System Aspects of Marine Current Energy Conversion

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Abstract

Free-flowing water currents such as tides and unregulated water courses could contribute to world electricity production given the emergence of robust technical solutions for extracting the energy. At Uppsala University, a concept for converting water currents to electricity using a vertical axis turbine with fixed blade pitch and a direct drive permanent magnet generator is studied. A system approach is desired, and in this thesis, a first analysis of two system components, the generator and the turbine, is presented. This thesis also deals with some issues concerning the design and construction of a low speed generator for this application.

An experimental generator for verification of simulations has been designed and constructed. For the electromagnetic design, a FEM simulation tool has been used. The construction work has given valuable practical experience concerning for example handling permanent magnets and winding the generator with cable.

Simulations and measurements of the experimental generator have been carried out for different speeds and loads. The generator can operate at the speeds and loads corresponding to maximum power capture for different turbines for water current velocities between approximately 0.5 and 2.5 m/s. At higher water current velocities the turbines may need to be run at a tip speed ratio that gives a lower power capture in order to limit the electrical currents in the generator, cavitation of the blades, or mechanical loads.

Comparisons of measurements and simulations show an agreement. The FEM simulation tool can be used to simulate and design electrical machines with a low electrical frequency, i.e. 2–16 Hz.
For my grandparents
List of Papers

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


IV  **Katarina Yuen**, Karin Thomas, Mårten Grabbe, Paul Deglaire, Mathias Bouquerel, David Österberg and Mats Leijon. Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion. Accepted for publication in *IEEE Journal of Oceanic Engineering* as of November 4, 2008.

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Nomenclature and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>$[m^2]$</td>
<td>Turbine cross section</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>[T]</td>
<td>Maximum magnetic flux density</td>
</tr>
<tr>
<td>$c$</td>
<td>[m]</td>
<td>Chord length</td>
</tr>
<tr>
<td>$C_p$</td>
<td></td>
<td>Power coefficient</td>
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<tr>
<td>$d$</td>
<td>[m]</td>
<td>Lamination thickness</td>
</tr>
<tr>
<td>$E$</td>
<td>[V]</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>$f$</td>
<td>[s$^{-1}$]</td>
<td>Electrical frequency</td>
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<tr>
<td>$I_a$</td>
<td>[A]</td>
<td>Armature current</td>
</tr>
<tr>
<td>$l$</td>
<td>[m]</td>
<td>Blade length</td>
</tr>
<tr>
<td>$n$</td>
<td>[rpm]</td>
<td>Rotations per minute</td>
</tr>
<tr>
<td>$N$</td>
<td></td>
<td>Number of turns</td>
</tr>
<tr>
<td>$N_b$</td>
<td></td>
<td>Number of blades</td>
</tr>
<tr>
<td>$p$</td>
<td></td>
<td>Number of poles</td>
</tr>
<tr>
<td>$P$</td>
<td>[W]</td>
<td>Power</td>
</tr>
<tr>
<td>$r$</td>
<td>[m]</td>
<td>Turbine radius</td>
</tr>
<tr>
<td>$R_g$</td>
<td>[Ω]</td>
<td>Generator internal resistance</td>
</tr>
<tr>
<td>$R_l$</td>
<td>[Ω]</td>
<td>Load resistance</td>
</tr>
<tr>
<td>$t$</td>
<td>[s]</td>
<td>Time</td>
</tr>
<tr>
<td>$U$</td>
<td>[V]</td>
<td>Voltage</td>
</tr>
<tr>
<td>$v$</td>
<td>[m/s]</td>
<td>Velocity</td>
</tr>
<tr>
<td>$V$</td>
<td>[m$^3$]</td>
<td>Volume</td>
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<tr>
<td>$X_s$</td>
<td>[Ω]</td>
<td>Synchronous reactance</td>
</tr>
<tr>
<td>$\lambda$</td>
<td></td>
<td>Tip speed ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>[kg/m$^3$]</td>
<td>Density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td></td>
<td>Turbine solidity</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>[Tm$^2$]</td>
<td>Magnetic flux</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>[rad/s]</td>
<td>Angular velocity</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td></td>
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<td>---------</td>
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<td></td>
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<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
<td></td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
<td></td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>Permanent Magnet</td>
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</tbody>
</table>
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1. Introduction

Free-flowing water currents such as unregulated water courses, tides and ocean currents contain energy that could be utilized for electricity production. The currents can be seen as bodies of water with a potential energy, driven forward by gravity, or as a fluid with kinetic energy.

