Studies of a Vertical Axis Turbine for Marine Current Energy Conversion

Electrical system and turbine performance

JOHAN FORSLUND
Ocean energy is a field of growing interest when it comes to renewable energy thanks to its high density of energy per unit area, and to the high predictability. Conversion of hydrokinetic energy, found in marine currents, is the utilization of the energy in free-flowing water for conversion to electric energy. This thesis presents experimental data from a test site with a marine current converter.

The converter system features a vertical axis turbine directly connected to a permanent magnet synchronous generator placed on the riverbed. The converter is controlled by an electrical system. The focus of the work is to evaluate power control methods and turbine performance.

Results of a simple voltage control system is presented and compared with operation without control. The turbine type in the converter system is not self-starting. The startup power and energy has been investigated through experiments. The converter system has been connected to the local electric utility grid and the first experimental results are presented.

The performance of the turbine for a range of water speeds is investigated. The range of experiments are limited by the water velocity at the experimental site. To address the issue, a simulation model coupling the electrical system and hydrodynamic model into one has been validated. One factor affecting the turbine's power capture is the angle of the blade pitch relative to the water flow. The influence of blade pitch on turbine performance is studied with experiments and two 3D simulation models.

The possibilities of powering a desalination plant using marine current converters is discussed. Water speed data from outside the east coast of South Africa has been used for a case study. The study investigates how many people can early be supplied with freshwater using the converter system at the experimental site as a model.

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urn:nbn:se:uu:diva-363256 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-363256)
To my lovely family
Lucie, Maël and Lélio

