Low Speed Energy Conversion from Marine Currents

KARIN THOMAS
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Abstract


The focus of this thesis is research on the performance of very low speed direct drive permanent magnet generators for energy conversion from marine and tidal currents. Various aspects involved in the design of these generators and their electromagnetic modelling using the finite element simulations are presented. For a detailed study, a 5 kW prototype generator has been designed and constructed based on finite element based simulations. Several experiments were conducted on the prototype generator. The experimental results were compared with the corresponding case simulations on the designed generator. The differences between the results predicted by the simulations and those predicted by the measurements were less than 10%. The part and overload performance of the generator has been investigated and it is found from both simulations and measurements that the generator is capable to efficiently operate at varying speeds. The tests on the experimental generator were made for speeds between 2 and 16 rpm and for load variations of 0.5 to 2 per unit. In this thesis it is shown that it is possible to design a very low speed direct drive generator for more or less any given marine current site and this is beneficial for projects aiming to develop a technical and economical viable marine current energy conversion system.

Keywords: Direct Drive Generator, Finite Element Method, Marine Current Energy, Synchronous Generator, Permanent Magnet, Tidal Current Energy

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List of Papers

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


VII Katarina Yuen, Karin Nilsson, Mårten Grabbe, Mats Leijon, ”Experimental setup: Low speed permanent magnet generator for marine current power conversion”, Proceedings of OMAE2007, June 2007, San Diego, USA, (reviewed conference article)


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The author has also contributed to the following papers not included in the thesis. These papers are partially within the scope of this thesis and they are largely a summary of the above listed papers.


The author also contributed to following popular presentations:

- ”Hon samlar kraft på havets botten”, Published in Ny Teknik, November 2007, (in Swedish)
- ”Electricity from flowing water” Published in News and Features from Uppsala University Innovation, Issue 2/07
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<tr>
<td>A</td>
<td>Tm magnetic vector potential</td>
</tr>
<tr>
<td>B</td>
<td>T magnetic flux density</td>
</tr>
<tr>
<td>D</td>
<td>C/m(^2) displacement field</td>
</tr>
<tr>
<td>E</td>
<td>V/m electric field</td>
</tr>
<tr>
<td>H</td>
<td>A/m magnetic field</td>
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<tr>
<td>J(_f)</td>
<td>A/m(^2) free charge density</td>
</tr>
<tr>
<td>A</td>
<td>m(^2) cross-sectional area of the turbine</td>
</tr>
<tr>
<td>A(_z)</td>
<td>Tm z-component of the magnetic vector potential</td>
</tr>
<tr>
<td>B(_a)</td>
<td>T magnetic flux in air gap</td>
</tr>
<tr>
<td>B(_{fe})</td>
<td>T magnetic flux in iron</td>
</tr>
<tr>
<td>B(_m)</td>
<td>T magnetic flux in permanent magnet</td>
</tr>
<tr>
<td>B(_r)</td>
<td>T remanence of permanent magnet</td>
</tr>
<tr>
<td>C(_p)</td>
<td>- power coefficient</td>
</tr>
<tr>
<td>E</td>
<td>V emf</td>
</tr>
<tr>
<td>F</td>
<td>N force</td>
</tr>
<tr>
<td>I</td>
<td>A current</td>
</tr>
<tr>
<td>L</td>
<td>H coil end inductance</td>
</tr>
<tr>
<td>N</td>
<td>- number of turns</td>
</tr>
<tr>
<td>N(_s)</td>
<td>- number of slots</td>
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<tr>
<td>N(_ph)</td>
<td>- number of phases</td>
</tr>
<tr>
<td>P</td>
<td>W power</td>
</tr>
<tr>
<td>Q</td>
<td>VAr reactive power</td>
</tr>
<tr>
<td>R</td>
<td>Ω resistance</td>
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<tr>
<td>S</td>
<td>VA apparent power</td>
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<tr>
<td>T</td>
<td>°C temperature i</td>
</tr>
<tr>
<td>U</td>
<td>V voltage</td>
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<td>V</td>
<td>Tm scalar potential</td>
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<td>V(_i)</td>
<td>V voltage</td>
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<tr>
<td>W</td>
<td>J energy</td>
</tr>
<tr>
<td>f(_f)</td>
<td>s(^{-1}) frequency</td>
</tr>
<tr>
<td>f(_C)</td>
<td>s(^{-1}) Coriolis parameter</td>
</tr>
<tr>
<td>g</td>
<td>m/s(^2) gravitational constant</td>
</tr>
<tr>
<td>h</td>
<td>m depth</td>
</tr>
<tr>
<td>h(_pm)</td>
<td>mm height of PM</td>
</tr>
<tr>
<td>k(_b)</td>
<td>- distribution factor</td>
</tr>
<tr>
<td>k(_e)</td>
<td>Js(^{1/2})/(m(^3)T(^{3/2})) excess loss material constant</td>
</tr>
</tbody>
</table>
$k_h$ $\text{J/(m}^3\text{T}^2\text{)}$ hysteresis loss material constant

$k_p$ pitch factor

$k_w$ winding factor

$l$ $\text{m}$ length

$n$ rpm rotor speed

$n_{ph}$ slots per phase

$p_{atm}$ $\text{atm}$ atmospheric pressure

$q$ W heat source

$r$ $\text{m}$ radius

$t$ s time

$v$ $\text{m/s}$ water current velocity

$z$ $\text{m}$ height above the seabed

$\delta$ $\circ$ power angle/load angle

$\alpha$ $\circ$ angular difference between pole and coil pitch

$\alpha_p$ $\text{W/m}^2\text{K}$ convective heat transfer coefficient

$\phi_l$ $\circ$ latitude

$\lambda$ $\text{W/m}^2\text{K}$ thermal conductivity

$\mu$ permeability

$\rho$ $\text{kg/m}^3$ density

$\phi$ $\circ$ phase angle

$\Phi$ Wb magnetic flux

$\gamma$ $\circ$ electrical angle between slots

$\sigma$ $\text{A/Vm}$ conductivity

$\omega_S$ rad/s angular speed of earths rotation
Introduction

Today’s global energy production is highly dependent on fossil fuel resources such as oil, gas and coal. These resources are limited and their use results in emission of greenhouse gases like carbon dioxide. According to e.g. the Kyoto protocol there is an agreement to reduce the emission of greenhouse gases to the atmosphere [1]. To provide a sustainable power production in the future and at the same time respecting the Kyoto protocol, there is a growing demand for energy from renewable sources such as wind, geothermal, solar and ocean.

The oceans cover more than 70 % of the earth’s surface and are an abundant source of renewable energy. The energy from the oceans is available in the form of thermal energy, kinetic energy (waves and currents) and partly in the form of chemical and biological products. In this thesis electrical energy conversion from marine and tidal currents (as well as unregulated or partly regulated rivers) is considered.

Research in the area of energy conversion from marine currents is carried out at the Division of Electricity at Uppsala University. Various aspects of such energy conversion systems has been presented in [2-5]. This thesis concentrates on low speed permanent magnet synchronous generators designed for energy conversion from unregulated water currents such as tidal streams, ocean currents and unregulated watercourses. Particular attention is given to the numerical simulations of the electromagnetic behaviour of such generators and construction of a laboratory type experimental generator for performance analysis. Experiences from such performance analyses will be valuable for design and construction of future marine current generators.

Marine Current Energy

Energy conversion from marine currents is quite similar to that of wind energy conversion but there are also several differences between them. The underwater placement of a marine current energy converter (MCEC) gives some advantages such as no noise disturbance for the public, low visual exposure and little use of land space but also adds some challenges like the need for water and salt proof technology, difficult and costly maintenance etc. Another characteristic is the difference in density between water and air, water has approximately 800 times larger density, which results in a higher
power density. For example a wind power plant with a turbine diameter of 33.4 m, designed for nominal wind speeds of 12 m/s gives 300 kW. A corresponding marine current power plant with a 20 m diameter turbine in a 2 m/s current velocity also gives 300 kW. In this example the turbine efficiency is assumed to be the same for wind and water. There are also some challenges associated with higher density e.g. turbulence which gives high strain on the turbine. A final characteristic to highlight is the relatively high degree of utilization, tidal streams are likely to have a utilization factor up to 40-50 % and currents of more constant nature are likely to have a utilization factor up to 80 % [6]. For wind power the corresponding utilization factor is usually between 25-30 %. The utilization factor is defined as the actual annual energy output divided by the theoretical maximum and is dependent on the rated power of the installed device [7] A high utilization factor is important to achieve an economically viable power production [8, 9].

A drawback with marine currents as an energy source is that the water currents usually have a low velocity, that rarely exceed 5 m/s [10-14]. Lower current velocities results in low turbine speeds, thus, if a conventional generator were used to produce electricity, a gearbox becomes essential to achieve higher rotor speeds. It is important to note that gearboxes contribute to mechanical losses and require maintenance regularly to avoid power generation failures. From the perspective of reliability and economics, a simple energy conversion system with minimum maintenance is desirable when the device is placed off-shore.

The Marine Current Energy Conversion System Studied in this Thesis

The energy conversion system studied in this thesis consists of a vertical axis turbine and a direct drive permanent magnet generator. This concept has few moving parts and is constructionally simple. Such a construction could reduce maintenance requirements which is desirable once the device is placed under water. The combined turbine-generator system is intended to be placed on the ocean floor in such a way that the generator and the turbine have the same axis of rotation. There are various available options for the grid connection of such generators [15]. In an underwater substation the output from a number of such generators will first be converted to DC. One of the options of grid connection is to transmit the DC power from the substation all the way to the grid wherein the DC power is inverted and transformed to grid voltage and frequency. Another option is to invert the generated DC power to AC and then step up the voltage using a transformer within the

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underwater substation for direct high voltage AC transmission and connection to the grid. An illustration of the above mentioned system is shown in Figure 1.

Figure 1. Illustration of the marine current energy system.