Viewing the resource as bodies of water driven by gravity, hydropower technology comes to mind. There, a dam is used to hold a reservoir of water with potential energy. Tidal-electric plants using dams also exist, most notably the La Rance tidal electric plant [1–3]. While dams contribute to efficient energy conversion, they are associated with major environmental impact as they fragment aquatic ecosystems, flood land masses, drain river beds, change sedimentation, lead to green-house gas emissions from decomposing organic material, etc. [3,4], and there is some concern about the extent of dam construction in river systems [5]. From a constructional point of view, dams may be feasible in rivers and narrow inlets, but at sites with a less channel-like bathymetry, dams may not be practical since they may require enormous amounts of material. As a complement, technology that does not require the use of a dam may give access to more of the resource since it is less evasive in a river system, and may be applicable in more ocean settings.

When viewing water as a free-flowing fluid with a certain velocity, a comparison with wind energy is relevant. There are many similarities concerning underlying physics and practical experiences. There are however also significant differences, for example resource characteristics.

Various research and development projects for free-flowing water current energy conversion are in progress around the world. In most of these, a turbine is used for power capture. Horizontal axis (propeller-like) turbines [6–11] as well as vertical axis (H-rotor) turbines [12–15] are studied. In [16] the progress of several of these projects is summarized. The characteristics of horizontal versus vertical axis turbine systems are similar to those of wind power, as explained in [17].

The potential of the resource is difficult to assess for regions, however, some attempts suggest that that the European tidal resource is 39–58 TWh annually [18–20]. In [21] the potential for tidal power is estimated to 10% of the tidal flux or 200 GW, although only technology with a dam is considered. In the same article, the potential for low-head hydropower (under 3 m) is guessed to be 2200 GW. Estimates for particular sites are also difficult, but may have better foundation. In [22] the potential for the Alderney race is estimated to be 7.4 TWh per year. Note that all of these reports are desk-top studies and
are not based on any measurements specifically made to quantify the resource potential.

1.1 Water current project at Uppsala University

1.1.1 System overview

At Uppsala University, a general system design has been chosen for more in-depth study. The basic design approach has been to form a whole system suited to the nature of the resource, i.e. flowing water, without limiting the equipment to already existing technology. Once a whole, functioning system is established, improvements can be made to specific components while taking the system effects into account. The reasoning for this is that specific components need to be able to be used in a system setting to have relevance, and improvements of the individual components may prove insignificant or even impossible to implement once the whole system is considered. It is the optimization of the system as a whole that is relevant, not individual components.

One of the fundamental design ideas is to minimize the need for maintenance and risk of failure, especially of components that will be submerged. Parts that move, and mechanical complexity in general have been avoided if possible. This reasoning is supported by [23], where causes for failure of wind power systems are analyzed. It is found that moving parts, more specifically the drive train, the gearbox and the yaw system, cause the most downtime. Gearbox failures, to which about 20% of the downtime can be attributed, are mainly caused by wear.

The general design comprises a vertical axis turbine with fixed blade pitch, a directly connected permanent magnet generator, and necessary power converters to enable grid connection, see Fig. 1.1.

**Turbine**

A vertical axis turbine has the advantage of being omnidirectional. This means that the turbine can function in for example a channel where the tide comes from different directions at different times without having to be redirected by means of a yawing system or similar. Several horizontal axis turbine designs without yawing systems exist [6, 7], but are only bi-directional, and tidal currents may not shift direction by 180°. The absence of a yawing mechanism means the absence of mechanical parts in the equipment that eventually will require maintenance and may cause failure.

Turbines with fixed blade pitch are mechanically less complex than those with pitch mechanisms. However, such a turbine will need to be run at different speeds in order to control the power capture and may require a start-up system.
Generator

The chosen turbine design requires a variable speed generator, i.e. one that can operate satisfactorily at a range of speeds and for a range of powers, as explained later in section 2. A gearbox is often used in order to increase the generator speed. In this application, however, it has been seen as desirable to avoid the need for a gearbox, so a low-speed generator is required. In order to reduce the need for maintenance of the generator, permanent magnets have been chosen rather than electromagnets.

Power converters

As the generator is to be run at different speeds, the output voltage and frequency will not be constant. Therefore, the output will need to be converted to grid frequency and voltage. Also, the output of the generator should be controlled in order to control the rotational speed, and thus maximize the power capture. A likely solution for this is a rectifier, a DC-bus, an inverter and a transformer.

1.1.2 Progress thus far

The project has so far resulted in two Ph.D. theses, [16, 24]. Currently, five Ph.D. students, including the author, are working within the project.
Low-speed permanent magnet generators for this application have been studied [25–27]. A prototype generator for laboratory experiments has been designed, constructed and evaluated, see [28] and articles I–IV.