"All it takes is a little push”
-Jack Napier
List of papers

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


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<th>Meaning</th>
</tr>
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<tr>
<td>$A$</td>
<td>$\text{m}^2$</td>
<td>Area of turbine cross section</td>
</tr>
<tr>
<td>$C$</td>
<td>-</td>
<td>Fraction of upstream and downstream water speed</td>
</tr>
<tr>
<td>$C_P$</td>
<td>-</td>
<td>Power coefficient</td>
</tr>
<tr>
<td>$C_{P_{\text{max}}}$</td>
<td>-</td>
<td>Maximum power coefficient (at $\lambda_{\text{opt}}$)</td>
</tr>
<tr>
<td>$c$</td>
<td>-</td>
<td>Correction factor for water speed</td>
</tr>
<tr>
<td>$c_{\text{incident}}$</td>
<td>-</td>
<td>Reduction of $C_P$ for incident water angle</td>
</tr>
<tr>
<td>$d$</td>
<td>$\text{m}$</td>
<td>Thickness of generator lamination</td>
</tr>
<tr>
<td>$f$</td>
<td>$\text{Hz}$</td>
<td>Electrical frequency</td>
</tr>
<tr>
<td>$i$</td>
<td>$\text{A}$</td>
<td>Current</td>
</tr>
<tr>
<td>$i_{\text{RMS}_{\text{phase}}}$</td>
<td>$\text{A}$</td>
<td>RMS current in one phase of the generator</td>
</tr>
<tr>
<td>$i_d$</td>
<td>$\text{A}$</td>
<td>d-axis current in dq0 frame</td>
</tr>
<tr>
<td>$i_q$</td>
<td>$\text{A}$</td>
<td>q-axis current in dq0 frame</td>
</tr>
<tr>
<td>$I$</td>
<td>$\text{A}$</td>
<td>Current</td>
</tr>
<tr>
<td>$J$</td>
<td>$\text{kgm}^2$</td>
<td>Inertia</td>
</tr>
<tr>
<td>$N_{\text{freshwater}}$</td>
<td>-</td>
<td>Number of people supplied with freshwater</td>
</tr>
<tr>
<td>$N_{MCC}$</td>
<td>-</td>
<td>Number of Marine Current Energy Converters</td>
</tr>
<tr>
<td>$P$</td>
<td>$\text{W}$</td>
<td>Power</td>
</tr>
<tr>
<td>$P_{\text{water}}$</td>
<td>$\text{W}$</td>
<td>Power available in the water</td>
</tr>
<tr>
<td>$P_{\text{turbine}}$</td>
<td>$\text{W}$</td>
<td>Power absorbed by the turbine</td>
</tr>
<tr>
<td>$P_{\text{load}}$</td>
<td>$\text{W}$</td>
<td>Power dissipated in the load</td>
</tr>
<tr>
<td>$P_{\text{Cu}}$</td>
<td>$\text{W}$</td>
<td>Power losses in the generator windings</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>$P_{losses}$</td>
<td>W</td>
<td>Power dissipated in the transmission line and generator winding</td>
</tr>
<tr>
<td>$Q$</td>
<td>m³/s</td>
<td>Volumetric flow rate</td>
</tr>
<tr>
<td>$r$</td>
<td>m</td>
<td>Turbine radius</td>
</tr>
<tr>
<td>$R_{load}$</td>
<td>Ω</td>
<td>Resistance of load</td>
</tr>
<tr>
<td>$R_{lines}$</td>
<td>Ω</td>
<td>Resistance of transmission lines</td>
</tr>
<tr>
<td>$R_{windings}$</td>
<td>Ω</td>
<td>Resistance of generator windings</td>
</tr>
<tr>
<td>$T$</td>
<td>Nm</td>
<td>Torque</td>
</tr>
<tr>
<td>$T_{turbine}$</td>
<td>Nm</td>
<td>Turbine torque</td>
</tr>
<tr>
<td>$T_{electric}$</td>
<td>Nm</td>
<td>Electromagnetic torque in generator</td>
</tr>
<tr>
<td>$V$</td>
<td>m³</td>
<td>Volume of the stator</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Water speed</td>
</tr>
<tr>
<td>$v_{turbine}$</td>
<td>m/s</td>
<td>Water speed at turbine</td>
</tr>
<tr>
<td>$v_{upstream}$</td>
<td>m/s</td>
<td>Water speed at upstream ADCP</td>
</tr>
<tr>
<td>$\eta_{system}$</td>
<td>-</td>
<td>System efficiency</td>
</tr>
<tr>
<td>$\lambda$, TSR</td>
<td>-</td>
<td>Tip speed ratio</td>
</tr>
<tr>
<td>$\lambda_{opt}$</td>
<td>-</td>
<td>optimal Tip Speed Ratio</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>°</td>
<td>Blade pitch angle for VACT</td>
</tr>
<tr>
<td>$\rho$</td>
<td>kg/m³</td>
<td>Density</td>
</tr>
<tr>
<td>$\omega$</td>
<td>rad/s</td>
<td>Rotational speed of turbine/generator</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Wb</td>
<td>Magnetic flux</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ALM</td>
<td>Actuator Line Model</td>
</tr>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>BLDC</td>
<td>BrushLess Direct Current</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>dq0</td>
<td>Direct-quadrature-zero</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MCP</td>
<td>Marine Current Power</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>PMSG</td>
<td>Permanent Magnet Synchronous Generator</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>SWRO</td>
<td>Seawater Reverse Osmosis</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>UU</td>
<td>Uppsala University</td>
</tr>
<tr>
<td>VACT</td>
<td>Vertical Axis Current Turbine</td>
</tr>
<tr>
<td>VAWT</td>
<td>Vertical Axis Wind Turbine</td>
</tr>
</tbody>
</table>
1. Introduction

As the interest for renewable energy is growing, the potential of the ocean and tidal energy resource is being investigated for many parts of the world. Waves and ocean current conversion to electric energy is being investigated through different concepts [1]. Marine current power utilizes the kinetic energy in free-flowing water. One of the main advantages of tidal power, besides being renewable, is its predictability. One of the main drawbacks is the variation of water speed throughout any given day and that the water speed is low. To be able to utilize as much as possible of the kinetic energy, the power take-off device must be efficient at low rotational speed and at the same time rated for handling high power. Resource characterization, developing the power conversion technology and the design of arrays are some of the biggest areas to develop if marine current energy will become economically viable [2, 3].

