [61-63].

If an incoming body shall be damped by a harmonic oscillator, an instant reaction of the oscillator is required to avoid an large deceleration and a high impulse force, i.e the delay time shall be minimized.
2.5.3. Tolerances

As mechanical parts are assembled together, the different parts deviations accumulates, and the final product dimensions will vary. Performing tolerance analysis of the assembled part provides a clear idea of the complete system and enables to conclude whether the possible tolerance drawbacks are too large or manageable.

Popular models used during tolerance analysis are the Worst Case- and the Statistical Analysis, presented briefly below [64].

2.5.3.1. Worst-Case Analysis

The individual variables tolerance limit, $T_i$, are summed as presented in Eq 2.25 in order to make the deviation, $\sigma_{\text{max,imum}}$, as large as possible.

$$\sigma_{\text{max,imum}} = \sum |T_i| \quad [\text{m}] \quad (2.25)$$

2.5.3.2. Statistical Analysis

The estimation of the deviation, $\sigma_{\text{statistical}}$, adds the value of the tolerance, $T$, as presented in Eq. 2.26.

$$\sigma_{\text{statistical}} = \sqrt{\sum \left( \frac{T_i}{3} \right)^2} \quad [\text{m}] \quad (2.26)$$

The result is more likely the reality, since the equation considers the statistical deviation of different combinations.
3. Method

All projects at the Division of Electricity at Uppsala University are divided in number of steps. Analytical and numerical calculations give the foundation to the modelling and laboratory verifying tests, leading to full-scale experiments. The thesis presents results and conclusion based on both analytical and numerical calculations as well as experimental results. The following chapter describes the calculation methods and the background as well as the scientific reasoning during the design of the experimental setups.

3.1. Electric Machine Modelling

In order to simulate the electric machine’s performance at different electrical load conditions, electromagnetic simulations utilizing FEM has been done. The electric and magnetic field within the machine is assumed to be axi-symmetrical and is therefore modelled as a two dimensional object. Three-dimensional effects such as end region fields are taken into account by introducing coil end impedances in the circuit equations of the windings. The mechanical parts are assigned with different material properties such as permeability, conductivity, sheet thickness, density etc. The mesh is finer close to more interesting parts like the air gap and coarser in areas such as the back iron of the stator. The permanent magnet is modelled by a surface current source. [65]

Simulations can be performed either in a stationary mode where the results are given for a fixed rotor alternative translator position or in a dynamic mode including the time-dependence movement of the rotor alt translator. The numerical calculations have previously been verified with experimental results for different generators [66-69], and are further described in Paper XI.

A numerical simulation tool is further used in order to simulate the mechanical behaviour of electric machines at different mechanical load conditions. The numerical simulation tool works with three-dimensional models, combined of one or more component. Simulations can be performed
either in a stationary mode where the results are given for a fixed load, or dynamical mode including fatigue. The designer defines the mesh for each part separately.

To model a larger part of the energy conversion system, i.e. the electric machine and the electric conversion as presented in Paper V, models are implemented in the simulation tool Matlab/Simulink.

3.2. Experimental Setup and Experiments

The purpose with the experimental setups is to develop the technology and calibrate and verify the analytical and numerical calculations. The following sections present the challenges and reasoning behind the presented experimental setup designs.

During the different full scale experiments oscilloscopes\(^8\) and probes\(^9\) were used to record the electrical output parameters.

3.2.1. The Linear Wave Energy Converter L12

Focus during the author’s work within the linear wave energy converter L12 has been:

- The electromagnetic design
- The mechanical design

and is further presented in Paper I, Paper II, Paper VI and Paper VII.

3.2.1.1. Background

In one of the first publications within the Lysekil Wave Power Project, Danielsson et al [70] presents a comparative study between a ferrite design and a rare-earth metal Nd\(_2\)Fe\(_{14}\)B design. The study concluded similar magnetic properties and the decisive parameter became the economical difference, at the time (2003) favoured Nd\(_2\)Fe\(_{14}\)B. Similar studies have been presented within other wave power projects [70-73], linear motors [74,75] and rotating wind power generators [76-78]. The general conclusion favours the Nd\(_2\)Fe\(_{14}\)B-designed magnetic circuit, and the ten first wave energy converters within the Lysekil Wave Power Project have a Nd\(_2\)Fe\(_{14}\)B-magnets circuit design.