Vertical Axis Turbines
The possible vertical axis turbines proposed for this type of marine current power plant could have three, or more, blades attached either directly to the generator rotor or to a centred shaft as shown in Figure 2. A vertical axis turbine is independent of the direction of the flow, which is an advantage in bidirectional flows e.g. tidal power applications. Direct drive generators usually have large diameters, which for a classical horizontal axis turbine can result in a disturbance of the flow profile, whereas this is avoided for a vertical axis turbine. Further, a vertical axis turbine can be more easily adapted to any specific site than a horizontal axis turbine, since there is more freedom to change the height and the radius of a vertical axis turbine. However, it requires a larger area for installation and if cavitation occurs it will affect the whole blade instead of just the tip as in the case of a horizontal axis turbine. Efficiencies up to 56% have been reported for a vertical axis turbine, although it is not clear how such an efficiency was determined [16].

Figure 2. Illustration of three different types of vertical axis turbines, Savonius, Darrieus and H-rotor, with two and three blades.
Direct Drive Permanent Magnet Generators

Direct drive generators suitable for marine current power conversion have very low rotation speeds. The nominal speeds will be in the range of 5 to 30 rpm depending on the site specific conditions. To compensate for the low speed many poles on the rotor is an option, however, this will result in a larger generator diameter.

The rotor can be magnetized either with electromagnets (separately excited) or with permanent magnets (PM). A PM generator eliminates the need for electrical couplings to the rotor, like carbon brushes. However, with permanent magnets excitation cannot be controlled in the event of load fluctuations and for variable water current speed. Permanent magnets could also suffer demagnetization due to a high opposing magnetic field from the armature winding in the event of severe overloads.

In conventional machines, the stator is wound using rectangular copper conductors. In this work the idea of a cable wound stator is adopted [17].

The direct drive generator will experience a varying speed and therefore deliver a voltage with varying amplitude and frequency. For such an intermittent energy source it is important to have high generator efficiency for a wide range of operating speeds. Can such a marine current generator be designed and built? This thesis aims at answering this question!

Outline of the Thesis

This thesis is a comprehensive summary of the appended articles which are results of the author’s research work within the project of marine current energy conversion with particular attention to electromagnetic design and construction of the generator.

Chapter 2 gives an introduction to the marine current energy conversion area and the marine current energy resource and available technologies to date. Parameters influencing the energy conversion process are discussed. This chapter also presents an overview of relevant past and ongoing projects applicable to the present study.

Chapter 3 presents a brief introduction to generator theory relevant for design of low speed direct drive PM generators. A description of the numerical modelling and finite element methods (FEM) used to analyse the generator characteristics and performance are also presented.

Chapter 4 gives an introduction to the forces due to magnetic fields in the air gap of PM generators. Numerical and magnetic circuit approach comparisons of the air gap forces are also made for both linear and rotating PM generators.
Chapter 5 presents the design and constructional aspects for the building of a laboratory experimental generator suitable for marine current energy conversion.

Chapter 6 presents the experiments on the experimental generator discussed in Chapter 5. These experiments are carried out to access the performance of the generator and also to compare numerical simulations and practice. Experiences from these tests could serve as a guide for the construction of future marine current generators.

Chapter 7 presents the major conclusions and also in chapter 8 some suggestions for future work that could be carried out for a better understanding of the various aspects involved in the marine current energy conversion process.

Chapter 9 gives a brief summary of each paper included in the thesis emphasizing the author’s contribution and also describes how the papers are related.
The aim of this chapter is to introduce the reader to the marine current energy resource characteristics that are important when energy conversion with a turbine and direct drive generator is attempted. Also a discussion on the available potentials is presented along with some of the available technologies and more important projects in the area.

Marine Currents

There is abundant energy in the oceans of the world. A part of the total energy from the oceans is due to the marine currents (including tidal currents, currents caused by salinity or temperature gradients, and/or the Coriolis Effect caused by the earth’s rotation [18]). The water current movements are usually slow but the seabed topography can increase the current velocities to up to 7 m/s [19], particularly between islands and the mainland, around ends of headlands and in river estuaries.

The current velocity is a key factor in the design of a marine current power plant, since it sets the limits for both the power output as well as the forces acting on the turbine and support structures. The available power increases rapidly with increasing current velocity. The velocity varies with the depth and the velocity profile approximately follows:

\[
v(z) = \left( \frac{z}{h} \right)^\alpha v_{\text{peak}}, \]

where \( h \) is the total water depth and \( z \) is any height above the seabed, \( \alpha \) is a constant and \( v_{\text{peak}} \) is the current velocity at the surface. The factor \( \alpha \) is commonly 1/7 but varies from site to site. Note that Eq. (1) is approximate and the vertical profile will vary between sites due to local seabed and coastal topography. For example Eq 1 is not applicable in case of river estuaries and for currents due to salinity or thermal gradients [19]. It can be assumed that about 75% of the energy is found in the upper 50% of the flow [10].
Tidal Currents

The main parameter that controls the temporal rhythm and height of tides is the position of the moon and the sun. Semidiurnal, diurnal and mixed tidal currents occur, usually having the same characteristics as the local changes in tidal sea levels, but this is not always the case. For example, the currents in the Singapore straits are often diurnal in character while the elevation changes are semidiurnal [20].

Strong tidal currents are often found in straits joining two sea areas where different tidal ranges and phases prevail at the two ends. These currents are driven by the pressure head generated by the differences in sea level acting along the short distance of the strait or channel. This distinguishes them dynamically from the currents due to tidal wave propagation. A chart of the peak flow at mean spring tide around UK is shown in Figure 3.

Similar currents are also found through narrow or shallow entrances to bays, fjords and harbours. Some of the examples of tidal currents in channels include flows through the straits of Messina between Italy and Sicily, flows between the Indonesian islands and flows in the East River, New York between Long Island Sound and New York Harbour [20].

The predictable behaviour of tides makes it easier to appropriately plan the base power production and capacity requirements, than for example for wind power production.

Ocean Currents

Apart from tidal currents, more constant water movements are also found in the oceans. There is a dynamic relationship between those constant ocean movements and the slope of the mean sea level (MSL) surface. The greatest surface slopes and deviances from the MSL surface are found in areas of great ocean currents for example the Gulf Stream, the Kuroshio Current and the Antarctic Circumpolar Current, see Figure 4. The relationship between the current velocity and the mean sea level surface slope for a steady current is given in Eq. 2,

\[ v f_c = g \cdot \beta , \]

Eq. 2

where \( v \) is the current velocity, \( \beta \) is the slope of the MSL, \( g \) is the gravitational acceleration and \( f_C \) is the Coriolis parameter given by:

\[ f_C = 2 \omega_s \sin \varphi_l = 1.459 \cdot 10^{-4} \sin \varphi_l . \]

Eq. 3

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2 The MSL is the average level of the sea surface measured relative a fixed level on land usually calculated as an average over a specified long time period.
In equation (3) $\omega_S$ is the angular speed of earth’s rotation and $\phi_1$ is the latitude [20].

In the Gulf Stream an average current velocity of 2.1 m/s has been measured [21] and the Kuroshio Current has a maximum velocity of 1 m/s around Taiwan and slightly higher outside Japan. [22, 23]

Figure 3. Example of the peak flow for a mean spring tide around the UK$^3$.

Figure 4. The major ocean currents, the red arrows illustrate warm water currents and the blue are cold water currents.

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Other Currents

In some places nearly constant currents occur due to density differences caused by salinity or temperature gradients. These types of currents exist for example in the Mediterranean in the strait of the Dardanelles and in the sites of Samos, Kafirea, Kea and Kithos in Greek waters [10]. In Skagerak/Kattegatt current velocities of up to 1.4 m/s have been measured. These currents are mainly due to barotropic flows and salinity gradients when the brackish water from the Baltic Sea meets the Atlantic Ocean. According to [24] the currents in this area are strongest along the Danish coast.

Potential for Energy Extraction

There have been some estimates made for evaluating the global tidal stream energy resource. Most reports discussing global resource quote Isaac and Seymour’s 1973 paper, who estimated the total power of ocean currents to be 5 TW giving a global energy resource of 44000 TWh per year [25]. A more recent study [26] estimates the extractable resource in the UK to about 22 TWh per year and for the rest of Europe about 17 TWh per year. Another study [19] estimates the energy potential from tidal streams in Europe to be about 58 TWh per year and [10] estimates the potential to 48 TWh. More recently, the IEA have estimated that the global resource for tidal currents is in excess of 800 TWh per annum [27]. Other reports [28-32] have concentrated on estimates for specific sites rather than continentally or globally. Note that the above figures only include tidal currents.

The reader should keep in mind that the results from the above mentioned studies are not always comparable since some of the figures are derived for the available theoretical potential [25] and some are for the expected extractable potential [10, 19, 26]. Most of the above mentioned studies are based on estimates and information from admiral charts and pilot books. Hence, these studies are not enough for someone who is looking into possibilities of installing a marine current energy converter (MCEC), as those numbers are derived based on various assumptions and only give an indication of the trends in the overall potential. In the above mentioned reports different variables and factors involved in the potential assessment calculations include expected average efficiency, device availability, extractable or available percentage of the total resource, spacing between different MCECs, lower limit of stream velocity for electricity generation, ratio between first and second tide, etc. For example the JOULE II study [10] included all sites with

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4 Barotropic flows: flows due to pressure differences
a mean maximum spring speed (MMSS) above 1.5 m/s, while other reports [19, 26] only concentrate on locations with MMSS greater than 2 m/s.

Very little information is available on the marine and tidal energy potentials in Scandinavia. The Norwegian utility company Statkraft has estimated the Norwegian tidal energy potential to be in the range of 5-15 TWh [33]. In Sweden, there are no major tidal or ocean currents, however, there are places where, due to geographical conditions, currents of several knots are found, for example in Öresund [34].

Another possible source of energy is unregulated or partly regulated rivers. The unused potential in partly regulated and unregulated Swedish rivers has been estimated to be about 23.8 TWh. If environmental and techno-economical limitations are considered one could exploit approximately 5 TWh from the above 23.8 TWh [35]. These numbers are based on the possibility of constructing conventional hydropower dams. It is not clear if such exploitation is possible since the remaining unregulated rivers are protected. With an unregulated power conversion system only a fraction of the 5 TWh can be utilized. However, harnessing this energy would still make an important contribution to the total electric energy production of Sweden.

Technology Assessment

The Marine Current Energy Converter (MCEC) industry is in its early days and no full-scale commercial MCEC farm has been deployed so far. By large the research has focused on adapting the principles of wind energy conversion systems to the marine current energy conversion systems. However there are various factors affecting the performance and maintenance of MCEC systems like cavitation, bio-fouling, turbulence and the sealing of the device, which needs to be considered in the development of marine current energy conversion systems.