Marine current power is an up and coming area in renewable energy. There are several types of turbines investigated for the converter, for example vertical axis, horizontal axis or flaps, and they can for example be placed on the sea bed or suspend down from floating platforms or on the surface. The technology is similar to that of wind power, but because of the higher density of water the kinetic energy in flowing water is higher than that of air, if compared at the same flow speed. This puts higher demand on the structure mechanically, and a submerged device makes maintenance more difficult. It does, however, also present an opportunity to harness more energy per unit area of the turbine.

In thesis a Vertical Axis Current Turbine (VACT) connected directly to a Permanent Magnet Synchronous Generator (PMSG) is investigated. The converter is meant to be placed on the river- or seabed. To reduce the need of maintenance, the design features as few moving parts as possible; No yawing mechanism, no pitching of the blades and no gearbox. The only way to control the turbine is electrically, and has been the main focus of the work in this thesis.

1.1 Previous work in the project

When the author joined the Marine Current Power (MCP) project at Uppsala University (UU) in the fall of 2012, there was a prototype generator, turbine and electrical system ready for deployment at an experimental site. Previous work in the project includes generator development [4–6], designing the electrical system in [7, 8] and hydrodynamic simulations in [9]. Measurement campaigns to estimate the marine current resource have been launched in several places in Sweden and in Norway and presented in [10, 11].
1.2 Aim of the work
Once the converter unit was deployed it was the authors task to get the prototype station up and running and to perform experiments. The aim of the work has been to investigate how the converter unit should be controlled and to determine the efficiency of the converter. The main part of the work has been focused and experimental work, backed up with simulations of the electrical system. The author sought help from colleagues at the division to help evaluate the performance of the turbine using hydrodynamic simulations.

1.3 Thesis outline
The thesis is divided into the following sections: Chapter 2 gives an introduction to the Marine Current Power concept at Uppsala University and the theory behind the developed generator, turbine and electrical system. Chapter 3 describes the methods used to perform the experiments. The deployment of the converter unit is presented in chapter 4. Experimental results from power control and turbine performance are described in Chapters 5 and 6 respectively. A case study of a marine current powered desalination plant is presented in Chapter 7. The main conclusions are summarized in Chapter 8 and future work is suggested in Chapter 9. Chapter 10 summarizes the papers in this thesis and the author’s contributions. Chapter 11 is a summary of the thesis in swedish and at last the acknowledgements of the author.
2. Background and Theory

This section aims to give an introduction of the work that has previously been done in the marine current power project at Uppsala University, as well as introduce the theory and concepts behind it.

2.1 Low water speed energy converter

The MCP project at UU is developing a converter system that can efficiently extract power from slow water currents, in the range of 1-2 m/s. Previously, water speeds below 2 m/s have been deemed too low for efficient energy conversion [12]. Since the converter system is submerged in water, the design needs to be robust with a small need of maintenance considering that any operations to reach the device under water is complicated and costly. The chosen concept consists of few moving parts, and is simple in design; a permanent magnet generator directly connected to a fixed pitch turbine. The generator consists of many small magnets placed on a rotating inner part, the rotor, which when it rotates induces a voltage in the windings placed on the outer part, the stator. Since the connection between the turbine and generator does not have a gearbox, the resulting voltage produced by the slowly turning generator will be low. Extracting power at low voltage increases the losses in the windings due to the increased currents. According to Faraday’s law of induction, the induced no-load voltage is a function of the change of the magnetic flux over time, $\frac{d\Phi}{dt}$. To increase the induced voltage of the generator, the diameter of the rotor is increased so the speed of the magnets on the rotor relative to the windings in the stator, the magnetic flux $\frac{d\Phi}{dt}$, is increased. The number of poles is increased to further increase the voltage. The copper losses (ohmic losses) in the stator windings are described by

$$P_{Cu} = R_{winding}I^2 \quad (2.1)$$

where $R_{winding}$ is the resistance of the generator winding, and $I$ is the current. In addition to the copper losses, there are iron losses which can in a simplified way be divided into hysteresis losses, eddy current losses and excess losses. They depend on the geometry of the machine and the electric frequency. Note that for a specific generator design, the copper losses are only dependent on the current, and the iron losses only on the frequency.

Hall sensors are placed inside the generator with a separation of 120 electrical degrees, used for measuring the rotational speed. The sensors register
when a magnetic pole passes by, resulting in poor resolution at low rotational speeds. The startup sequence is especially hard to analyze since the generator reaches nominal speed from few electrical periods, leading to few data points.