However, an extreme price increase of Nd\(_2\)Fe\(_{14}\)B has occurred during the last five years, the debate regarding the environmental aspects of rare-earth metal

\(^8\) TDS 2024 Tetrionix
\(^9\) Voltage probe Tektronix P2220
is louder as well as an unstable political situation as 97% of all mining currently occurs in China [79]. These circumstances convinced us to investigate the alternative and to replace the Nd$_2$Fe$_{14}$B magnets with ferrites. During 2012-2013, the first full scale prototype was designed and constructed. As the generator is the twelfth prototype, the name of the wave energy converter became L12.

Figure 3.1 illustrates an overview of L12 whereas Table 3.1 presents the main dimensions of the machine. The stator and translator is divided in three sections, where each section represents one phase. Each section is in turn divided in three sides, illustrated in Fig. 3.2, i.e. the generator is a nine side-construction.

![Figure 3.1. An overview of the machine.](image1)

![Figure 3.2. The nine side-construction.](image2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull [mm]</td>
<td>6000</td>
</tr>
<tr>
<td>Translator [mm]</td>
<td>3000</td>
</tr>
<tr>
<td>Stator [mm]</td>
<td>1976</td>
</tr>
<tr>
<td>No of Stator Phases</td>
<td>3</td>
</tr>
</tbody>
</table>
3.2.1.2. Magnetic Design

Figures 3.3-3.4 present an overview of the magnetic circuit whereas Table 3.2 presents the main material parameters and dimensions.

![Figure 3.3. The magnetic circuit, designed with pole shoes and ferrite.](image1)

![Figure 3.4. The introduced definitions.](image2)

Table 3.2.
The dimension and material parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_r ) [T]</td>
<td>0.45</td>
</tr>
<tr>
<td>( H_c ) [kA/m]</td>
<td>330</td>
</tr>
<tr>
<td>( l_{mg} ) [mm]</td>
<td>3</td>
</tr>
<tr>
<td>( l_{pp} ) [mm]</td>
<td>19</td>
</tr>
<tr>
<td>( L_{ps} ) [mm]</td>
<td>15</td>
</tr>
<tr>
<td>Pole_width [mm]</td>
<td>35</td>
</tr>
</tbody>
</table>

The choice of a cable wound design is done with the physical statement completed by Maxwell and Poynting. B. Bolund, [58], presents a detailed study of the electric and magnetic stresses on different shapes of conductors, all with strongly benefits of the circular design. The 1 mm thick PVC insulation enclosing the copper strands, is short time tested with a dielectric strength up to 40 kV and can continuous withstand a temperature up to 70°C\(^{10}\).

\[10\] Draka Kabel, www.draka.se 2011-11-22
To gain further knowledge and understanding of the material parameters and different areas/dimensions impact on the specific magnetic circuit of L12, the author derived an analytical expression of the B-field in the air-gap, \( B_{ag} \). With help of Ampere’s and Gauss’s laws and assuming constant width between the stator and the translator, following expression was stated:

\[
B_{ag} = \frac{B_T l_{pm} A_m}{2 \pi l_{agt} + 2 \pi (\frac{A_{agI} l_{agII}}{\mu_0 A_{agII}} + \frac{A_{agI} l_s}{\mu_0 \mu_s A_s} + \frac{A_{agI} l_{ps}}{\mu_0 \mu_{ps} A_{ps}})} \text{[T]} \tag{3.1}
\]

where \( \mu_0 \) represents the permeability, \( \mu_r, \mu_m, \mu_s \) and \( \mu_{ps} \) represent the relative permeability of each part, whereas \( A_{ag}, A_{agII}, A_{ps}, A_s \) and \( A_{pm} \) represent the different cross-section areas. The length parameters \( l_{pm}, l_{ag}, l_{agII}, l_{fe} \) and \( l_{ps} \) are defined in Fig. 3.4.

### 3.2.1.3. Mechanical Design

As the complete system develops, the economical perspective and signification increases, i.e. reduction of both material and production cost had a major impact on the generator’s final design. In order to achieve these cost-reductions without decrease of the power plants sustainability, the forces exposed to and within the generator have to be estimated in an accurate way.

This section presents the fundamental, primary theory and reasoning behind the mechanical design.