A fluid dynamics simulation tool for vertical axis turbines has been developed [29]. So far it has mainly been applied to wind turbines, but can also be used for under water turbines and has been used in article IV.

Measurements of water current velocity profiles using an ADCP (Acoustic Doppler Current Profiler) have begun.

The planning of a full system experimental station in an outdoor setting has been initiated.

1.2 This thesis

The area of interest for the author as a Ph.D. candidate is the system as a whole; how different components within the system interact and what constraints they lay on each other. This licentiate thesis summarizes the work of the author so far, which mainly concerns the generator and its performance when operated together with the turbine. The generator designed specifically for water current energy conversion has been evaluated based on its performance when operated with three turbines. The author’s work has also included participation in the construction of this generator for use in an experimental setup. Simulations and experimental results from the generator have been compared.

The thesis has the following structure. After this introduction, a short review of the concepts used later is presented in section 2, Theory. The turbines used when evaluating the performance of the generator, generator simulations and measurements are presented in section 3, Method. In section 4, Experimental setup with generator, some of the design of the generator and practical experience from the construction work is documented. Sections 5, Results and discussion and 6, Conclusions summarize the results, discussion points and conclusions found in articles I–IV. Finally, the path ahead is commented in section 7, Future work.
2. Theory

The purpose of the theory presented here is to introduce the concepts that are treated in later sections. The reader is presumed to have a general knowledge of basic mechanics and electrical engineering. The theory presented in this section is by no means comprehensive, and for more detail and depth the referenced textbooks may be suitable.

2.1 Resource characteristics

Water currents are found in many bodies of water including rivers, straights, inlets and along coasts. Rivers are the result of water with potential energy, driven toward the sea by gravity. Tides are caused by the pull of the moon and sun. Differences in atmospheric pressure and salinity gradients are also forces that cause flow of water. [30]

The power through a cross section $A$ in a flowing fluid, such as water or air, can be expressed as

$$P = \frac{1}{2} \rho A v^3$$

(2.1)

where $\rho$ is the density of the fluid and $v$ is its velocity [31]. Water has a density of 1000 kg/m$^3$ at 5°C [32]. Current velocities may be in the order of up to a few m/s. As an example, the Alderney race, estimated to have a potential of 7.4 TWh per year, has current speeds of up to about 5 m/s [22].

There are several other characteristics of a water current site that may affect an energy conversion system but are not treated in this thesis. Some of these are the depth, the available cross section, the type of sea- or river bed, how the water current speed varies with the depth, other uses of the water, and closeness to land and a power grid.

2.2 Turbine

The function of the turbine is to capture power from the flowing water and transfer it to torque on a shaft. The turbine can capture a portion of the power that passes through its cross section, known as the power coefficient, $C_p$. From equation (2.1) we see that the power transferred to the shaft will be

$$P_{\text{shaft}} = \frac{1}{2} C_p A_{\text{turbine}} \rho v^3.$$

(2.2)
The type of turbine treated in this thesis is a vertical axis turbine with fixed blade pitch. $C_p$ depends on the tip speed ratio, $\lambda$, and for a specific tip speed ratio, $\lambda_0$, $C_p$ is maximized, see Fig. 2.1. The tip speed ratio is defined as

$$\lambda = \frac{\Omega r}{v}$$

(2.3)

where $\Omega$ is the angular velocity and $r$ is the radius of the turbine. In order to extract as much energy as possible from the water current, the turbine should be allowed to rotate at a fixed tip speed ratio, $\lambda_0$.

According to equation 2.3, the rotational speed of the turbine will not be high, considering that typical values of $v$ are in the order of a few m/s [22], and that $\lambda_0$ may be around 2–3 [13].

![Figure 2.1: $C_p$–curves for two turbines used in article IV.](image1)

$Figure\ 2.1:\ C_p$–curves for two turbines used in article IV.

![Figure 2.2: The cross section of a turbine blade. The chord length is the distance from the leading edge to the trailing edge of the blade.](image2)

$Figure\ 2.2:\ The\ cross\ section\ of\ a\ turbine\ blade.\ The\ chord\ length\ is\ the\ distance\ from\ the\ leading\ edge\ to\ the\ trailing\ edge\ of\ the\ blade.$

The cross section of a turbine blade resembles that of an airplane wing, see Fig. 2.2. The chord, $c$, is the length from the leading edge of the blade to the trailing edge. The solidity, $\sigma$, of a turbine is a measure of the size of the blades in relation to the swept area, $A$. With $N_b$ as the number of blades and $l$ as the blade length, [33] defines the solidity of a vertical axis turbine as

$$\sigma = \frac{N_b cl}{A}.$$  

(2.4)
2.3 Generator

The function of the generator is to convert the torque applied to its shaft to electricity. This is achieved through induction. According to Faraday’s law [34], an electromotive force, $E_i$, is induced in a coil with $N$ turns experiencing a changing magnetic flux, $\Phi$

$$E_i = -N \frac{d\Phi}{dt}.$$  \hfill (2.5)

Fig. 2.3 illustrates a permanent magnet, synchronous generator. Magnets are placed with alternating magnetic poles facing the stator so that the magnetic flux experienced by the coils alternates as the rotor turns. The stator and rotor usually have iron cores in order to help conduct the magnetic flux.