An in-house developed simulation tool based on the program ACE [13] has been used to study the generator design. A first prototype generator was designed with a rating of 5 kW at 10 RPM, constructed and tested at the Ångström laboratory [14–18], see Fig. 2.1. To further increase the efficiency

![Figure 2.1. The first prototype 5 kW generator constructed in the Ångström laboratory. Fig. 5 from [16].](image)

some modifications of the generator were done, and a second prototype rated at 7.5 kW and 15 RPM [19, 20] was constructed. The second prototype is the generator now in use at the experimental site, in Söderfors, and is the one used for all experiments in the papers. The site is described in section 4. The generator efficiency has been found in [19] to be 87% at nominal operation. The process of designing, constructing and evaluating the machine is described in [6]. The parameters of the generator are listed in Table 2.1.
Table 2.1. Specifications for the second generator prototype developed at Uppsala University, with a 7.5 kW power rating. The listed values are for nominal operation. This generator is used for all experiments in the papers.

<table>
<thead>
<tr>
<th>Generator specification</th>
<th>Value and Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical rotational speed</td>
<td>15 RPM</td>
</tr>
<tr>
<td>Electrical frequency</td>
<td>14 Hz</td>
</tr>
<tr>
<td>Poles</td>
<td>112 -</td>
</tr>
<tr>
<td>Line-to-line rms voltage</td>
<td>138 V</td>
</tr>
<tr>
<td>Stator rms current</td>
<td>31 A</td>
</tr>
<tr>
<td>Nominal Power</td>
<td>7.5 kW</td>
</tr>
<tr>
<td>Nominal Torque</td>
<td>5.6 kN</td>
</tr>
<tr>
<td>Stator phase resistance</td>
<td>0.335 Ω</td>
</tr>
<tr>
<td>Armature inductance</td>
<td>3.5 mH</td>
</tr>
<tr>
<td>Flux linkage</td>
<td>1.28 Vs</td>
</tr>
</tbody>
</table>

Low speed vertical axis turbine

Within the MCP project a five-bladed fixed-pitch VACT has been designed and developed with the aid of hydrodynamic models and simulations. The advantages of using a vertical axis turbine over a horizontal axis turbine include: The turbine can absorb power from any incoming water direction (omni-directional), which also removes the need of a yawing system, manufacturing costs could be reduced since there is no twist along the blade, lower installation and maintenance costs because the generator (and gearbox depending on the design) can be placed at the bottom of the structure.

The turbine for the converter is a Darrieus type turbine with straight blades. A schematic of the turbine and generator mounted on the foundation can be seen in Fig. 2.2. Power for a rotating body is described by $P = \omega T$ where $T$ is torque and $\omega$ is the rotational speed in rad/s. Since the device is slow turning, extracting high power means extracting a high torque. To reduce the amplitude of the torque oscillations, the number of turbine blades is increased from the more standard (in wind power) three blades, to five. By increasing the number of blades, the ratio of the total blade surface area to the area swept by the turbine, called the solidity, is increased. A higher solidity can reduce the power absorption of the turbine. The implications of the increased solidity has been taken into account by reducing the size of the blades. Moreover, to withstand the high forces on the blades, carbon fiber was chosen due to its high strength. The power absorbed by the turbine depends on the difference in pressure between the water before and after the turbine. The power in free-flowing water with a cross sectional area $A$ can be described with

$$P_{\text{water}} = \frac{1}{2} \rho v^3$$

(2.2)

where $\rho$ is the density of water and $v$ the water speed. There is a theoretical limit of how much power a turbine can absorb from the power in the incoming
water flow, called the Betz limit, that is $16/27 \approx 59\%$. The fraction of extracted power to undisturbed water flow is called the turbine power coefficient, $C_p$. The power coefficient for a specific water speed depends on the speed of the tip of the blades relative to the water speed, called the Tip-Speed-Ratio, written TSR or $\lambda$, described by

$$\lambda = \frac{\omega r}{v}$$  \hspace{1cm} (2.3)$$

where $r$ is the turbine radius. To characterize the efficiency of a turbine, the power capture versus $\lambda$ is usually plotted, the $C_p$-curve, described by

$$C_p = \frac{P_{turbine}}{P_{water}}$$  \hspace{1cm} (2.4)$$

The $C_p$-curve for a VACT of Darrieus type usually has the shape seen in Fig. 2.3. The turbine at the experimental site is designed to have a maximum power capture of 0.35 at $\lambda=3.5$. All the turbine parameters are listed in Table 2.2.