#### 3.2.1.3.1. The Hull

The installed and operating wave energy converter is continuously subjected by loads from the buoy, the electromagnetic energy conversion and magnetic circuit, resulting in both horizontal and vertical forces on the machine’s hull, illustrated in Fig. 3.5.
The hull shall be dimensioned to withstand these forces without harm any mechanical parts.

3.2.1.3.2. Upper End Stop
The direct driven magnetic part of the generator, the translator, follows the motion of the heaving ocean waves. An assumption of a sinusoidal motion, \( x \), of the wave, gives the velocity, \( \dot{x} \), of the translator:

\[
x = \frac{H_s}{2} \sin(\omega t) \quad \text{[m]} \quad (3.2)
\]

\[
\dot{x} = \frac{H_s}{2} \omega \cos(\omega t) \quad \text{[ms\(^{-1}\)]} \quad (3.3)
\]

\( H_s \) represents the significant wave height whereas \( \omega \) states the translators angular frequency.

As the translator hits the spring with the velocity, \( \dot{x} \), the spring compressed and its reaction force, \( F_{spring} \), exposes the buoy for a greater downward force. The buoy submerges further down in the water, presented in Fig. 3.6, and a relative motion between the surface and buoy is obtained, an important parameter when the upper end stop shall be designed.

![Figure 3.6. The partially submerged buoy at two different moments.](image)

To ensure a stable and proper design of the mechanical system and to avoid a great impulse force on the hull, the upper end stop shall be designed to smoothly decrease the velocity of the translator.
3.2.1.3.3. Snap Load
Due to the irregular motion of the ocean surface, two most likely scenarios are presented in Fig. 3.7. The line goes from slack to tense in a short moment, i.e. the line and its connection is exposed to a so called *snap load* and exposes of a high impulse force.

![Figure 3.7. Scenarios creating snap loads.](image)

To decrease the amplitude of this impulse force on the system, a rubber damper is installed in the buoy, presented in Fig. 3.8. The damper is implemented to increase the deceleration time, and thereby decrease the impulse force.

![Figure 3.8. The rubber damper in the buoy.](image)

To achieve a correct function of the device, i.e. to avoid the snap load’s large deceleration and upcoming impulse, an instant reaction of the rubber is required.
3.2.1.3.4. Internal Forces

As the translator magnetizes the stator, an attractive force between the stator and translator occurs. The fixture and back iron of the stator shall be dimensioned to withstand this force.

The symmetry of the generator’s design shall in the ideal case eliminate the resulting magnetic forces on the translator. However, in reality, a small displacement of the translator relative to the stator is expected as tolerances in all mechanical parts are more or less impossible to avoid. With different length of the air gap, illustrated in Fig. 3.9, the magnetic flux density and the magnetic force differs from width to width.

The mechanical design of the generator shall therefore be dimensioned for a non-zero resulting horizontal magnetic force, i.e. support structure between the stator and translator is required.
3.2.1.4. Summary of the Assembling of the Experimental Setup

During the development of L12, the assembling was taking into account. This section presents a brief summary of the assembling methods, developed during the design progress of L12.

3.2.1.4.1. The Stator

As written in Section 3.2.1.1, the nine-sided generator is divided into three sections, one for each phase. These stator-sections are wound straight, in line, presented in Fig. 3.10. To achieve the angle between the different stator-sides, the sections are folded relative each other before installation in the stator fixture, presented in Fig. 3.11.

Figure 3.10. A wound stator-section, before and after it has been folded.

Figure 3.11. The stator-section, installed in the stator fixture.
3.2.1.4.2. The Translator
The translator composes of pole shoes and ferrite magnets, shown in Fig. 3.12. Different tools are included in the design to reach the required dimensions and to keep the magnets in place.

Figure 3.12. The translator.
3.2.1.4.3. *The Complete Assembling*

The final assembling of the hull and installing of the translator in the stator is shown in Fig. 3.13 whereas Fig. 3.14 presents transportation of the linear generator out of the warehouse and down to the harbor. All pictures presents the first L12, deployed the 12th of March 2013.

Figure 3.13. A collage of the installing of the translator and welding of the hull.

Figure 3.14. To the harbor.
3.2.2. The Resonance Circuit

The aim of this section is to present an electrical conversion system based on the electric resonance phenomena, further presented in Paper III, Paper IV and Paper V.