![Figure 2.3: A PM synchronous generator with four magnets on the rotor and four slots for the one-phase winding in the stator.](image)

The induced voltage of the generator depends on a number of parameters, including the amplitude of the magnetic flux density, $B_{\text{max}}$, the electrical frequency, $f$, and the number of turns in the winding, $N$.

$$E_i \propto N f B_{\text{max}}$$  \hfill (2.6)

The electrical frequency, $f$, of the generator is determined by the number of poles, $p$, and the rotational speed, $n$ (here $n$ is in rpm).

$$f = \frac{p}{2} \cdot \frac{n}{60}$$  \hfill (2.7)

A generator will commonly have several phases, i.e. several shifted sets of winding, in order to achieve a smoother output power. In a three-phase generator the phases will be 120 electrical degrees apart. Each phase can be modeled as an equivalent circuit, see Fig. 2.4. $R_g$ is the internal resistance per phase in the generator. $X_s$ is the synchronous reactance. Assuming the generator is connected to a purely resistive load, $R_l$, the power output for each
The losses in a generator are in part mechanical and in part electromagnetic. The mechanical losses include friction in the bearings and windage losses.

The electromagnetic losses in the generator are generally subdivided into copper losses and iron losses. The copper losses are mainly resistive losses in the winding. For each phase the resistive copper losses are \[ P_{Cu} = R_g I_a^2. \] (2.9)

Iron losses can be subdivided into hysteresis, eddy current and excess losses. As can be seen below the iron losses are frequency dependent. Hysteresis losses occur as the magnetization of the laminated iron stator core is reversed, and depend on the maximum value of the flux density, \( B_{max} \), the frequency, \( f \), the volume of the stator, \( V \), and material properties included in the coefficient \( k_h \) [35].

\[ P_{hysteresis} = k_h B_{max}^2 f V \] (2.10)

Currents are induced not only in the copper winding, but also in the stator iron, resulting in eddy current losses. In the expression below, \( d \) is the thickness of the laminations, and \( k_e \) an eddy current coefficient [36].

\[ P_{eddy} = k_{eddy} B_{max}^2 f^2 d^2 V \] (2.11)

Some literature also includes an excess dynamic loss component approximated by [37] as

\[ P_{excess} = k_{excess} (B_{max} f)^{3/2} V. \] (2.12)
2.4 Operation with maximum power capture

As seen in section 2.2, the turbine should be allowed to rotate at a specific tip speed ratio, \( \lambda_0 \), in order to achieve maximum power capture, \( C_{p}^{\text{max}} \). This means that the rotational speed of the turbine should be

\[
\Omega = \frac{v\lambda_0}{r}.
\]

(2.13)

The power captured by the turbine is then

\[
P_t = \frac{1}{2} \rho A v^3 C_{p}^{\text{max}}.
\]

(2.14)

Since the water current velocity, \( v \), is proportional to the rotational speed, \( \Omega \), the captured power will be proportional to the rotational speed cubed:

\[
P_t \propto \Omega^3.
\]

(2.15)

In this application, the turbine and generator are on the same shaft, and thus have the same rotational speed. The torque applied to the shaft by the turbine will be absorbed by the generator, and will result in either output electrical energy, losses, an increase in speed or magnetic energy. In order for the turbine to have tip speed ratio \( \lambda_0 \), the sum of the generator’s output power and losses should also be proportional to the speed cubed:

\[
P_g + P_{\text{loss}} \propto \Omega^3
\]

(2.16)

Ignoring losses, we would like to have

\[
P_g \propto \Omega^3.
\]

(2.17)

Recalling equation 2.8, we see that \( R_l \) cannot be kept constant as the water current velocity varies, since \( U \) is roughly proportional to \( \Omega \), and thus \( v \).

At some point, the water current velocity will become too high for operation at \( \lambda_0 \) to be desirable. This may be due to the capacity of the generator or cavitation on the turbine. Cavitation is wear of the turbine’s blades by the formation of small vapor pockets when the speed of the blades is high enough to cause local pressure drops below the vapor pressure of the water. Should the water current reach such velocities, the turbine can be operated at a lower tip speed ratio.