The research of vertical axis turbines at the division of electricity at UU extends to wind power. A combined aerodynamic vortex model and electrical system model is studied in [21, 22]. Different turbine and generator design combinations have been discussed in [16, 17, 23] as well as the influence of the struts and the vertical velocity profile on turbine performance in [24] and [25].
respectively, and the effect the incident angle and spacing between turbines has on turbine performance has been studied with simulations in [26].

Table 2.2. Specifications for the vertical axis current turbine with a 7.5 kW power rating. The listed values are for nominal operation. The first turbine had a 0° pitch angle, the second 3°.

<table>
<thead>
<tr>
<th>Turbine specification</th>
<th>Value and Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Straight-bladed Darrieus</td>
</tr>
<tr>
<td>Mechanical rotational speed</td>
<td>15 RPM</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>5</td>
</tr>
<tr>
<td>Struts per blade</td>
<td>2</td>
</tr>
<tr>
<td>Blade pitch angle</td>
<td>0 or +3°</td>
</tr>
<tr>
<td>Blade material</td>
<td>Carbon fiber</td>
</tr>
<tr>
<td>Blade profile</td>
<td>NACA 0021</td>
</tr>
<tr>
<td>Chord length</td>
<td>0.18 m</td>
</tr>
<tr>
<td>Radius</td>
<td>3 m</td>
</tr>
<tr>
<td>Height</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Projected cross-sectional area</td>
<td>21 m²</td>
</tr>
<tr>
<td>Design optimal $C_p$</td>
<td>0.35</td>
</tr>
<tr>
<td>Design optimal $\lambda$</td>
<td>3.5</td>
</tr>
<tr>
<td>Weight (blades + struts)</td>
<td>230 kg</td>
</tr>
</tbody>
</table>

Load control of a Vertical Axis Turbine

When a turbine is extracting power, it is delivering torque to the shaft, $T_{turbine}$. The torque drives the generator that in turns is counteracted by the load connected to the generator, the electromagnetic torque, $T_{electric}$. If the magnitude of the torque on the shaft is equal in size to the electromagnetic torque, the turbine has reached an equilibrium state. It can be written as

$$\frac{d\omega}{dt} J = T_{turbine} - T_{electric}$$  \hspace{1cm} (2.5)

where $\omega$ is the rotational speed and $J$ is the inertia. If $T_{turbine} > T_{electric}$, the turbine will accelerate, and if $T_{electric} > T_{turbine}$, the turbine will decelerate.
Hence the size of the load affects the operation of the turbine, and is called load control. The electric power extracted is divided into power losses in the generator and transmission line, $P_{\text{losses}}$, and the load, $P_{\text{load}}$, described by

$$P_{\text{turbine}} \sim P_{\text{losses}} + P_{\text{load}}.$$  

(2.6)

where there generator losses consist of both copper losses and iron losses. Since there is no pitching of the turbine blades, the load control is the only way to change the operating point of the turbine.

**Startup of a vertical axis current turbine**

Generally lift-based turbines, such as the one in this project, are not self-starting. To start the turbine you can either adapt the turbine or implement an external starter system [27–29]. For this project it was decided to use an electrical startup system, which starts the turbine by injecting electric power to the generator. At low water speeds, it is necessary to give the turbine some rotational energy so the turbine can reach a tip speed ratio (power capture) high enough for the turbine to give a net positive torque to the generator. During two occasions during the author’s time in the project, the turbine broke during experiments. The problem originated from the fact that the turbine reaches nominal rotational speed before the turbine has built a wake, and will therefore quickly accelerate to above the nominal rotational speed. This runaway behavior is studied in [30, 31] and can clearly be seen in the startup in Fig. 5.6, section 5.3.