3.2.2.1. Background

The use of direct driven generators for energy conversion from renewable energy sources have increased during the past years. The robustness and longer expected lifetime compared to systems including gearbox or a hydraulic device is one of the reasons. However, a consequence of the choice to work with a direct-driven permanent magnet generator design is the continuously amplitude- and frequency- varying output voltage from the machine. To connect the wave energy converters to the electrical grid, an electrical conversion system is therefore required. Figure 3.15 presents the circuit layout of the electrical system, installed in a marine substation, utilized until now, including passive diode rectifier, filter, a two-level IGBT-inverter and a transformer [7].

![Figure 3.15. The implemented electrical schedule.](image)

Hence, the generator is electrical damped by a non linear load.

3.2.2.2. Electrical Damping

If the electrical damping, $F_{damp}$, in the generator increases, an increased output power is reached:

$$ P = F_{damp} \cdot \dot{v} = UI \quad [W] \quad (3.4) $$

where $\dot{v}$ is the translator’s velocity, $U$ and $I$ represent the voltage and current output of the machine.

Experiments performed with the WEC connected to non-linear load presents an increased electrical damping of the generator as the value of the load decreases, i.e increasing the current with a decreasing output voltage [36].
A damping approach with high currents and low voltages is however not optimal in the wave power system, as it gives large losses. The winding in a generator is an inductor, a coil. The value of the winding inductance depends on the winding distribution, the magnetic circuit geometry and the material properties in the magnetic circuit. A way to increase the electrical damping and at the same time still generate a high voltage can be by achieving electrical resonance with the generator and an external circuit, as the reactance term then diverges to zero. A pure resistive current, $I$, is then drawn from the generator, resulting in a high voltage over the winding inductance, as presented in Eq. 2.19.

If external capacitors are integrated in the rectifier, illustrated in Fig. 3.16, an electrical resonance between the capacitors and the generators winding can be achieved.

For better understanding the novel resonance circuit, experimental tests with a single phase linear generator connected to the resonance circuit has been performed. To have full control and be able to perform the experiment as required, the test with the full-scale linear generator was performed onshore. The translator was connected to a crane, lifting the translator up and down through the stator, illustrated in Fig. 3.17, whereas Table 3.3 presents the generators main parameters.
Figure 3.17. The generator used during the experiments.

Table 3.3.
Main parameters of the generator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator resistance $R_g$ [Ω]</td>
<td>1.5</td>
</tr>
<tr>
<td>Generator inductance $L_g$ [mH]</td>
<td>30</td>
</tr>
<tr>
<td>Pole width [mm]</td>
<td>27</td>
</tr>
<tr>
<td>Air Gap [mm]</td>
<td>3</td>
</tr>
<tr>
<td>Stator Length [mm]</td>
<td>1200</td>
</tr>
<tr>
<td>Translator Length [mm]</td>
<td>2200</td>
</tr>
</tbody>
</table>
3.2.3. Electrical Motor for Variable Speed Operation

Focus during the author’s work within the electric motor has been:

- The electromagnetic design
- The mechanical design

and is further presented in Paper XI and Paper XII.

3.2.3.1. Background

Ongoing related research [4] argues for a relatively small power rating on the motor, and the electrical frequency at rated voltage is selected with the motor directly driven, alternative with a differential with low ratio, to a small vehicular wheel in mind. If a high efficiency over a wide frequency interval can be reached together with the ability to utilize the electric motor’s capability to develop significant torque at low electrical frequency, the gearbox can be removed from the system. The total efficiency and mechanical stability of the system can therefore be increased.

The geometry of the rotor is illustrated in Fig. 3.18, presenting an embedded permanent magnet, located between the pole shoes.

Figure 3.18. The rotor with the magnet embedded in between the two pole-shoes.
The main dimensions of the motor are presented in Table 3.4.

Table 3.4.
Main dimension of the machine. Published in Paper XI.

<table>
<thead>
<tr>
<th>No of Stator Phases</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slots/Pole and Phase</td>
<td>7</td>
</tr>
<tr>
<td>Coil Pitch</td>
<td>18</td>
</tr>
<tr>
<td>Outer Stator Radius [mm]</td>
<td>165</td>
</tr>
<tr>
<td>Outer Rotor Radius [mm]</td>
<td>75</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>180</td>
</tr>
<tr>
<td>Stator steel</td>
<td>M250-35A</td>
</tr>
<tr>
<td>Specific loss density for M250-35A</td>
<td>2.35 W/kg at 1.5 T</td>
</tr>
<tr>
<td>Air gap</td>
<td>5 mm</td>
</tr>
<tr>
<td>Cable dimension [mm²]</td>
<td>16</td>
</tr>
</tbody>
</table>

3.2.3.2. Electromagnetic Design

Fig. 3.19 presents an overview of the magnetic circuit whereas Table 3.5 presents the design case of the motor.