Cavitation

Cavitation phenomena is a limiting design parameter for MCECs as it could lead to surface damage of the turbine and a subsequent decrease in efficiency [10]. Cavitation occurs when the local water pressure drops below the vapour pressure. This local pressure drop, due to the high velocity of the turbine blade relative to the water, will result in small vapour cavities on the turbine blades. When these cavities collapse they give rise to shock pressures which can damage the turbine. The maximum allowed rotation speed, without risk of cavitation, can be derived from Bernoulli’s equation:

\[
p_{atm} + \frac{1}{2} \rho v^2 + \rho gh = \text{constant}.
\]

Eq. 4
Eq. 4 is Bernoulli’s equations for an ideal\textsuperscript{5} fluid with density $\rho$ flowing at a speed $v$ and where $p_{\text{atm}}$ is the atmospheric pressure.

To avoid cavitation, a limited rotor tip-speed of around 7 m/s relative to the incoming water is recommended for first generation devices [10]. This limit is rather strict and for example in [36] it is mentioned that only rotor tip speeds greater than 12 m/s contribute to cavitation effects. However, this needs to be complemented by experiments. Propeller designs for ships etc., to avoid cavitation is well studied but the hydroplanes or turbine blades for a MCEC application have larger size than any propeller constructed so far\textsuperscript{6}, hence needs more study.

**Bio-fouling**

Marine growth on the turbine blades will increase the drag load due to an increase in surface roughness and effective area. This leads to a reduced efficiency. Influence of barnacles on a marine current turbine efficiency has been studied in [37]. The results suggest a reduction in efficiency by 20 % at low levels of fouling and about 70 % at higher levels.

The marine growth is affected by the presence of nourishment and air supply, temperature, current speed etc., and is therefore most significant near the splash zone\textsuperscript{7}. Placing the power plant on the seafloor far below the splash zone could reduce the growth. The anticipated current speed at potential sites will also reduce the fouling rate [10]. Antifouling paint could be used effectively, but may be toxic even in small concentrations [38].

**Sealing of the device**

Sealing technology in general is well developed and many manufacturers can provide information on the performance of different type of seals for various applications [6].

**Turbulence and vibrations**

Turbulence and varying flow velocities could lead to vibrations resulting in wear of mechanical parts such as bearings and gearbox. In the long term this could lead to increased need for maintenance [38].

**Environmental aspects**

The environmental impact is expected to be limited for MCEC as there is no direct emission of green house gases, very little disturbance for the public. The impact on the marine habitat is believed to be small, however more research is required to better understand the possible environmental impacts

\textsuperscript{5} ideal fluid = incompressible and nonviscous
\textsuperscript{6} The largest propeller ever built so far is 9 meters in diameter, www.english.hhi.co.kr
\textsuperscript{7} Splash zone: the area where the waves hit the shore
due to MCECs. Some of the environmental factors to be considered before the deployment of an MCEC are presented in [39].

**MCEC farm configurations**

Currently research is ongoing to characterize the wake behind a tidal current turbine [40, 41] and to better understand the changes in velocity around arrays of MCECs [42]. Also theoretical modelling approaches has been done for optimization of farm configurations with vertical axis turbines [43] and studies on how closely spaced the MCEC can be without significantly affecting the flow for specific sites has been performed [44]. A sketch of a possible MCEC farm is shown in *Figure 5*.  

![Figure 5. Illustration of a future MCEC farm (picture from MCT LTd).](image)

**Grid connection**

There are various options available for the connection of individual generator systems to the grid. A possible method of connection of the MCEC to the grid is shown in *Figure 6*. The power from each generator unit reaches an underwater substation which houses the passive diode rectification systems. The DC power is then inverted to AC power, which is stepped up to grid
frequency and voltage using a three phase power transformer before connecting to the grid [15].

**Different Approaches for Marine Current Energy Conversion**

In the literature there are mainly four different techniques available for energy conversion from free flowing marine currents; horizontal axis turbine, vertical axis turbines, oscillating hydrofoils and venturi systems.

**Horizontal and vertical axis turbines**

There are two types of turbines; horizontal axis (propeller type) and vertical axis (cross flow turbines). Horizontal axis turbines or axial flow turbines are similar to the wind turbines usually seen in wind farms. The turbines used for the first MCECs have shorter, thicker blades than wind turbines. This is to withstand the larger stresses due to the higher density of the water. Furthermore, axial flow rotors need to face the incoming current and thus require a mechanism that allows the turbine to operate with the flow in both directions. This could be achieved by pitch control of the rotor blades through 180° at turn of tide.

Vertical axis turbines vary more in design than the horizontal axis turbines, see Figure 2. Common to all different designs are that they have the axis of rotation perpendicular to the flow (i.e. vertical). Most of the turbine designs have been adapted from the wind power industry. Characteristic for the cross flow rotor is that it does not need to be oriented to the flow. This design also allows the gearbox and generator to be located above or below the rotor to avoid interference with the flow across the rotor.

Regardless of the design, a turbine can only harness a fraction of the available power in the free flowing water. The extractable power, $P$, depends on the cube of the velocity according to Eq. 5:

$$P = \frac{1}{2} C_p \rho A v^3$$  \hspace{1cm} \text{Eq. 5}

where $C_p$ is the turbine power coefficient, $\rho$ is the density of the fluid, $A$ is the turbine cross-sectional area and $v$ is the current velocity. Horizontal axis turbines have a maximum $C_p$ value of 59% based on Betz theorem [45]. The Betz theory does not include two dimensional effects, i.e. the energy transfer is regarded as one dimensional retardation of the flow.

**Venturi system**

Venturi systems are based on the Bernoulli principle. Shapers are placed into a primary flow to accelerate the flow and generate a reduction in pressure at the point where that flow is most constricted. The principle is illustrated in Figure 7, here the pressure $p_1>p_2$, the velocity $v_2>v_1$ and the cross-sectional
area $a_1 > a_2$. The venturi system is usually used in combination with a turbine located at the maximum velocity point.

**Figure 7.** Illustration of the venturi principle, when the cross sectional area decreases the velocity increases and the pressure drops.

### Oscillating hydrofoils

In an oscillating hydrofoil system, a hydroplane oscillates like a whale’s tail with an angle of attack decided by the incoming flow. These oscillations are used to either operate hydraulic cylinders to pump high pressure oil or to drive a generator. **Figure 8** shows an illustration of such an energy converter system.

**Figure 8.** Illustration of an oscillating hydrofoils system

### Prototypes

Here a short overview of the developments in MCEC technology is presented. Some of the different MCEC prototypes that have been tested offshore are summarized in Table 1. The emphasis here is on systems with both turbine/hydrofoil and generator, however, other offshore trials of turbines have been conducted [46] and many more MCEC concepts are in the stage of development.

---

8 “Close couple tandem oscillating hydrofoil tidal stream generator”, EWTEC2007
<table>
<thead>
<tr>
<th>Project/ company</th>
<th>Device</th>
<th>Power (kW)</th>
<th>Project period</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Coriolis program</td>
<td>ducted turbines</td>
<td>?</td>
<td>1973-?</td>
<td>model tests performed [21]</td>
</tr>
<tr>
<td>The Davies turbine, Blue Energy</td>
<td>vertical axis Davies\textsuperscript{9} type turbine</td>
<td>?</td>
<td>1982-</td>
<td>tidal fence technologies [47, 48]</td>
</tr>
<tr>
<td>The ENERMAR project</td>
<td>3-bladed Kobold\textsuperscript{10} turbine on floating platform</td>
<td>130</td>
<td>1990-</td>
<td>deployed in the Messina strait [49, 50] Figure 9</td>
</tr>
<tr>
<td>The Engineering Business</td>
<td>oscillating hydrofoil device</td>
<td>150</td>
<td>1997-2005</td>
<td>demonstrator was designed, built and installed in 2002 and 2003\textsuperscript{11}, project withheld due to lack of funding\textsuperscript{12} Figure 9</td>
</tr>
<tr>
<td>MCT Ltd, (Seaflow)</td>
<td>axial flow rotor mounted on a monopile</td>
<td>300</td>
<td>1999-</td>
<td>installed and tested 2002-2006</td>
</tr>
<tr>
<td>Lunar Energy\textsuperscript{13}</td>
<td>ducted turbine</td>
<td>?</td>
<td>2001-</td>
<td>10 kW model tested in 2004.</td>
</tr>
<tr>
<td>The Blue Concept</td>
<td>axial flow turbine</td>
<td>300</td>
<td>2002-</td>
<td>first tidal stream installation connected to the grid Figure 10</td>
</tr>
<tr>
<td>Verdant Power\textsuperscript{14}</td>
<td>axial flow turbine</td>
<td>35</td>
<td>2002-</td>
<td>6 turbines installed in East River, NY in 2007 Figure 10</td>
</tr>
<tr>
<td>Open Hydro\textsuperscript{14}</td>
<td>axial flow turbine</td>
<td>250</td>
<td>2002-</td>
<td>tested at the European Marine Energy Centre (EMEC) Figure 11</td>
</tr>
<tr>
<td>TidEl</td>
<td>axial flow turbines</td>
<td></td>
<td>2003-</td>
<td>one tenth model tested in 2004 at NaREC\textsuperscript{16}</td>
</tr>
<tr>
<td>MCT Ltd, (Seagen)</td>
<td>twin rotors mounted on monopile</td>
<td>1000</td>
<td>2004-</td>
<td>Installation in Strangford Narrows planned for spring 2008. Figure 10</td>
</tr>
<tr>
<td>Clean Current</td>
<td>bidirectional ducted axial flow turbine</td>
<td>2005-</td>
<td></td>
<td>2007 a prototype was tested at the Race Rocks marine reserve\textsuperscript{17}. Figure 11</td>
</tr>
</tbody>
</table>

\textsuperscript{9} The Davies turbine is a Darrieus type of turbine, developed by Barry Davies founder of Nova Energy.
\textsuperscript{10} The Kobold turbine is a vertical axis turbine that uses automatic pitching.
\textsuperscript{11} http://www.engb.com, 2005-06-01
\textsuperscript{12} http://www.narec.co.uk/pdf/Resource%202005%20March.pdf, 2005-06-01
\textsuperscript{13} http://www.lunarenergy.co.uk/, 2007-11-01
\textsuperscript{14} www.verdanpower.com, 2007-10-01
\textsuperscript{15} www.openhydro.com, 2007-10-01
\textsuperscript{16} The New and Renewable Energy Centre (NaREC) is an organization set up to bring substantial benefits to the UK's new and renewable energy industry. NaREC is a Centre of Excellence, fast-tracking concept evaluation, feasibility studies and prototype evaluation and testing through to early commercialization. http://www.narec.co.uk, 2007-10-01
\textsuperscript{17} http://www.racerocks.com, 2007-10-01
Figure 9. To the left a photograph of the Kobold turbine platform deployed in the Messina strait. To the right an illustration of the stingray hydrofoil concept constructed by the Engineering Business Ltd.