**Blade pitch angle of a vertical axis current turbine**

One way to increase the power coefficient of the turbine is to optimize the blade pitch angle, $\gamma$, defined in Fig. 2.4 There are not many published results for current turbines, but some results from experiments and simulations on Vertical Axis Wind Turbines (VAWT) conclude that a few degrees negative pitch angle gives the highest power coefficient [32–35].

Fortunately, on the two occasions when the turbine broke, the weak link of the construction was the attachment on the blade side. Both times, the attachment broke and the blades drifted away, leaving the strut side fully intact. New blades could be installed directly by divers in the water, without having to lift the device out of the water. After the first failure, the blades were mounted in a different pitching angle than the original setup. First the blades were mounted in an angle of $0^\circ$, and then at an angle of $3^\circ$. For the third generation of the turbine, the blades were again mounted at $0^\circ$. Note that the angle defined here is opposite of the definition used for the papers cited on the impact of pitch angle on VAWTs.
Hydrodynamic simulation models
Numerical modeling is often used to study marine current conversion. A full Computational Fluid Dynamics (CFD) model is computationally demanding for simulating the flow in and around turbines. Instead, other approaches to simplify model of the flow has been developed, and many of these models originate from wind turbine research that has been modified for water environment. Since the goal of the energy conversion is to generate electricity, it would be a big advantage to have a simulation model that can simulate both the hydrodynamic behavior as well as the electrical output. A two-dimensional free vortex method has been implemented in refs. [9, 36, 37]. Two hydrodynamic 3D models have been validated against measurements of the normal forces of a 12 kW vertical axis wind turbine [38, 39]. One is the Actuator Line Model (ALM) described in [40] and the other is a vortex filament method implemented in 3D. The validation of the two models is not yet published. There is a reasonably good agreement with experimental data in terms of the trend, magnitude and amplitude of the predicted forces. The models can identify the region for optimal TSR operation. The ALM predicts a lower $C_{P_{max}}$ than the vortex model.

2.2 Electrical system and control
There is little published in the area of control methods for VACTs with a PMSG in marine currents, but it has been a popular field of research the last two decades for vertical axis wind turbines (VAWT) with a PMSG [41–46]. Control systems for vertical axis turbines with permanent magnet synchronous generators in renewable energy with an intermittent primary resource typically operate by rectifying the generator voltages and controlling the rotational speed of the turbine using the DC bus voltage. There are a few different ways of trying to achieve maximum power point tracking (MPPT) once the turbine
has reached the nominal operation region [47, 48], and different electronic components are required depending on the application.

Two electrical systems that can extract power from the energy converter have been designed and tested at the Ångström laboratory. These are described in [7] and [8] respectively. One system injects the power to a resistive load while the other one can inject power to the grid. The two systems are separately installed at the experimental site, each with control and measurement systems implemented in LabVIEW with a CompatRIO and a Field Programmable Gate Array (FPGA). Since there are no mechanical parts for control of the turbine and generator, all control aspects of the converter have been entrusted with the electrical system. Both systems are connected to the power cables from the generator entering the cabin on-shore. When neither of the systems are operating, the power cables are short circuited to prevent the generator from rotating. Both systems feature an electrical starter for the turbine, injecting power into the generator windings to run it as a motor.

**AC-load and DC-load system**

An overview of the system is shown in Fig. 2.5, and a photo of the electrical enclosure can be seen in Fig. 2.6. The generator is started by electrically running it as a BrushLess DC (BLDC) motor using the three phase inverter. The inverter draws power from the grid through a transformer and a three phase rectifier. Hall sensors are placed inside the generator for estimating the rotor position. The BLDC applies torque to the generator by injecting bidirectional currents into two of the phases until the Hall sensors detect a new position, and the next set of predetermined phases are injected with currents. The BLDC control is implemented with a hysteresis current controller with a hysteresis band of width $\pm 1$ A of the current set point. This technique requires knowledge of the position of the rotor and a predetermined switching schedule for the control system. If the turbine is absorbing enough power from

![Figure 2.5](image.png)