Operation at \( \lambda_0 \) gives the best power coefficient, i.e. \( C_{p}^{\text{max}} \), but does not necessarily give the best system efficiency, since this also depends on the performance of the generator at the corresponding speeds, and the subsequent converters. In practice, the control of the system may be determined by other means than operating purely at \( \lambda_0 \). For example, maximum power point tracking may be used as in [38].
3. Method

In combining basic knowledge of the generator and the turbine, as in section 2.4, we see that the generator and turbine do not function independently, but do indeed set requirements on each other. The performance of the generator becomes more relevant when combined with a turbine. In order to evaluate the versatility of the generator, three hypothetical vertical axis turbines have been used together with generator simulations. Results from the simulation program have also been compared with measurements.

3.1 Simulations

Simulations of the generator have been performed using an in-house FEM solver. A cross section of the generator is drawn and assigned material properties and boundary conditions. The mesh that is created for the geometry can be made finer close to critical areas such as the airgap, and coarser in for example the stator yoke. A combined field and circuit equation model is solved giving information about the B-field, currents, losses, temperature, etc. See [16] for more information on the simulations performed for this generator. The electromagnetic design of the experimental generator has been chosen using this simulation tool. Simulations in articles II to IV are performed using this tool.

In article IV, simulations corresponding to maximum \( C_p \) operation for rotational speeds from 4 to 16 rpm have been performed for turbines A and B, see table 3.1. This has been done by creating a look-up table with load and speed cases, and then comparing the sum of generator power output, iron losses and copper losses, with the power capture of the turbines. For each speed, a load matching \( C_p^{\text{max}} \) operation has been identified.

3.2 Measurements

Measurements of the generator voltage and current have been performed for speeds from 2 to 16 rpm and loads in steps from 2.7 to 10 \( \Omega \) per phase. The specific load cases are determined by the possible combinations of the resistors that constitute the load. Two switches per phase are used to allow three load cases per wiring. Other load cases are obtained by manually reconnecting the resistors. The speed of the generator is controlled through the frequency converter that feeds the induction motor drive.
In article II a Tektronix TPS2014 four channel digital oscilloscope with 8-bit resolution (±3% accuracy) and a metric multimeter clamp MX240/MX2040 (accuracy ± (1%R + 8D)) have been used. Voltages in article III have been measured using a Le Croy Wave Surfer 424 200 MHz Oscilloscope (accuracy ± (1.5% + 0.5% of full scale)).

In article IV a metric multimeter clamp MX240/MX2040 (accuracy ± (1%R + 8D)) has been used for measuring current. Voltages have been measured using a Le Croy Wave Surfer 424 200 MHz Oscilloscope (accuracy ± (1.5% + 0.5% of full scale)).

3.3 Example turbines

In article IV the versatility of the generator has been investigated using three hypothetical vertical axis turbines with fixed blade pitch, see table 3.1. Turbine A is the turbine used in designing the prototype generator. It can be compared with e.g. a high solidity turbine in [39]. Turbines B and C are larger than turbine A, and have higher tip speed ratios for maximum power capture. Turbine B is designed with 8 blades with a chord length of 0.25 m, while turbine C has 6 blades with chord length 0.23 m. The $C_p$-curves in Fig. 2.1 were generated by a double multiple stream tube model developed at Uppsala University [40]. Constructional issues have not been considered for these turbines; they are used to exemplify the operational range of the generator.

Table 3.1: Example turbines

<table>
<thead>
<tr>
<th>Turbine</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (m)</td>
<td>2.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>1.7</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>$C_p$ (at $\lambda_0$)</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
</tbody>
</table>
4. Experimental setup with generator

A number of design and construction issues are treated in papers I to III. This section presents some of the design and construction of the experimental setup.

4.1 Design

4.1.1 Generator

The generator is designed for 5 kW and 10 Hz at 10 rpm, but is also designed to have good under- and overload capabilities and be operable at a range of speeds. The design values are seen as typical operational values rather than upper limits, as the term ‘rated’ would indicate. For this application, variable speed may refer to operation from less than 50% of the design speed to more than 200%.

![Diagram of generator components](image)

*Figure 4.1: A segment of the generator in cross section.*

The stator contains six rows of cable winding and steel laminations of 1 mm thickness. The geometry can be seen in Fig. 4.1. The stator steel is M800-100A and has been laser cut. The cable winding is a commercial cable, MK 16 450/750 V \(^1\). A 3-phase wave winding with 7/5 slots per pole and phase is used.