Figure 10. To the left an illustration of the SeaGen\textsuperscript{18}. In the middle the 300kW tidal stream power plant installed in Hammerfest, Norway\textsuperscript{19}. To the right an illustration of one of the turbines installed in East River New York by Verdant Power\textsuperscript{20}.

Figure 11. To the left the installed Open Hydro turbine\textsuperscript{21} and to the right the clean current turbine after deployment at Race Rocks\textsuperscript{22}.

\textsuperscript{18} courtesy of MCT Ltd
\textsuperscript{19} www.tidevannskraft.no
\textsuperscript{20} http://verdantpower.com
\textsuperscript{22} http://www.racerocks.com/racerock/energy/tidalenergy/april07fouling/turbinenup.jpg
Generator Theory and Modelling

A generator is an integral part of most mechanical to electrical energy conversion systems. For MCEC systems one design choice is whether to use a conventional, relatively high speed generator together with a gearbox or to use a direct drive generator. Experiences from the wind power energy conversion systems indicates that a system without a gearbox offers higher overall efficiency and reliability (low maintenance) [51-53].

This chapter presents a brief introduction to generator theory, with emphasis on low speed direct drive PM generators. A description on the numerical modelling using finite element methods to analyse the generator characteristics and performance are also presented.

Generator Theory in General

According to Faraday's law of induction an alternating magnetic flux, $\Phi$, induces a voltage in $N$ coils.

$$E = -N \frac{d\Phi}{dt}.$$  \hspace{1cm} \text{Eq. 6}

In the case of a generator, the total induced voltage, $E$, is the sum of the voltages induced in each individual coil of the machine. In the magnetic circuit of a generator the magnetic flux, $\Phi$, is the magnetic flux density, $B$, in the stator integrated over the loop area due to the coil sides of the stator winding.

The root mean square (rms) line voltage for a generator can be derived from Faraday's law of induction resulting in:

$$E_i = \sqrt{3} \cdot \frac{2\pi}{\sqrt{2}} \cdot N \cdot f \cdot \Phi_{\text{max}} \cdot k_w \cdot \frac{N_s}{N_{ph}},$$  \hspace{1cm} \text{Eq. 8}

where $N_s$ is the number of slots, $N_{ph}$ is the number of phases, $k_w$ is the winding factor and $\Phi_{\text{max}}$ is the maximum magnetic flux in the air gap. The frequency $f$ of the generated voltage is given by Eq. 9, where, $n$, is the rotor speed in revolutions per minute and $p$ is the number of poles.
From the above equations it is seen that the induced voltage largely depends on the rotational speed and the air gap flux. From Eq. 8 it can be seen that the low rotational speeds can be compensated by increasing the number of poles [54]. One effect this has is an increased diameter of the rotor.

The apparent power \( S \) delivered by the generator to a load connected at its terminal is given by:

\[
S = P + jQ = V_t I_a (\cos \phi + j \sin \phi),
\]

where \( P \) is the active power in Watts (W or kW), \( Q \) the reactive power in Volt-Ampere reactive (VAR or kVAR), \( \phi \), is the phase angle between the armature current \( I_a \) and the terminal voltage \( V_t \) as described by the equivalent circuit and the phasor diagram in Figure 12 [55].

![Figure 12. Equivalent circuit for a generator connected to a load and phase diagram](image)

**Power Angle**

The power angle or the load angle, \( \delta \), is the angle between the terminal voltage \( V_t \) and the induced emf \( E_i \), see Figure 12.

Generators for the MCEC studied here have low internal voltage and are usually few tens or few hundreds kW power rating. Further, they are not connected directly to the grid (since the frequency is varying due to the varying turbine speed) as the generated power has to pass through the underwater substation via the power converter and inverter systems before final connection to the grid. Hence, for the MCEC generators with PM excitation system, the values of power angle is relevant and should be accounted for considering the wide variations of input marine current speeds and not based on the load connected to the generator. In the conventional synchronous machines with separate field excitation, the changes in the power angle of the machine could be controlled by variations of field excitation. However, since the field excitation is fixed in the case of a PM synchronous machines, it is appropriate...
ate to have low power angles to be able to handled variations in marine current speeds, without affecting the machines performance from a stability point of view. For these reasons in the present work importance is given to design machines with low load angles.

Permanent Magnet Excitation Systems

A synchronous generator can be either electro magnetized or permanent magnetized. In this thesis only PM systems are considered. A PM generator eliminates the need for electrical couplings to the rotor, like carbon brushes, etc. and also the pole pitch can be made smaller hence more poles can be placed or the rotor size can be reduced as applicable [56]. However, with PMs excitation cannot be controlled in the event of load fluctuations and for variable water current speed. PMs could also suffer demagnetization due to a high opposing magnetic field from the armature winding in the event of severe overloads.

Armature Winding

In this work a standard cable with circular cross-section is used for the stator winding. Easy handling and low price are the main motives for this choice of winding. PVC insulated cables can handle transient voltages up to 25 kV/mm and withstand temperatures of more than 70°C in continuous operation23.

There are two types of windings commonly employed, lap winding and wave winding. The difference between the two is merely due to the different arrangement of the end connections. The advantage of the wave winding is that for a given number of poles and armature conductors, it requires shorter total end winding which results in lower winding costs. Wave winding is suitable for small generators with few hundreds of volts generation.

Fractional pitched windings are mainly used in synchronous generators with large number of poles, in order to reduce cogging and harmonics. Cogging is a phenomena occurring due to the non homogenous stator reluctance and therefore the magnets tends to cling to the stator teeth. A fractional winding reduces such effects since the stator slots are not consistently distributed across every pole. The symmetry is broken and cogging is reduced considerably [57]. When fractional windings are used the induced voltage is reduced with a winding factor, \( k_w = k_b \cdot k_p \), where \( k_p \) is the pitch factor and \( k_b \) is the distribution factor. If the coil span falls short of full pitch by an electrical angle \( \alpha \), the pitch factor can be expressed as:

\[ k_b = \frac{\sin(\frac{\alpha}{2})}{\frac{\alpha}{2}} \]

\( k_p = \cos(\alpha/2) \)  

Eq. 12

The pole pitch is the distance between the centre of one magnet to the centre of the adjacent magnet, see Figure 13. The coil pitch is the distance between the two sides of one coil. If there is a full pitch winding the electrical angle \( \alpha \) will be zero but if the winding is short pitched or long pitched \( \alpha \) will be the angular difference between the pole pitch and the coil pitch.

The distribution factor, \( k_b \), is given by:

\[
k_b = \frac{\sin(n_{ph}\gamma/2)}{n \sin(n_{ph}\gamma/2)}
\]

where \( n_{ph} \) is the number of slots per phase and \( \gamma \) is the electrical angle between the slots [58].

**Figure 13.** Example of a winding scheme for a fractional pitch winding of 7/5 slots per pole and phase

**Generator Losses and Efficiency**

The electromagnetic losses in a generator can be categorized as copper losses and iron losses depending on where in the generator they occur. Copper losses are due to the losses in the armature windings while the iron losses occur in the stator steel. The copper losses in the machine can be divided into resistive losses, due to the winding resistance, and eddy current losses. However, the eddy current part is so low in this application so it can be neglected the reason for this is use of stranded conductors and the low permeability of copper. Therefore the copper losses can be expressed as:

\[
P_{cu} = I^2 R.
\]

Eq. 14
where $R$ is the winding resistance and $I$, is the current.

The total iron losses are due to the varying magnetic field in the stator core and are given by sum of hysteresis, eddy current and excess losses, respectively as shown in Eq. 15

$$P_{Fe} = k_h B_{\text{max}}^2 f + k_{\text{eddy}} (B_{\text{max}} f)^2 + k_e (B_{\text{max}} f)^{3/2}, \quad \text{Eq. 15}$$

In the above empirical Eq. 15, the right hand terms represents the hysteresis losses, eddy current losses and excess losses respectively, where $k_h$, $k_e$ and $k_{\text{eddy}}$ are coefficients of hysteresis, excess and eddy current losses, $B_{\text{max}}$ is the maximum magnetic field and $f$ is the fundamental frequency. Hysteresis losses are due to the energy needed to reverse the magnetisation of the armature core. Eddy current losses are ohmic losses in the stator steel due to induced currents in the armature core. Excess losses (or anomalous losses) are due to changes in the magnetic domain structures when a variable magnetic field is applied to the magnetic material [59]. As can be seen from Eq. 15 the eddy current losses depend on the frequency squared and the excess losses on the frequency to the power of 1.5, since the generators studied here have very low frequencies compared to 50 Hz applications, these losses will have less influence on the total efficiency. Hence the resistive and hysteresis losses will be more important to study in the case of low frequency applications.

Other non electrical losses such as ventilation losses and frictional losses in bearings, etc. also contribute to the lowering of the overall generator efficiency. In marine current applications when the generator is surrounded by the flowing water a cooling system is assumed to be unnecessary, since it is a large machine with low power, low frequency and with low surrounding temperatures, although, this remains to be proven either through experiments or theory.