*Figure 2.5. An overview of the control of the turbine using the first electrical system. (a) Startup BLDC using rectified power from the grid (b) DC control system (c) AC-load operation (d) emergency brake (e) parking brake.*
Figure 2.6. The electrical system with resistive load operation. Adapted from Fig. 3 in Paper II.

the water to give a positive net hydrodynamic torque when the startup is turned off, the turbine will rotate without a load, also called free-spin operation. The generator can be electrically loaded in three configurations:

1. No load connected.
2. Three phase AC load.
3. DC-load.

During no-load operation, there is no control of the turbine. This mode is used for evaluating the turbine during free-spin operation. The rotational speed and the voltages of the generator are recorded. For AC-load operation, a fixed resistance three phase Wye-connected load is connected. Resistors with a power rating of 0.5 kW each are connected to form the desired resistance of the load. The max capacity is 30 kW. For experiments with this connection, the turbine
is first started until it can achieve free-spin. The AC-load is then connected and the voltages and currents are recorded. The resistive load cannot be changed during operation. To estimate the power extracted by the turbine, one has to assess the tip speed ratio the turbine will operate at a specific load. The DC load consists of a resistive load, a diode-based passive three phase rectifier, a capacitor bank with 26.4 mF, and an IGBT with a snubber circuit in parallel. Further details about the hardware and the measurement system are described in section 2.2 of Paper II. The duty cycle of the IGBT can either be constant or continuously adjusted to control the DC bus voltage using a P-controller loop. The constant duty cycle is an open loop controller with a fixed duty cycle. The target DC voltage is implemented as a closed loop P-controller that uses the difference of the measured DC bus voltage minus a reference value as input. The loop has three states depending on the error. For a negative error the duty cycle is set to 0 %. This results in that no load is connected, so the generator will accelerate. When the generator accelerates, the voltage is increased. For an error higher than +5 V, the duty cycle is set to 100 %. This results in that full load operation, that will decelerate the generator and lower the voltage. For an error between 0 V and 5 V, the controller enforces a linear relationship between error and duty cycle.

**Grid connection system**

The system design is fully described in [49] and has been verified in a laboratory setup connected to a generator, presented in [50]. The grid connection features a full scale back-to-back 2L-3L cascaded H-Bridge bi-directional power converter, see Fig. 2.7. The control system is implemented with LabVIEW and a CompactRIO. The electrical enclosure is shown in Fig. 2.8.

![Figure 2.7. Overview of the full scale Back-To-Back Power Converter using an active rectifier and a 3L-inverter connected to a shared DC-link. LCL-filters before each converter and a Y-Δ connected 340/400 V transformer is connected between the grid converter and the grid. Adapted from Fig. 3 in [50].](image)

The proposed design is intended to be able to grid-connect multiple marine current converters using one shared DC-link. A 3-level power converter is connected on the grid side and a 2-level power converter on the generator side. A multi-level converter has been chosen for the grid side. This adds complexity to the system but reduces the high-frequency harmonics produced by the switching components [51, 52]. A Y-Δ connected 340/400 V transformer is
connected between the grid converter and the grid. LCL-filters before both converters are used to filter high frequency harmonics and reduce stress on the components. During startup, the generator is run as a BLDC motor with a hysteresis current controller and the grid converter as a passive rectifier. There is no rotational speed feedback or DC bus voltage control implemented during startup. When extracting power from the generator, the generator converter is run as an active rectifier, and the grid converter as a multi-level inverter.

Direct-quadrature-zero (dq0) current control [53] is used to control both converters. By applying the Clarke and Park transform of the sensed currents, the control is moved from three phase currents in the time domain to the synchronous reference frame (dq0 frame). The advantage of the dq0 frame is that the three sensed sinusoidal AC currents have become two DC variables called d-axis and q-axis current, $i_d$ and $i_q$. The two variables correspond to the active and reactive power control. PI-regulators are implemented directly to the DC variables to compare with reference currents. The PI-regulators will generate reference voltages for the generator converter.