The rotor holds 120 poles. Rare earth Nd\(_2\)Fe\(_{14}\)B permanent magnets are used. The magnets are 68x32x13 mm and four magnets are used for each pole. The rotor ring is designed to be at least 10 mm thick. The rotor ring is made from a steel cylinder in which grooves for the magnets have been milled.

\(^1\)Data sheet for MK 450/750 cable from Draka Kabel Sverige AB. Online November 14, 2008: http://www.draka.se/Portals/0/Produkter/Pdf/MK_450750_V.pdf
Some of the data for the constructed generator is presented in table 4.1. In paper III data for the constructed experimental setup is presented together with the design values.

Table 4.1: Generator data

<table>
<thead>
<tr>
<th>Data for the experimental generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Line voltage</td>
</tr>
<tr>
<td>Nominal speed</td>
</tr>
<tr>
<td>Frequency</td>
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<td>Outer diameter</td>
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<td>Air gap</td>
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<td>Slots per pole and phase</td>
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<td>Cables per slot</td>
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<td>PM dimensions</td>
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<td>Rotor ring thickness</td>
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<td>Stacking factor</td>
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<td>Coil end winding</td>
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<td>Resistance per phase</td>
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<tr>
<td>Nominal load</td>
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<td>Nominal current</td>
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<td>Nominal torque</td>
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4.1.2 Artificial drive system

A 22 kW induction motor and gearbox with a gear ratio of 89.89 (SEW K127DVi80L4/BM/TF), and a frequency converter (ABB 800-series) are used to drive the generator, see [41] for more detail. The drive system can operate the generator at 0-15 rpm and provide up to about 12 kNm torque. The motor and gearbox are mounted in a bracket that can be tilted and moved so that the axes of the gearbox and generator can be aligned.

4.1.3 Load

The load for the experimental setup is a symmetric resistive AC-load. An AC load is used for simplicity, as suggested by [42].
In the laboratory, the load consists of three sets of resistors mounted on heat sinks. Using two switches and connecting the resistors in different configurations, the load can be varied in steps between 10 and 2.7 Ω per phase.

Figure 4.2: The experimental setup with artificial drive and resistive load.

4.2 Construction

A photograph of the completed experimental setup is shown in Fig. 4.2, and Fig. 4.3 shows a close-up of a section of the generator. The construction work gave the individuals involved valuable experience as engineers. Winding the generator with a cable was initially found tedious, however improved technique significantly reduced the effort involved. Once the generator was wound, only a few connections needed to be made in order to complete the winding. The permanent magnets that were used to magnetize the rotor required careful handling, and specially made plastic tools were used, see Fig. 4.4. However, the process of inserting them in the milled grooves in the rotor proved easier than expected and was performed without any incidents.

As described in article I, the construction steps for the setup were roughly as follows:

1. Framework for generator elevation erected in laboratory.
2. Stator support beams erected and positioned.
4. Load built and connected.
5. Motor and gearbox connected to frequency converter.
6. Rotor and shaft positioned and fastened in generator.
7. Magnets inserted in milled grooves on rotor.
8. Gearbox shaft and generator shaft aligned and connected.
4.3 Frictional losses

After fastening the bearings that hold the rotor in place, but before connecting the gearbox and mounting the permanent magnets, the frictional losses were investigated. This was done by first accelerating the rotor, and then measuring its speed as it decelerated. The speed was measured using an optical sensor and reflective patches mounted on the rotor by every other pole. The moment of inertia for the rotor (273 kgm$^2$) was obtained from the 3D CAD software used for drawing the rotor parts.
For nominal speed, i.e. 10 rpm, the decelerating torque was calculated to 2 Nm, which is 0.04 % of the nominal torque. Other speeds within the range of operation of the setup result in a similar decelerating torque, see Fig. 4.5. After magnetizing the rotor, the friction is expected to have increased slightly due to radial forces on the bearings.

![Deceleration of the unmagnetized rotor](image)

*Figure 4.5: Deceleration of the unmagnetized rotor.*
5. Results and discussion

5.1 Generator performance with turbines

The performance of the generator in combination with three different turbines, including the turbine used for designing the generator, is presented in article IV. Fig. 5.1 shows simulations of the generator at four different load cases from 4 rpm to 16 rpm together with the maximum power capture for the three example turbines at corresponding speeds. The generator data includes output power, iron losses and copper losses. As can be seen in the figure, the power captured by the turbines mostly falls within the power output for the simulated range of loads, which implies that the generator can operate these turbines at $C_{\text{p}}^{\text{max}}$.