### Detailed Generator Modelling

Coupled electromagnetic field and circuit theory models are commonly used in generator modelling [60]. Those models are used to relate and transform the time and space varying electric and magnetic fields to corresponding voltages and currents delivered to a load. The electromagnetic model of the generator is based on Maxwell’s equations:

$$\nabla \cdot \mathbf{D} = \rho_f, \quad \text{Eq. 16}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \text{Eq. 17}$$
In the above equations, \( \rho_f, J_f, E, D \) and \( B \) are the free charge density, the current density, the electric field, the displacement field and the magnetic flux density, respectively in given medium having a permeability (\( \mu \)) and permittivity (\( \epsilon \)). Eq. 16 and Eq. 18 are referred to as Gauss’s law for electric and magnetic fields, respectively. Eq. 17 and Eq. 19 are referred to as Faraday’s and Ampere’s law, respectively. The current density in a medium is related to the electric field through the medium and the conductivity (\( \sigma \)) as:

\[
J_f = \sigma E, \tag{20}
\]

The magnetic flux density inside the generator at any point is related to magnetic vector potential, \( A \) as:

\[
B = \nabla \times A. \tag{21}
\]

Using the above equations, the electric field inside the generator at any point is given by:

\[
E = -\frac{\partial A}{\partial t} - \nabla V, \tag{22}
\]

where \( V \) is the scalar potential.

When the displacement currents (second term in Eq. 19) are neglected due to the low frequencies the following expression can be derived [61]:

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) + \sigma \frac{\partial A}{\partial t} = -\sigma \nabla V. \tag{23}
\]

If the flux is assumed to be two dimensional and symmetric along the z-direction (axial length of the generator), Eq. 23 can be rewritten as:

\[
\nabla \left( \frac{1}{\mu} \nabla A_z \right) + \sigma \frac{\partial A_z}{\partial t} = -\sigma \frac{\partial V}{\partial z}, \tag{24}
\]

The term \( \sigma \frac{\partial V}{\partial z} \) is the current density in the z-direction which connects any external circuits to the appropriate field quantities. The term \( \sigma \frac{\partial A_z}{\partial t} \) models the eddy currents, which for a laminated steel core is very small, and can therefore be neglected in the finite element model, (described in the next section). The above field equations are coupled to circuit Eq. 25-27. And the
combined field and circuit model is solved by a time stepping finite element technique [60].

\[ I_a + I_b + I_c = 0 \quad \text{Eq. 25} \]

\[ U_a + R_s I_a + L_{s}^{\text{end}} \frac{\partial L_a}{\partial t} - U_b - R_s I_b - L_{s}^{\text{end}} \frac{\partial I_b}{\partial t} = U_{ab} \quad \text{Eq. 26} \]

\[ U_c + R_s I_c + L_{s}^{\text{end}} \frac{\partial L_c}{\partial t} - U_b - R_s I_b - L_{s}^{\text{end}} \frac{\partial I_b}{\partial t} = U_{cb} \quad \text{Eq. 27} \]

In the above equations, \( U_a, U_b \) and \( U_c \) are the phase voltages, \( I_a, I_b \) and \( I_c \) are the phase currents, \( U_{ab} \) and \( U_{cb} \) are the line voltages and \( R_s \) is the phase resistance. End regions are taken into account by coil end impedances, \( L_{s}^{\text{end}} \), in the circuit equations of the windings.

**Finite Element Modelling**

The finite element method (FEM) is a numerical method for solving partial differential equations (field equations) for a given geometry by subdividing it into spatial nodes. The fields are calculated at all nodes for every time step iteratively. FE methods are used widely for modelling electrical machines. The magnetic field in the stator core region of the generator is assumed to be two dimensional, which is a valid simplification for radial flux machines [62], and therefore Eq. 24 can be applied. The laminated iron core in the stator is treated as a magnetically nonlinear material.

**Boundary Conditions**

Suitable boundary conditions can simplify the numerical calculations. A 2D unit cell, with periodic boundary conditions, is used. A unit cell can contain one or more rotor poles depending on the symmetry of the magnetic circuit. Radial flux generators have an axial symmetry, with a geometry that is cyclically repeated around the perimeter of the machine. If periodic boundary conditions are employed this symmetry can be used to minimize the computational problem.

Insulating boundaries are used at the outer stator diameter and the inner rotor diameter, which assumes no flux outside the magnetic circuit.

Internal moving boundary technique is used which permits modelling motion without re-meshing the FE-mesh [63]. The rotor and the stator are meshed separately and are joined by a mutual boundary in the air gap. The connection points are connected cyclically as the rotor is moved. The step length is equal to the tangential grid length in the air-gap.
Permanent Magnet Modelling

The permanent magnets are modelled by a current sheet approach described in [61]. The approach can be illustrated with an artificial field coils see Figure 14. The currents in these coils are determined based on Eq. 28.

\[ I_f = \frac{B_r h_{pm}}{\mu}, \]  
Eq. 28

In the above equation \( I_f \) is the field current corresponding to the used permanent magnet, \( B_r \) is the remanence of the permanent magnet, \( h_{pm} \) is the height of the PM [64].

![Figure 14. Illustration of the current sheet approach. The arrows illustrate the created magnetic field.](image)

Thermal Modelling

Thermal modelling is important to set the operational range for a generator. During this work Eq. 29 is used to solve the model problem to study the thermal behaviour of the generator.

\[ \nabla \cdot \lambda \nabla T = -q. \]  
Eq. 29

where \( \lambda \) is the thermal conductivity for a specific material, \( T \) is the temperature, \( q \) is the heat source [65]. Eq. 29 is used together with mixed boundary conditions expressed by:

\[ \lambda \frac{dT}{dn} = \alpha_c (T - T_a). \]  
Eq. 30

Where \( \alpha_c \) is the convective heat transfer coefficient and \( T_a \) is the ambient temperature.
Simulation Procedure

1. The user provides a two dimensional cross-section of the generator geometry based on straight lines and circular arcs creating closed domains.

2. Each geometrical domain is assigned a specific material with its properties (resistivity, permeability, coercivity, sheet thickness, density etc.) Sources such as currents and thermal sources are presented in scalars or, in more complicated cases, by circuit equations.

3. Boundary conditions are applied to the outer bounds, symmetry boundaries and moving boundaries in the air gap.

4. The next step is mesh generation. In order to provide a higher accuracy of the solution in the essential parts of the generator and to speed up the calculations, the FEM mesh is finer in the air gap and in the stator teeth and coarser in the yoke.

5. Solving the electromagnetic field models for a given moment in time (steady state) provides a rapid estimation of fields and currents. The length of the machine is calculated from the amount of permanent magnets needed to reach the given voltage.

6. Fields, currents, iron losses etc are the results of the stationary solution.

7. Solving of the coupled field and circuit model as a function of time (transient regime) gives a more accurate description of the magnetic flux in the generator.

8. From the time dependent losses the heat sources are given and the thermal equations can be solved (this can be done stationary).
Electromagnetic Forces in PM Generators

The wave energy concept that is being developed at the Swedish Centre for Renewable Electric Energy Conversion is based on a linear generator connected via a rope to a point absorber. During the construction of the first prototype the author took part in the theoretical evaluation of the electromagnetic forces in air gap of the machine. Since then, a full-scale wave power plant of this technology has now been installed off the west coast of Sweden [66].

The electromagnetic (EM) forces in PM generators are of interest when the support structures are to be dimensioned. Since the magnetic field inside the generator is largely fixed due to PM (no control on excitation), it is important to dimension the support structure to be able to withstand maximum forces. In this chapter a linear generator for wave power is studied, however, the same methodology can be applied to rotating generators for marine current energy conversion.

In the linear generator studied here the generator consists of a piston with surface mounted PMs with a vertical motion (up and down as shown in Figure 15.) relative to the cable wound stator. In the ideal case of linear generator the net normal EM forces on the piston are negligible due to symmetry. In practice there would be unbalances due to manufacturing defects leading to piston displacements and non-uniformities in the air gap.

![Figure 15. Illustration of a linear generator in a wave power plant.](image)
The resulting normal forces under such circumstances tend to increase the piston displacement even more (due to unequal forces on the different sides of the piston). Support structures are thus necessary to prevent the piston deviating from its centred position. For rotating generators a bending moment, or radial load, would arise if the rotor is displaced from its centre position.

Numerical Methods to Calculate EM Forces

Methods based on Maxwell’s Stress Tensor (MST) or the Virtual Work principle can be used for the calculation of global forces in ferromagnetic devices [67, 68]. These methods are investigated and explained in for example [69-71]. The EM force calculations based on FEM depends on the accuracy of the mesh structure and the chosen integration path. Note that the EM force calculations in FEM based on the above two methods essentially gives the same result for the resulting force [72].

Virtual Work Principle

Here the force exerted on a body is evaluated by determining the work done when it is slightly displaced from its rest position. In the absence of frictional losses, this work must equal the change in the energy stored in the electromagnetic field. Thus, if the stored energy is evaluated for the device at two positions separated by a small displacement, then the difference in energy divided by the distance will give a value for the force.

\[ F_s = \frac{-\Delta W}{\Delta x} \]  

Eq. 31

Here \( W \) is the energy stored in the electromagnetic field as a function of the position of the device. The method is valid for differential small displacements. The disadvantage of this method is the need for two FEM computations to obtain a single force value, thus it requires more computational power.

Coulombs Virtual Work Method

A further development of the virtual work method, called the local Jacobian method or Coulombs Virtual Work method [73], eliminates the drawback of having to make two FE computations. This method employs the fact that the finite element solutions are functions of space as given by the trial functions and not just the explicit nodal values that are returned. The results obtained through this scheme are more accurate than the classical virtual work method because it uses the explicit energy expression which is highly accurate in finite element analysis. The derivation is carried out within the FE calcula-
tion, therefore only one FE solution is needed, and the accuracy is improved considerably. More details of the method can be found in [73].

Maxwell Stress Tensor

Another approach to determine electromechanical forces is to use the Maxwell stress tensor method. In contrast to the virtual work technique, which employs a volume integral to determine the stored energy the Maxwell stress approach computes local stress at all points of a bounding surface. The global force acting on an object is then obtained by integrating these components over its bounding surface, as in Eq. 32,

\[ \mathbf{F} = \oint_S \mathbf{T} \, d\mathbf{S} . \]

Eq. 32

From a user point of view the methods give the same results provided that a suitable surface, \( S \), is chosen for the tensor integration [70]. However, it is worth noting that MST has the advantage of being computationally cheap, it requires just one field solution, while the classical virtual work approach demands a minimum of two. If Maxwell’s stress tensor is written in terms of the normal and tangential component, the electromagnetic forces in a linear generator can be calculated from:

\[ \mathbf{F} = \iiint \frac{1}{2\mu_0} \left( B_n^2 - B_t^2 \right) \hat{n} dS + \iiint \frac{1}{\mu_0} B_n B_t \hat{t} dS . \]

Eq. 33

where the first term corresponds to the normal forces and the second to the tangential forces. \( B_n \) is the magnetic flux density in the normal direction and \( B_t \) correspondingly in the tangential direction [71].