Figure 3.19. An overview of the design.
The choice to work with a cable wound design is done on the same bases as with the linear generator, discussed in Section 3.2.1.2.

As presented in Paper XI, negligible core losses in the rotor and simplification in the mechanical design argued for construct the pole shoes in solid, not laminated, steel.

### 3.2.3.3. Mechanical Design

A brief summary of the mechanical design is provided here.

#### 3.2.4.2.1. The Critical Speed

As the rotor rotates, heavy oscillations achieves at one of more rotational speed, illustrated in Fig. 3.20, known as the mechanical resonance frequency and its multiples.

![Pole shoe, Magnet, Support structure](image)

**Table 3.5.**
Design cases for the simulated motor. Published in Paper XI.

<table>
<thead>
<tr>
<th></th>
<th>No load</th>
<th>Full load</th>
<th>100 % over load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [kW]</td>
<td>0</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>Current density [Amm⁻²]</td>
<td>0</td>
<td>3.3</td>
<td>6.6</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Power Factor</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Load angle [°]</td>
<td>0</td>
<td>20.8</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure. 3.20. The structure at the resonance frequency. Not drawn to scale.
These critical mechanical frequencies must be found and kept away from to avoid mechanical breakdown. Moreover, both the stator and rotor fixture shall be designed to withstand the attractive magnetic force, Eq. 2.10-2.11 and the centrifugal force, $F_c$:

$$F_c = me\omega^2 \ [\text{N}] \ (3.5)$$

where $m$ is the rotating mass, $e$ presents the distance from mass-centrum to the rotational axis and $\omega$ is the angular frequency [60].

3.2.3.4. Summary of the Assembling of the Experimental Setup

Figure 3.21 presents the assembled rotor and its support structure.

![Figure 3.21. A collage of the up to now constructed parts.](image)

The work concerning the electric motor is so far an individual project. A future goal is to integrate the research on the electric motor for electrical vehicles with closely related ongoing research regarding a flywheel based electric driveline for electric propulsion system [4, 81-84].
4. Summary of Results

This section presents a summary of the results from the author’s most dedicated work. The main dimensions of the presented electrical machines are found in Chapter 3, Table 3.1 and Table 3.4.

4.1. The Linear Wave Energy Converter L12

Two generators with the L12’s design have been assembled and deployed, presented in Fig. 4.1.

Figure 4.1. The first L12, deployed the 12th March, can be seen to the left, whereas the second, the yellow, was installed the 11th July 2013.
Figure 4.2 presents the simulated magnetic flux density, whereas the three phase voltage output from the generator, experimental measured onshore during the final assembling of the full scale generator, is presented in Fig. 4.3.

![Figure 4.2. The simulated magnetic flux density. Published in Paper I.](image)

Table 4.1 presents the induced voltage and the output power relative the air gap variation due to the tolerances in the system in p.u., normalized to the air gap set point.

![Figure 4.3. The output voltage from the first wave energy converter. Non published material.](image)
Table 4.1.
The induced voltage and output power. Published in Paper VII.

<table>
<thead>
<tr>
<th>Maximum airgap</th>
<th>Setpoint</th>
<th>Minimum airgap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage [-]</td>
<td>0.83</td>
<td>1</td>
</tr>
<tr>
<td>Power [-]</td>
<td>0.69</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 4.4 presents the translator’s decreasing velocity, the acceleration, the increasing spring reaction- and excitation force as it hits the end stop solution, implemented in the machine. The results are presented normalized to the initial velocity of the translator, and measured wave data presented in [34] was used as input parameters concluding the ‘worst’ wave amplitude and period.

![Figure 4.4. The resulting scenario. Published in Paper VI.](image)

4.2. The Resonance Circuit
For better understanding the novel resonance circuit, full scale experimental tests with a single phase linear generator connected to the resonance circuit have been performed. Figure 4.5 presents the electrical drawing of the experimental test circuit and defines the different measurement points.
By measuring of the voltage $V_2$ the author wanted to investigate the voltage behaviour over the capacitors in the rectifier, presented in Fig. 4.6.