In Fig. 5.2 the maximum power capture of turbine A is shown together with simulated generator performance at different speeds. Here, the generator is simulated for speeds and loads such that the sum of the output power, iron losses, and copper losses equal the maximum power of turbine A. To the left, the data is presented on a logarithmic scale, and to the right on a linear scale. The logarithmic scale graph clearly shows that iron losses dominate at lower speeds (and powers), while copper losses dominate at higher speeds.

In Fig. 5.3 the efficiency and armature current of the generator corresponding to Fig. 5.2 are presented. From about 6 rpm an efficiency of more than...
Figure 5.2: Generator performance when matching $C_{p}^{\text{max}}$ operation of turbine A. To the left data in logarithmic scale, to the right linear scale. For turbine A 4-16 rpm corresponds to 0.6-2.5 m/s. From article IV.

Figure 5.3: Efficiency and RMS current of generator when operated at $\lambda_{0}$ for turbine A. From article IV.

80% is obtained. The efficiency plot shows a wide efficiency ‘peak’, which is an important characteristic for this type of generator. Preferably, the generator should function well for all of the most commonly occurring water current velocities at a site. Deviating from $\lambda_{0}$ may improve system efficiency, as mentioned in section 2.4, since the performance of the generator and power converters also affect the result. Also note the wide peak of the curves in Fig. 2.1. While there may be a specific $\lambda$ that gives maximum power capture, $C_{p}$ may be fairly good over an interval of tip speed ratios.

As can be seen in Fig. 5.2, iron losses approach the amount of power captured turbine A at low speeds. The results are similar for turbine B and C. At 4 rpm, the corresponding water current velocities are low: 0.6, 0.5 and 0.4 m/s for turbine A, B and C respectively. At these speeds the available power is low, and the iron losses become significant. At higher speeds, the current in the winding is higher, and the loss in efficiency of the generator is attributed to the copper losses.
5.2 Operational constraints

In article IV the operational limitations of the generator are discussed. As noted in the previous section, iron losses contribute to the electrical limitations when it comes to slow speeds, while copper losses may limit the operation of the generator at higher power inputs. The losses become heat in the machine, which is cooled passively through heat transfer to the surroundings. Simulations show that continuous operation with a current of approximately 60 A and an ambient temperature of 20$^\circ$C will lead to maximum temperatures in the stator close to 70$^\circ$C, see Fig. 5.4, which is what the winding insulation is specified to handle.

Considering the turbine, the rotational speed should be limited in order to prevent cavitation of the blades, as noted in articles III and IV. The exact limitation of rotational speed set by cavitation depends on a number of parameters including water depth and turbine radius. Structural mechanics issues may also limit the rotational speed of the turbine. In [18] a maximum relative blade velocity of 7 m/s is suggested, which for turbine A corresponds to a water current speed of 2.55 m/s and 17 rpm when operating at $\lambda_0$.

5.3 Site, turbine and generator

As discussed in article IV, the combination of turbine, generator and site affect the overall performance of the equipment. If the water speed distribution and available cross section of a site are known, a turbine and generator can be chosen to suit the site. In Fig. 5.5 the generator efficiency can be seen for operation of turbine A and B at $C_p^{max}$ for different water current speeds. Turbine B gives better generator performance at lower water current speeds than turbine A, so it would be a more appropriate choice in a site with a larger available cross section and lower water current speeds.

Maximizing energy output is one guide in choosing equipment, but other issues are also relevant to consider. In [43] it is discussed that at sites where
Figure 5.5: Generator efficiency versus water current speed when the generator is operated to maximize $C_p$ for turbine A and B. From article IV.

the water current velocity varies a lot, it may not be desirable to install equipment rated for maximum velocities as this may give a smoother base-load contribution, and may be cheaper in relation to the energy yield.

5.4 Comparison of simulations and measurements

Article II presents simulated and measured no-load and load voltage for three phases. The RMS values of the no-load voltage at 10 Hz has been measured to 94.6, 94.8 and 94.3 V for the three phases. As can be seen in Fig. 5.6 and 5.7, the machine is well balanced.

In article III measured and simulated voltages for the generator are shown for 2 and 16 rpm at rated load. In article IV RMS values of the current and voltage are shown for a range of loads and speeds. Measured and simulated values differ approximately 10%, which is attributed to measurement uncertainties and inaccuracies in reproducing the modeled generator.
Figure 5.6: No-load voltages for three phases at 10 rpm. Dashed lines are simulated values; solid lines are measurements. From article II.