Magnetic Circuit Approach for Modelling the Magnetic Forces

A straightforward approach for calculating the forces in the air gap is to use the concepts of magnetic circuits. An expression for the magnetic flux between the piston/rotor and the stator can be derived using Amperes law. A simplified magnetic circuit as shown in Figure 16 can be used, if the magnetic flux and the magnetization of the stator steel are known.
Figure 16. Illustration of the simplified magnetic circuit used for the analytical derivation for the electromagnetic force for one pole.

Here $w_m$ and $w_{fe}$ is the width of the flux path and $l_{air}$, $l_{pm}$, and $l_{fe}$, is the length of the flux path in the air, in the PM and in the highly magnetized part of the iron, respectively. The iron is divided in two areas, one with high magnetic flux density and one with low magnetic flux density. The reluctance of the iron with low magnetic flux density is ignored. The regions with high magnetic inductance, i.e. the saturated part of the iron, is said to be constrained to a well defined area with constant cross-section and the permeability is modelled by a non-linear BH curve.

The magnetic flux in the air gap, $B_a$, can be expressed in terms of the geometrical factors and the material parameters using Ampere’s law:

$$\oint H \cdot dl = \int \frac{B_a}{\mu_0} dl + \int \frac{B_{fe}}{\mu_0 \mu_{fe}} dl + \int \frac{B_m - B_r}{\mu_r \mu_0} dl = 0,$$

Eq. 34

$B_r$ is the remnant flux density of the PM, $\mu_r$ is the recoil permeability of the PM, $\mu_0$ is the permeability of vacuum, and $\mu_{fe}$ is the permeability of the iron.

Assuming that there is no leakage flux and that the cross sectional areas occupied by the flux are constant the magnetic flux density in the steel can be expressed as:

$$B_{fe} = \frac{B_a A_a}{A_{fe}},$$

Eq. 35

and the magnetic flux density in the permanent magnet can be expressed as:

$$B_m = \frac{B_a A_a}{A_m}.$$

Eq. 36

Inserting these two equations in Eq. 34 gives the following expression for the magnetic flux density in the air gap.
The calculated magnetic flux density is assumed to be perpendicular to the air gap and $B_a = B_n$. This inserted into Eq. 33 yields an expression for the global normal force in the air gap. $B_a$ is calculated in an iterative manner, matching the permeability of the iron $\mu_{fe}$ and the flux intensity in the steel $B_{fe}$, with the non-linear $BH$-curve of the steel.

In paper V it is indicated that the electromagnetic forces on a piston of a linear generator will be canceled out when the piston is perfectly centered but as soon as the piston is slightly shifted a resulting force will act on the piston and possibly lead to further displacements. In Figure 17 the resulting force for a 1 mm displacement of the piston is shown, it can also bee seen that the resulting force is varying as the piston is moved up and down relative the stator, hence could lead to vibrations.

\[
B_a \left( \frac{B_r l_{pm}}{\mu_r} \right) \frac{l_{air} A_a}{\mu_{fe} A_a \mu_r A_m}. \tag{Eq. 37}
\]

\[
R_{air}(\alpha) = l_d \cos(\alpha) + \sqrt{r_i^2 - l_d^2 \sin^2(\alpha)} - r_r. \tag{Eq. 38}
\]
Where $l_{air}$ (denoted $l_d$ in Figure 18) is given as a function of the angle $\alpha$, $l_d$ is the displacement of the rotor from the centred position, $r_s$ is the inner radius of the stator and $r_r$ is the outer radius of the rotor. In Figure 18 an exaggerated rotor displacement is shown to illustrate the principle.

![Figure 18. Simplified illustration of a displaced rotor](image)

The resulting B-field as a function of the width of the air gap can then be derived for both the linear and rotating generators and from this the electromagnetic force can be derived using the earlier discussed methods.

![Figure 19. Calculated B-field as a function of air gap for the experimental generator.](image)

The resulting radial force for a 5 mm displacement is 72 kN. This was used to dimension the shaft of the experimental generator.
Design of the Experimental Generator

This chapter describes the design of the experimental generator using the numerical methods presented in previous chapters. The primary aim was to construct a laboratory type generator for performance studies. The experience gained from such studies can be used when designing a robust, efficient and reliable marine current generator for real offshore operation. The design and simulation of the experimental generator is studied in paper VII and VIII.

Design Considerations

The design of the generator is based on electromagnetic field simulations together with information for a turbine assumed to have a size of 8 m², a radius of 2.5 m and a power coefficient ($C_p$) of 0.35. Also a water current velocity of 1.5 m/s was used. According to Eq. 5 this results in an energy yield of 5 kW. A rotational speed of 10 rpm is assumed. This is below the critical limit for cavitation in the present case. Note that the data for the turbine will be different depending on the site, required power output, water current velocities etc. However, the generator design strategy remains the same for any given turbine.

For known turbine characteristics the generator is designed to keep the turbine at a constant tip speed ratio (TSR) never exceeding the critical velocity for cavitation. At higher velocities, the turbine will be electromagnetically slowed down by the generator to operate at a lower TSR. A direct drive machine will experience variable generator rotor speed depending on the current velocities. The design of the machine was largely based on achieving high efficiency at all possible rotor speeds and loads. The part load and overload capabilities of a very low speed PM generator are studied in paper VII.

The available space in the laboratory was a constraint for deciding the generator size i.e. the outer diameter of the machine was restricted to 2 m. Under such circumstances, the axial length of the generator is largely decided by the power and voltage of the machine and the air gap flux density. A nominal frequency of 10 Hz was chosen for the present variable speed machine, which gives a total of 120 poles for the rotor. Furthermore, the load angle was kept below 10°. This was found necessary to prevent the machine
from unstable operation in the event of overload conditions, e.g. during spring tide.

Armature Winding
A 3-phase cable winding is chosen for this generator. The approach with cable windings has been found effective in larger machines [17],[74]. The cable used in the present work was commercial PVC insulated MK 16 450/750 with a conductor area of 16 \text{mm}^2 and an average insulation thickness of 1 mm. Experience from development of cable wound linear generators [66] and wind generators [75] have shown that this cable is convenient from a constructional point of view.

Further, a fractional pitch winding is appropriate to prevent cogging and suppress possible harmonics in the machine. In the present case a fractional winding with the number of slots per pole and phase equal to 7/5 was found suitable. This results in a distribution factor, $k_{sh}$, of 0.977 and a pitch factor, $k_p$, of 0.952.

Stator Dimensions
The stator steel sheet geometry, especially the shape of the stator tooth, was designed to minimize the leakage flux without significantly increasing the cogging torque or decreasing the flux in the air gap [76]. The stator steel sheets chosen were 1 mm thick. This choice of a relatively thick stator steel sheet is owing to the low frequency dependant losses of the machine at 10 Hz. The stator material used for the construction of the machine is M800-100A25. Note that the maximum permissible magnetic field inside the machine was limited to 1.8 T as the saturation effects are dominant at higher magnetic fields for the chosen stator steel material.

Rotor Design
In the present work, the magnets are mounted in milled groves instead of for example using aluminium wedges to separate the magnets. A comparison of the magnetic field distributions for different PM mounting schemes have been studied in Paper VII.

The fields from a PM rotor systems are uncontrollable and a non centred rotor will give rise to non uniform forces in the air gap leading to vibrations and possible mechanical damage of the machine. To avoid such problems an air gap between the rotor and stator of 10 mm was decided, as stated in [77], the air gap for various types of synchronous electric machines usually vary between 0.5 and 25 mm depending on speed and power output. Another

The reason for the choice of a relatively large air gap is due to constructional difficulties in the assembly of this first prototype. The rotor material is construction steel with a density of 7800 kg/m³, conductivity $\sigma = 2.0 \times 10^6$ S/m and relative permeability $\mu = 965$.

**Summary of the Machine Design Parameters for Construction**

The main input parameters for the design of the prototype machine are presented in Table 2. Based on this design data, the machine was built. However, due to constructional inaccuracies and tolerances, some of the geometrical and winding parameters of the built machine were found to be different from the actual design values, see Table 2.

The axial length and currents in the machine are given as outputs from the simulations based on the below inputs and constraints due to maximum permissible magnetic field at any point in the machine. For this machine, one symmetrical cross section of the generator is shown together with the magnetic field distribution under nominal load conditions in Figure 20.

<table>
<thead>
<tr>
<th>Simulated Machine</th>
<th>Constructed Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong> 5 kW</td>
<td>5 kW</td>
</tr>
<tr>
<td><strong>Voltage</strong> 150 V</td>
<td>150 V</td>
</tr>
<tr>
<td><strong>Nominal speed</strong> 10 rpm</td>
<td>10 rpm</td>
</tr>
<tr>
<td><strong>Frequency</strong> 10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td><strong>Outer diameter</strong> 2000 mm</td>
<td>2000 mm</td>
</tr>
<tr>
<td><strong>Inner diameter</strong> 1835 mm</td>
<td>1835 mm</td>
</tr>
<tr>
<td><strong>Air gap</strong> 10 mm</td>
<td>10.5 mm</td>
</tr>
<tr>
<td><strong>Slots per pole</strong> 7/5</td>
<td>7/5</td>
</tr>
<tr>
<td><strong>Cables per slot</strong> 6</td>
<td>6</td>
</tr>
<tr>
<td><strong>PM dimensions</strong> 270 mm<em>32 mm</em>10 mm</td>
<td>68 mm<em>32 mm</em>13 mm (4 magnets/pole)</td>
</tr>
<tr>
<td><strong>Rotor ring thickness</strong> 10</td>
<td>12-15mm (14 mm for simulations)</td>
</tr>
<tr>
<td><strong>Stator height</strong> 270 mm</td>
<td>294 mm (276 mm for simulations)</td>
</tr>
<tr>
<td><strong>Stacking factor</strong> 1</td>
<td>0.956</td>
</tr>
<tr>
<td><strong>Coil end winding</strong> 80 mm</td>
<td>150 mm</td>
</tr>
<tr>
<td><strong>Resistance per phase</strong> 0.48 $\Omega$</td>
<td>0.47 $\Omega$</td>
</tr>
<tr>
<td><strong>Load</strong> 4.5 $\Omega$ per phase</td>
<td>4.44 $\Omega$ per phase</td>
</tr>
</tbody>
</table>
The Experimental Setup

A photograph of the constructed generator is shown in Figure 21. After the rotor was centred and fastened, the friction and winding resistance were measured before the magnets were mounted on the rotor. The generator was permitted to decelerate without PM according to the IEEE standard [78]. The frictional moment was measured to be 2 Nm, or 0.04 % of the nominal torque, compared to 1.575 Nm as specified by the manufacturer. The bearings used were deep groove ball bearings 6228/C3 with lubricant LGWA2 from SKF. The magnets were inserted in the milled grooves of the rotor with the aid of a purpose-built plastic mould. A picture showing the air gap and the rotor PM and the cables in the stator slots are shown in Figure 22.