As Fig. 4.6 presents, the voltage amplitude increases when the translator speed decreases.

To assure a correct rectified power, measurements on the DC-side were done, see Fig. 4.7.
The measurement in Fig. 4.7 proves that the voltage over the load does not vary in polarity, i.e. a successful conversion of the output voltage from the generator has been achieved.

4.3. The Electrical Motor

The motor’s flux density at three different electrical loads is presented in Fig. 4.8.

![Figure 4.8. The magnetic flux density at: The top) No Load, The middle) Full Load and The bottom) 100% Overload.](image)

The efficiency of the motor is modelled as stated in Section 2.2, Paper XI. The numerical and analytical calculations of the operating characteristics of the machine are presented in Fig. 4.9-4.10. Figure 4.9 presents the results for the permanent magnet motor from nominal to rated load with the control-algorithm Scalar Control, whereas Fig. 4.10 presents the motor’s performance where efficiency is plotted versus different loads.
A brief presentation of the mechanical design, i.e. stresses in the structure at 3000 rpm, is shown in Fig. 4.11.
5. Discussion

5.1. The Linear Wave Energy Converter L12
The presented linear permanent magnet generators were designed and assembled during 2012-2013. The generators belong to the third generation of wave energy converters developed within the project and the large difference compared to earlier designs is the ferrite and pole shoe based translator. Sustainability as well as economy and production have been in major focus during the design. Knowledge has been gained during the development of L12 and different challenges have been greater than other. The increased active area, the decrease of machined surfaces and reduction of the material put higher demands on the analytical and numerical calculations as well as the tolerances in the system. The developed assembling methods facilitated and improved the first L12 to the second generator greatly, a development continuing with the three next full scale versions of the L12 design. Attention has been put on the tolerances affecting the air gap width, necessary to reach a magnetic flux density equal to the simulated values, presented in Fig. 4.2 and Paper I. The performed tolerance analysis, with the results presented in Table 4.1 and Paper VII, shows that the design is sufficient to reach the required air gap interval. However, as the constructed components have been out of the tolerances, the two first generators have a slightly larger air gap than expected.

5.2. The Resonance Circuit
As Fig. 4.6 presents, the voltage amplitude increases when the translator speed decreases. This is not the expected behaviour according to Faraday’s law of induction which states that the voltage amplitude shall increase with the frequency. The result presented in Fig. 4.6, can be explained as a successful resonance test, i.e. when the translator’s velocity decreases, the generator enters the electrical resonance interval, resulting in higher amplitude of the voltage. Further experimental studies are required for evaluating the resonance circuit connecting to a DC-filter and grid connection devices.
5.3. The Electrical Motor
The author argues for the importance of testing the motor during realistic conditions with accepted drive-cycles. Figure 4.10 presents an efficiency map over the operating area, but it does not specify the operation sequence of an electric vehicle. Experimental verification of the analytical and numerical calculations is the next step of the development of the two pole permanent magnet motor.
6. Conclusions

The purpose with this thesis was to present the general design approach of the first ferrite based wave energy converter L12, the resonance circuit and to give a brief description of The Electrical Motor Project.

The work performed by the author focuses on the electromagnetic and mechanical design of energy converter L12, the electromagnetic and mechanical design of an electric motor as well as the novel resonance circuit. Numerical calculations play a vital role in the design-process. Important parameters as material properties, geometry etc are investigated and included at the design stage.

The results presented in this thesis, Paper I and Paper II concludes the possibilities to design a ferrite permanent magnet machine with a comparable magnetization as for an Nd$_2$Fe$_{14}$B-based magnetic circuit, with a permanent magnet cost of less than one fifth. Two linear generators with ferrites have been constructed and tested. The first generator was installed on the 12$^{th}$ of March 2013 at the Lysekil research site and the second was deployed a few months later, on the 11$^{th}$ July.

The results regarding the novel resonance circuit presented in this thesis, Paper III, Paper IV and Paper V conclude that a successful resonance between the generator and external circuit was achieved. The results strongly argue for a continued study and off-shore experiments with the resonance circuit.