Figure 5.7: Load voltages for three phases at design load (4.44 Ω per phase) and 10 rpm. Dashed lines are simulated values; solid lines are measurements. From article II.
6. Conclusions

The work presented in this thesis shows that a generator suitable for variable speed and load operation can be designed and constructed. Such a generator has been constructed for experimental verification. The generator can match operation corresponding to maximum power capture for several turbines for current speeds between approximately 0.5 and 2.5 m/s. For the most part, the efficiency of the generator is above 80%.

Comparisons of measurements and simulations show an agreement. The FEM simulation tool can be used for designing and simulating electrical machines with low electrical frequency, i.e. 2–16 Hz.
7. Future work

Within the area of electric energy conversion from free-flowing water currents the research issues are numerous. For the author, future work will deal with expanding and refining a system perspective.

So far, the generator has been simulated and operated with an AC load. In practice, the generator will be connected to a rectifier, and the effect of this should be studied. The existing experimental setup can be developed in order to allow some testing within this subject. Different control methods, their energy yield and requirements for equipment are another interesting topic.

On the input side, it would be interesting to incorporate actual variations in water currents. Annual water current velocity distributions will show what circumstances the equipment should be best at handling. Dimensioning issues are also affected by velocity variations and distributions. Short term fluctuations are interesting to study as they have repercussions on e.g. the control system and may result in mechanical loads that the equipment needs to tolerate.

The effect of different types of control schemes would be interesting to test on a system setup including a turbine, generator, rectifier, DC-bus and inverter in a natural aquatic setting.
8. Summary of papers

Article I

Experimental setup: Low speed permanent magnet generator for marine current power conversion.

This reviewed conference article describes the experimental setup constructed for verification of simulations of the generator. The generator is designed for 5 kW, 10 rpm and a 1.5 m/s water current. The setup also includes a resistive load and a drive system consisting of a frequency converter, an induction motor and a gearbox.

The author designed parts of the setup (mainly support structures for the stator), participated in the construction, and did most of the preparation of the article.

Published in Proceedings of OMAE2007; Presented orally by the author in June 2007, San Diego, USA.

Article II

A direct drive generator for marine current energy conversion - first experimental results.

This reviewed conference paper presents first measurements from the experimental generator. No-load and load voltages for 10 rpm are presented and compared to FEM simulations. Differences range from 2.2% (no-load, peak to peak voltage) to 10% (load voltage, peak to peak). The generator is also found to be well balanced.

The author participated in the construction of the setup and contributed to the preparation of the article.

Published in Proceedings of EWTEC2007; Presented orally by the author in September 2007, Porto, Portugal.

Article III

A low-speed generator for energy conversion from marine currents - experimental validation of simulations.

This article presents the design and construction process of a low speed generator for marine current energy conversion. Considerations and practical issues involved in adapting the generator to suit this particular application are dis-
cussed. The constructed generator differs somewhat from the original design. For example, the coil ends are longer than in the initial design. Measured and simulated voltages at 2 and 16 rpm are compared and show good agreement.

The author participated in the construction of the experimental generator and contributed to the preparation of the article.


Article IV

Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion.

This article treats how the generator performs at different speeds and loads, and in combination with different turbines. The generator’s performance is compared with maximum power capture for fixed blade pitch turbines in different water current speeds. It is found that the experimental generator can operate at the speeds and loads required to match maximum power capture of the turbines. Measurements of voltage and current are compared with simulations.

The author performed measurements, data analysis and did most of the writing of the article.

Accepted for publication in IEEE Journal of Oceanic Engineering as of November 4, 2008.
9. Sammanfattning på svenska

Fritt strömmande vatten, exempelvis tidvattenströmmar och oreglerade älvar, kan bidra till världens elproduktion förutsatt att det finns robusta tekniska lösningar för att omvandla energin. Vid Uppsala Universitet studeras ett koncept för energiomvandling av vattenströmmar till el. Konceptet omfattar en vertikalaxlad turbin med fixerade blad som driver en permanentmagnetiserad generator utan mellanled, samt kraftelektronikutrustning för att omvandla elen. Ett systemperspektiv är önskvärt, och i denna avhandling presenteras en första analys av hur två av systemets komponenter interagerar, nämligen generator och turbin.


Generatorns verkningsgrad har studerats för olika rotationshastigheter och laster. Generatorn ger en verkningsgrad på ca 80% eller mer vid hastigheter och laster som motsvarar optimal styrning av tre olika turbiner för strömhastigheter mellan ca 0,5 och 2,5 m/s.

Jämförelser mellan mätningar och simuleringar stämmer överens. FEM-verktyget kan användas för generatorer med låg elektrisk frekvens, d.v.s. 2–16 Hz.
Acknowledgments

I appreciate the path I am on, where it has taken me so far, my surroundings at present, and where I may be heading. Part of this path is learning about research and energy conversion.

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