A separate motor drive system consisting of a 22 kW four pole induction motor, with rated speed and torque of 1500 rpm and 143 Nm respectively, in conjunction with a gearbox (gear ratio of 89.89) is used to drive the generator. This arrangement provides generator rotor speeds in the range of 0 – 16 rpm and a maximum torque of 11 kNm. Speed control of the motor is achieved using an ABB frequency converter [79]. This arrangement allows us to run the generator 60 % above the nominal design speed which is necessary for studying the machine’s performance at overload conditions.

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Figure 21. The experimental marine current generator setup with load and motor drive system.

In the actual oceanic environment several marine generator units will be connected to a passive rectifier and DC link in the underwater substation as discussed previously. The actual load on the marine current generator is thus a typical DC load. For simulating the variable three phase loads the experimental set up presented here are connected to standard resistors mounted on heat sinks\textsuperscript{28}. The loads can be varied by connecting the resistors in either series or parallel.

Figure 22. A photograph showing the air gap, PM and the cable windings.

\textsuperscript{28} HS300 standard resistors from Arcol (www.arcolresistors.com) and KS 300.6 heat sinks from Austerlitz Electronics (http://www.austerlitz-electronic.de).
Generator Performance Analysis

This chapter describes the experiments on the laboratory marine current generator discussed in the previous chapter. The measurements are also compared with the corresponding simulations based on FEM. Note that simulations involve assumptions and experiments involve uncertainties. The generator performance is studied in paper IX-XI.

Experiments: Analysis and Results

The method of testing PM synchronous generators can be classified as, standstill tests, no-load and short circuit tests, and load tests [80]. Stand still tests are used for parameter estimation and no load tests at varying speeds may be used to identify the mechanical plus core losses at the given speed. Load tests should generally be performed with normal operating conditions, i.e. if a diode rectifier is used in the application it has to be connected to the generator as a load. However, for relatively new machines like in the present case it is appropriate to begin with simplified test arrangements [80]. For these reasons the generator is connected to the resistive loads for the initial analysis. For safety and to avoid possible floating conditions of either the generator or the loads, the neutral of both the generator and the load are shorted and grounded to the common power supply ground of the motor drive unit.

Preparatory Measurements

Electrical circuit parameters and geometrical parameters of the experimental generator were measured under standstill conditions. This is useful for the calculation of resistive losses. At low frequencies of few tens of Hz, the displacement currents are negligible; hence the capacitive effects are neglected. The resistance and inductance per phase of the winding is 0.475 Ω and 11.5 mH.

No Load Analysis

The no load experiments were carried out at the nominal speed of 10 rpm. Once the generator has reached the constant speed, the magnetic fields were
first measured in the air gap on a stator tooth, wherein the Hall probe (7010 Gauss/Tesla meter\(^{29}\)) was placed at one stator tooth perpendicular to the magnetic flux. Note that in the air gap there are two components of magnetic fields, namely normal, \(B_n\), and tangential, \(B_t\), components. The measured normal component of magnetic fields is shown in Figure 23. Also shown in Figure 23 are the magnetic fields predicted by the simulations under no load conditions on the designed generator at a point 1 mm away from the stator tooth in the air gap. It is found that the maximum normal component and tangential components of the magnetic field in the air gap are around 0.6 T and 0.15 T, respectively. The difference in the peak normal component of the measured and calculated magnetic fields is about 6 %. The force per unit area at no-load in the air gap is calculated to 65 kN/m\(^2\) using the simulation tool.

The no-load phase voltages were measured for all the three phases. One of the phase voltages is shown in Figure 24 together with the voltage predicted by the simulations on the designed generator. It is found that the rms value of the simulated voltages are about 9 % higher when compared with the measurements, even though the differences in the measured and simulated magnetic fields were only 6 %. This difference is most likely due to measurements uncertainties and due to the unequal lengths of the rotor, stator and magnets. All the measured phase voltages were balanced therefore only measurements for one phase is presented in this thesis. A four channel Lecroy Wavesurfer 424 oscilloscope\(^{30}\) was used for all the voltage and current measurements.

![Figure 23](image_url)

Figure 23. The simulated and measured no-load B-field at 10 rpm

\(^{29}\) http://www.sypris.com/stm/content.asp?page_id=359

\(^{30}\) http://www.lecroy.com
Load Analysis

The generator load tests were carried out at the nominal speed of 10 rpm and with a Y-connected load of 4.44 Ω/phase. The magnetic fields were measured similar to the no-load test cases. The measured normal component of the magnetic field is shown in Figure 25. Also shown in Figure 25 are the magnetic fields predicted by the simulations under same load conditions on the designed generator at a point 1 mm in front of the stator tooth in the air gap. The currents were measured using a universal power clamp Metrix MX24031.

Figure 25. The simulated and measured B-field components in the air gap

---

It is found that the calculated maximum normal and tangential components of the magnetic field in the air gap are around 0.6 T and 0.04 T, respectively. As far as the differences in the magnetic fields under no-load and load conditions are concerned, it is seen that the tangential component of the magnetic field under nominal load has decreased by 74% compared to the no load case; this is due to the armature reaction. However, the normal component of the magnetic field is not significantly affected by either load conditions at nominal speeds. Using the simulation tool the force per unit area in the air gap under nominal load is about 63 kN/m².

The phase voltages and phase currents measured under load conditions are shown in Figure 26 and Figure 27, respectively. Also shown in Figure 26 and Figure 27 are the voltage and currents predicted by the simulations on the designed generator under the same load conditions. From Figure 26, it is found that the differences between the simulated and the measured rms voltages at nominal load are less than 1%. In Figure 27 it is seen that the differences between the simulated and the measured rms currents are around 4%. The difference here is due to measurement uncertainties. The power delivered to the load at nominal speed of 10 rpm is shown in Figure 28. The designed generator has a rating of 5 kW under nominal load conditions. From the measured phase currents and voltages the total power delivered to the load is about 4.7 kW.

The electromagnetic losses are calculated numerically, the results can be seen in Table 3. At this stage it was not possible to measure the input torque on the generator shaft therefore the total efficiency of the generator cannot be measured.

![Phase Voltage at Nominal Load](image)

*Figure 26. Voltage at nominal load across one of the phase resistor of 4.44 Ω at nominal speed of 10 rpm.*
Figure 27. Current at nominal load across one of the phase resistor of 4.44 Ω at nominal speed of 10 rpm.

Table 3. Calculated electromagnetic losses and efficiency

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{Fe}$</td>
<td>Iron losses</td>
<td>0.25 kW</td>
</tr>
<tr>
<td>$P_{Cu}$</td>
<td>Copper losses</td>
<td>0.53 kW</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
<td>85.5 %</td>
</tr>
</tbody>
</table>

Figure 28. The total simulated and measured power output from the experimental generator at nominal load and 10 rpm.
The work aimed at having the generator efficiency as high as possible at rated speed and load of 10 rpm and 4.5 Ω/phase while keeping the current density low to maintain good thermal capabilities at overload. The resulting efficiency and current density at rated load and variable speed is shown in Figure 29. The efficiency is well above 80% in the expected range of operation and the current density is low which implies that there is plenty of room for overload without causing the temperature to rise above the thermal limit of the conductors. Thermal simulations and measurements for different loads and speeds are discussed in paper XI together with a study of the coupling of a turbine/generator system for marine current energy conversion.
Conclusions

The following conclusions can be drawn from this thesis in terms of new knowledge, modelling techniques and experimental data.

It has been shown that low speed PM generator with efficiencies of more than 85 % can be designed and constructed for energy conversion from marine currents. This has been theoretically demonstrated for small river sites and larger sites like the Messina strait in the Mediterranean. Hence a low speed PM generator can be adapted to more or less any given site and turbine.

For a more detailed study a low speed (10 rpm) direct drive generator of 5 kW capacity with PMs has been designed and constructed. The design is based on electromagnetic simulations using a FEM tool. The generator was designed to operate at high efficiency at both part load and overload situations.

Several experiments were carried out on the prototype generator. The results between the measurements and corresponding simulations on the designed generator differ by about 1 % for the phase voltage and 4 % for the currents. Measurements of voltages and currents for rotational speeds between 2-16 rpm for both no load and load cases show good agreement with simulations.

The electromagnetic forces in the air gap of a PM linear generator have been investigated numerically and with magnetic circuit analysis. The results show that if the piston is displaced a resulting force will act to displace the piston even further and also that this resulting force has a ripple that is increasing for increasing displacements.
The work presented in this thesis is only a part of the research project on marine current energy conversion system that is being studied at the Division for Electricity of Uppsala University. The results and conclusions presented within this thesis and the appended papers is a step ahead into a better understanding of the marine current power generation systems presented in this thesis. It is also acknowledged that much more theoretical and experimental investigations are still needed so as to develop an efficient and cost effective electrical energy conversion from marine currents especially for very low speeds. Some of the future work that could be studied or continued with reference to the present work are the following:

The experimental generator setup has to be modified, to include mechanical strain gauges for measuring input torque to be able to quantify the input to the generator for the efficiency measurements.

Thermal measurements on the experimental generator and corresponding FEM simulations for comparisons are to be performed.