A presentation of an electric motor with a high efficiency over a wide frequency operation interval has been done. Comparison between the simulated motor and existing, full scale motors used in electrical vehicles shows a substantial possibility to increase the electrical and overall efficiency in an All Electric Propulsion System. A higher efficiency, on one hand, saves energy and on the other hand reduces cooling equipment, thus a simpler and more stable overall system design is reached.
7. Future Work

- Perform offshore experiments with L12, with focus on non-linear load-experiments and controlled damping strategies.
- Study and investigate the leakage flux within the linear ferrite generator L12.
- The next step in the development of the resonance circuit is to perform experimental tests when the generator and the resonance circuit are connected to a constant DC-level.
- Experimental test and measuring the efficiency, the thermal and the mechanical stability of the two pole permanent magnet motor during accepted drive-cycles.
- Further investigation of the electric motor’s parameters in a system perspective. Different voltage levels, design-frequency, different shapes of the magnet, the possible implementation of a differential in the system etc are all important and shall be designed in the system perspective.
8. Summary of Papers

This chapter presents short summaries of each paper in the thesis.

Paper I

Supplementing rare-earth metal with ferrite in wave power generator
The paper presents a comparative study between Nd$_2$Fe$_{14}$B and ferrite magnets in electric machines. Focus is directed to the magnetic and economical parameters. The paper concludes that the same magnetic parameters in the circuit can be reached, where the ferrite price is less than one fifth of the Nd$_2$Fe$_{14}$B price. Further, the first primary experimental results from a full scale ferrite design linear generator are presented and discussed.
The author has performed the electromagnetic and the mechanical design of the linear generator, and had the leading roll during the mounting of the generator. 

Paper II

Ideal Analytical Expression of the Magnetic Circuit in a Permanent Magnet Linear Machine
An analytical expression of the magnetic flux density in a linear permanent magnet generator is derived and utilized to calculation of the magnetic flux density in the air gap of the machine. The material parameters and dimensions impact on the circuit are discussed, as well as the presented results.
The author wrote the paper, derived the expression, performed the analytical calculations and presented the paper at the conference.
Paper III

**Experimental Results from a Linear Generator connected to a Resonance Circuit**
The aim of this paper is to give a deeper and more detailed presentation of a rectifier circuit with integrated capacitors. Results from experiments with a full scale single phase linear generator connected to the circuit is presented, discussed and gave positive feedback to the author. The author wrote the paper and performed the experimental tests presented in the paper.


Paper IV a)

**Electric resonance-rectifier circuit for renewable energy conversion**
Paper IV a) gives a technical description of the resonance circuit for electric conversion in a wave power system. Experimental tests with a single phase linear generator connected to the resonance circuit are presented and discussed. The author performed the experimental tests presented in the paper.

*Published in Applied Physics Letters 100(4): 2012.*

Paper IV b)

**A resonance circuit for electrical conversion systems**
The paper gives a popular science description of the resonance circuit and the possible implementation of the circuit in the wave power system. Experimental results are presented and the results are discussed, strongly related to Paper IV a). The author has written the paper and performed the experimental tests presented in the paper.


Paper V

**Linear generator connected to a resonance circuit**
Offshore experimental tests with a linear generator connected to the resonance circuit are here presented. The output power is compared to a similar generator, connected to a simple resistive load. Conclusions are difficult to draw, both due to non-optimal experimental setup and lack of reference-data. The author contributed to the experimental setup and the preparatory work.

Paper VI

Theory and Simulations of an End Stop Solution in a Linear Wave Power Generator
A hydrodynamic model is utilized to dimension the upper end stop in a linear wave power generator. An assumption about a sinusoidal movement of the buoy and the translator has been made. The author dimensioned the end stop solution based on the hydrodynamic model and wrote a major part of the paper. 
*Manuscript, September 2013.*

Paper VII

Tolerance Analysis in a Linear Permanent Magnet Generator
The paper presents two sensitivity analysis of the mechanical and magnetic design in a linear generator. The *Worst-case analysis* was performed to investigate the extreme values in the system whereas the second study, the *Statistical analysis* intended to reach results more likely the reality. The results are aimed to improve the machine’s quality and to reduce the overall cost as the tolerances will influence the final assembled product, the production, method and setup cost as well as inspection during the mounting. The author wrote the paper, designed the generator and performed the analytical calculations. 
*Submitted to Machines, August 2013.*