The generator in the actual system is connected to a diode rectifier. It would be beneficial to investigate the generator performance with coupled rectifier load system.

The project aims at finding a site for testing the turbine-generator system. The choice of appropriate location for testing depends on site topography and current velocities in the region. During the spring 2008, measurements using Acoustic Doppler Current Profiler (ADCP) will be carried out.
Summary of Papers

The work presented in this thesis is mainly focused on simulations and design of very low speed permanent magnetized generators designed for energy conversion from free flowing water currents such as tidal currents, ocean currents and unregulated watercourses. Paper I and II are examples of applications where these types of low speed generators are suitable. Paper III to V focus more on specific details such as forces, magnet fixation and frequency optimization. Paper VI and VII discuss overload capabilities and electrical systems for the low speed marine current applications. Paper VIII and IX are focused on the construction of the experimental setup and paper X and XI are focused on the first experiments on the prototype generator.

Paper I

Converting kinetic energy in small watercourses using direct drive generators ( Reviewed conference paper)
The scope of this paper is to show that it is possible to dimension a marine current energy system for a small un-regulated watercourse. The starting point was cross-sectional data and water discharge data from the chosen river. A relatively small 1kW direct drive generator was designed with the electromagnetic losses and load angle as the main optimization parameters. Simulations and writing of most of the paper is done by the author. Published in Proceedings of OMAE 2004, Presented orally by Erik Segergren, June 2004, Vancouver, Canada

Paper II

Design of a very low speed PM generator for the patented KOBOLD tidal current turbine ( Conference paper)
This work was performed in cooperation with Prof. D. P. Coiro, Italy. The intention was to design a 160kW direct drive PM generator to the developed KOBOLD turbine. The starting point was a given outer dimension, the output power and rotation speed data from a full scale prototype. It was shown that it is possible to design such a generator with relatively high electromagnetic efficiency, 93 %. The author participated in simulations and writing of
Paper III

**Frequency optimization of direct drive synchronous current power generator**

When the output current is rectified at some stage between the generator and the grid hence the frequency is a free design parameter. In a situation where the size of the generator is of less importance, for example when a vertical axis/cross flow turbine is used, a large diameter generator can be used to increase the frequency. The main idea in this article is to show that a direct drive generator could be designed to efficiently convert energy under virtually any conditions. The author did simulations and participated in the writing of this paper. *Published in IEEE Journal of Oceanic Engineering, July 2005, Vol. 30, Issue 3.*

Paper IV

**Permanent magnetized generator for marine current power conversion - Proposed experimental setup (Reviewed conference paper)**

An experimental setup is proposed where the main focus is on the practical and theoretical considerations of the permanent magnet fixation concepts. The proposed setup comprises a frequency transformer, a motor, a gear box and the studied generator. On page two in the first sentence in the generator section a typing error has occurred, the frequency should be 10 Hz instead of 40 Hz. The author did the simulations of the different magnet fixation concepts. *Published in Proceedings of OMAE2005, Presented orally by the author June 2005, Halkidiki, Greece.*

Paper V

**Electromagnetic forces in the air gap of a permanent magnet linear generator at no-load.**

The electromagnetic forces in the air gap of a linear generator are investigated theoretically. The basis for the work is the low speed energy conversion of ocean wave energy into electricity using a direct-drive three-phase PM linear generator. One of several important issues is the normal forces in the air gap, which is critical when designing the support structure of the generator. An unstable condition of the global force on the piston occurs due to the increasing normal force as the air gap width decreases. The magnetic
circuit model used is very simplified and it is assumed that the magnetic flux density in tangential direction, $B_t$, is zero. The same theory and method can also be applied to rotating machines. The author did most of the work in this paper except for the magnetic circuit model. *Published in Journal of Applied Physics 2006, Volume 99, Issue 3 (2 citations)*

**Paper VI**

**Direct electric energy conversion system for energy conversion from marine currents. (Invited paper)**
This paper presents simulation results regarding the magnet mounting method and also discussions on the grid connection. Also simulations on the operation of a 5 kW generator at both part load and overloads are calculated and presented. This work is carried out to provide a base for the construction of an experimental generator. The author did simulations and writing of this paper. *Published in Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Volume 221, Number 2 / 2007*

**Paper VII**

**Experimental setup: Low speed permanent magnet generator for marine current power conversion (Reviewed conference paper)**
This paper presents the construction work of a 5 kW, 10 rpm experimental generator. In the generator design electrical properties in section 4 a misprint has occurred, the $C_p$ of the turbine should be 0.35 instead of 0.4. The author participated in the construction work and wrote parts of the paper. *Published in Proceedings of OMAE2007, Presented orally by Katarina Yuen, June 2007, San Diego, USA,*

**Paper VIII**

**A low speed generator for electrical energy conversion from marine currents – Experimental validation of simulations**
This paper presents the complete design and construction work of the 5 kW, 10 rpm experimental generator. A number of issues encountered when adapting the generator design to the nature of marine and tidal currents is discussed. The paper is ended with a presentation of measurements of phase voltage for different speeds compared to simulations. The author did the simulations, participated in the construction work and wrote most of the paper. *Submitted to Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 8th December 2007*
Paper IX

A direct drive generator for marine current energy conversion - first experimental results (Reviewed conference paper)
The preliminary results from the experimental generator is presented, measurements of the no-load and load voltages for nominal speed (10 rpm) are compared to the finite element based simulations. The laboratory experiments are carried out using a speed controlled motor drive system and resistive three phase loads. The author did measurements, simulations and most of the writing of this paper. Published in Proceedings of EWTEC2007, Presented orally by Katarina Yuen, 10-14 September 2007, Porto, Portugal.

Paper X

A low speed generator for electrical energy conversion from marine currents – No Load and Load Experiments
Detailed results from both no-load and nominal load experiments of the constructed 5 kW, 10 rpm machine is presented. The B-field, voltage and currents are measured for no load and nominal load at 10 rpm. The losses are simulated and the total power are presented also harmonic analysis of the voltage is presented. Comparisons of measurements and simulations are made. The author did the simulations, measurements and most of the writing of this paper. Submitted to IET Journal of Renewable Power Generation, December 2007

Paper XI

Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion
Variable speed and load operation of the experimental generator presented earlier is evaluated in terms of how the constructed generator performs in relation to simulations, and in terms of how the generator could perform with three different fixed pitch vertical axis turbines. Performance analysis with example turbines shows that the generator can accommodate fixed tip speed ratio operation of several turbines for current velocities between 0.5 and 2.5 m/s. The author did some of the measurements and electrical and thermal simulations and participated in the writing of the paper. Submitted to IEEE Journal of Oceanic Engineering, December 2007
Energibehovet i världen ökar kontinuerligt samtidigt som vi har ett ökande problem med utsläpp av växthusgaser bland annat från förbränning av fossila bränslen. På grund av detta har intresset för att hitta alternativa miljövänliga energikällor blivit allt större.

Ett av de miljövänliga förnybara alternativen är energiomvandling från strömmande vatten såsom tidvatten och andra havsströmmar. Idag har ett tiotal experiment i större skala gjorts på olika håll i världen men hittills har ingen gjort detta på ett kommersiellt hållbart sätt. Ett av problem som bör övervinna för att lyckas med detta är att effektivt kunna utnyttja de låga vattenströmhastigheterna som är vanligast förekommande samt att minimera underhållsbehovet för ett strömkraftverk.


Detta arbete behandlar främst direktdrivna permanentmagnetiserade generatorer anpassade för energiutvinning ur marina strömmar. Generatorns elektriska egenskaper har studerats med hjälp av simuleringar som bygger på finita element modelleringar av de magnetiska fälten i generatorn. Resultaten från dessa simuleringar ger en mycket noggrann bild av generatorns elektriska egenskaper. Utifrån dessa simuleringar och ett par detaljstudier, bland annat av hur permanentmagneterna monteras på rotorn, har en första prototypgenerator med en nominell effekt på 5 kW och en nominell rotationshastighet på 10 varv per minut byggs i laboratoriemiljö.

Ett flertal experiment har utförts för att testa generatorns prestanda och för att validera simuleringarna, bland annat mätningar av magnetfelten i luftgapet samt ström och spänning för olika rotationshastigheter och laster. Experimenten stämmer väl överens med simulerade resultat. Konstruktionen av denna generator har gett viktiga erfarenheter för framtida konstruktioner.
Denna avhandling är en del av ett större projekt där olika aspekter av ett marint strömkraftverk studeras. Slutmålet är ett tekniskt och ekonomisk hållbart system som kan producera elektricitet till nätet.
Acknowledgements

Jag vill börja med att tacka Mats min handledare under denna tid. Tack för de möjligheter och goda förutsättningar jag fått på avdelningen för elektricitetslära. Du har försett mig med en trygg bas och sett till att jag hållit mig på rätt spår i drygt fyra år av forskning och utveckling.

Ytterligare tack till alla på avdelningen för ellära, bättre och roligare arbetskamrater kan man inte. Särskilt vill jag tacka er som varit lite mer involverade i mitt dagliga arbete nämligen:

Nelson, you stepped in and debated measurements, data interpretation and relevancy issues (and my way of writing…) - several long evenings a week for months. I wish everyone faced with the task of summarizing their research could turn to such a competent, patient and generous friend.

Mårten och Katarina, utan er hade flera av artiklarna aldrig blivit klara i tid, och ingen avhandling varit inom synhåll, sannolikt inte ens en generator värd namnet. Tack för allt!

Oskar, ständig rumskamrat de första fyra åren, det blev allt lite tomt när du försvann… Tack för din noggranna genomläsning av avhandlingen. (Nu är det min tur att bjuda igen.)

Urban, tack för att du har tagit dig tid att diskutera alla mina mer eller mindre dumma frågor genom åren, tack också för dina kommentarer på avhandlingen.


Arne och Karl Erik vill jag tacka särskilt för all hjälp med simuleringarna.

Ulf, Thomas och Gunnel, Tack för alla gånger ni hjälppt mig med praktiska, datorrelaterade och administrativa problem utan er hade det inte funkat lika bra.
Sist men inte minst vill jag tacka min familj och min man. För att ni alltid finns där för mig, för att ni gör livet lättare när allt känns tungt och för att ni gläds med mig åt mina framgångar.
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