Paper VIII

Analysis of longitudinal ends effects in a Linear Permanent Magnet Generator
The paper presents numerical calculations of the longitudinal ends impact on the magnetic circuit in a linear permanent magnet generator. The results present significant core losses in the translator and an increased cogging force due to the longitudinal ends. The author wrote the paper and performed all the numerical calculations. 
*Submitted to International Journal of Marine Energy, August 2013.*
Paper IX

**Prediction of the Inductance in a Synchronous Linear Permanent Magnet Generator**

The aim of the paper is to present analytical, numerical and measured values of the self-inductance in each phase in a linear generator. By utilizing numerical calculations, the variation of the term at no load is investigated and discussed. The obtained results were expected.

The author wrote the paper, performed the measurement and the analytical as well as the numerical calculations.

*Published in Journal of Electromagnetic Analysis and Applications, 3:154-158, 2011*

---

Paper X

**Electric Motor Drivelines in Commercial All Electric Vehicles: A Review**

Paper X is a critical review of electrical vehicles. Main focus is put on the electric motors, where the positive and negative properties of the main topologies are discussed.

The author contributed to the background research and had a minor role in the writing process.


---

Paper XI

**On a Two Pole Motor for Electric Propulsion System**

This paper present a two pole permanent magnet motor, designed to achieve a high electric efficiency over a wide frequency spectrum. The design approach is presented together with the simulated results of the efficiency and the basic mechanical design.

The author has written major part of the paper and performed all the analytical and numerical calculations behind the motor design.

Paper XII

**Delad Rotor**

The invention in the patent is a novel design of the rotor. The principle of the design, an embedded magnet, increases the electromagnetic active area and protects the magnet’s material properties. The author has contributed to the design and function of the rotor, implemented in an electric motor.


Installationen av projektets första vågkraftverk, döpt L1, skedde i mars 2006. Ytterligare tio vågkraftverk och två marint ställverk har därefter installerats på projektets testanläggning utanför Lysekil vid den svenska väst-kusten.

Författaren arbetar med den elektromagnetiska och mekaniska designen av denna typ av långsamgående linjära permanentmagnetiserade generatorer. Störst fokus har lagts på designen av den senaste generatorn, döpt till L12. Dess elektromagnetiska design, en ferritbaserad tre-fas-maskin, har undersöks med ett datorbaserat finitelementmodellerat simuleringsprogram. Denna typ av simuleringar är accepterade världen över och ger en mycket noggrann beskrivning av maskinens elektromagnetiska delar. Ferrit designen är den första i sitt slag och innebar en stor omkonstruktion av den mekaniska designen. Två st identiska L12or har sjösatts samt är, i skrivande stund tre st nu under monteringsfasen och beräknas bli installerad på projektets test område utanför Lysekil under hösten 2013.

Denna avhandling inkluderar även studie av en två-pol permanentmagnetiserad motor, designad för att utnyttjas i elfordon. Genom att designa motorn med en hög verkningsgrad över ett brett frekvensintervall kan växellådan reduceras bort, vilket ökar både systemets totala hållbarhet och verkningsgrad. Resultat från simuleringar samt jämförelser med
fullskaliga existerande generatorer, visar att det finns potential att öka den elektriska motorns verkningsgrad och samtidigt förenkla drivlinan genom att reducera bort växellådan. Den första prototypen är under konstruktion och skall användas för att verifiera de numeriska och analytiska beräkningarna. Framtida planer är att integrera den elektriska motorn med avdelningens forskning angående ett svänghjulsbaserat Helt Elektriskt Framdrivningssystem.
10. Acknowledgment


Andrej, min rumskompis. Tack för all hjälp och inte minst alla roliga diskussioner 😊

Jag vill tacka Ulf Ring för dina förståndiga visdomsord och även ett tack till Gunnel, Maria, Tomas och Ingrid för den administrativ hjälp.

This research was carried out as part of the Statkraft Ocean Energy Research Program, sponsored by Statkraft. (www.statkraft.no). This support is gratefully acknowledged.

The author would also express gratitude’s to:

The author would also like to express gratitude’s to the founders in The Electrical Motor Project; Märta och Göran Öberg’s stiftelse, Stiftelsen J. Gust Richert, Ångpanneföreningens Forskningsstiftelse and StandUp for All Electrical Propulsion Systems.
Bibliography


73


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.