Independent of the current control, a PI-regulator limits the DC bus voltage to 425 V as a safety measure. If the voltage exceeds the limit, an IGBT connected to a resistor ("DC chopper") is activated to dissipate power.
The DC bus voltage is used to create the reference current for the active power injected. Active power will be extracted from the DC bus until the voltage is reduced to 400 V. When the grid side converter is activated, the DC bus voltage will be reduced from 425 V to 400 V as power is injected to the grid. The reference for injected reactive power to the grid is always set to zero.

Startup, grid connection and a step response to a change in current reference of active power injected to the grid is simulated in [49]. The DC bus voltage was 400 V before extracting power from the generator, and a small overshoot in the DC bus voltage occurred as the power flow shifted from startup to power injection to the grid. The system was stable during operation until the change in current reference. When the injected power was reduced, a small ripple in the DC bus voltage was observed. During the experimental verification in the laboratory [50], there was a bigger dip in the DC bus voltage than predicted in the simulations, from 400 V to 385 V.

2.3 Site selection and water speed measurement

The marine current resource was investigated with ADCP measurements to choose a site for the experimental station. The riverbed was inspected and local authorities were contacted regarding permits. The river Dal (Dalälven) in Söderfors was chosen as the experimental test site for the project since it had a suitable water depth (∼7m) and water speeds in the desired interval (0.5-1.5 m/s). Dalälven is a regulated river and is a major resource for hydro power, with 35 hydro power plants installed for a total capacity of 1.1 GW. About 800 m upstream of the chosen site is a 20 MW hydro power station, which gives an opportunity, providing the operator is willing, for some influence of the discharge to the river. There is a bridge for cars crossing the river which is of use for the deployment, see more in section 4. Söderfors is located one hour by car north of Uppsala, in the river Dal (Dalälven), see Fig. 2.9.

The ADCP device can be placed on the bottom of the river or sea bed facing the surface to give a vertical water speed profile, or perpendicular to the surface to give a horizontal profile. The user can define how many sections the profile will be divided into, called bins, and the frequency of the sound signal to emit. The smaller the bins, the higher the noise and the higher the frequency, the shorter the measuring range. Workhorse Sentinel 1200 kHz/600 kHz ADCP devices1 has been used for all measurements.

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The water velocity distribution of the river could in 2009 be estimated [17]. The water speed was measured for 30 days, and a linear relationship between the measured water velocity and discharge data supplied by the upstream hydropower plant, was found. Using the relationship and discharge data from within the past five years, the water velocity for the past five years could be estimated. The velocity distribution is shown in Fig. 2.10.

*Figure 2.9.* (a) The location of Uppsala and Söderfors in Sweden. (b) At the test site in Söderfors, the location of the turbine and generator downstream of a hydropower plant and the measurement cabin on shore. Figures 1 and 2 from Paper I.

*Figure 2.10.* The velocity distribution of the river Dal averaged over five years of data, from 2004 to 2008. Adapted from Fig. 4 in [17].
2.4 Desalination plant powered by marine currents

Some parts of the world face combined problems of lack of fresh water and access to electricity. Seawater Reverse Osmosis (SWRO) plants are commonly used to generate freshwater from water with high salinity, such as seawater. The process requires about 2.5-4 kWh/m$^3$ [54]. A Marine current converter could be used to solve both the lack of fresh water and access to electricity. Using equation 2.2 and by estimating the efficiency of the converter system, $\eta_{system}$, an expression of the output power depending on the water speed can be found using

$$P_{converters} = N_{MCC} \cdot \eta_{system} \cdot v^3$$  \hspace{1cm} (2.7)

where $N_{MCC}$ is the number of converters and $v$ the water speed.
3. Method

This section describes the methods used to conduct the experiments.

3.1 Power control

**DC Bus voltage control**

Paper II presents experimental results from a DC bus voltage level control of a marine current converter. Three load control methods are analyzed for the variance of rotational speed, losses in the system and system efficiency. The methods are three phase resistive AC load, fixed PWM DC-load and target DC voltage control (in the paper called constant DC). The three methods are evaluated during 30 minutes of operation at similar water speed. The power extracted by the turbine is calculated with Eq. 2.6. First the AC-load experiment is conducted, then the setting of the other two methods are matched to try to give approximately the same rotational speed. The water speed, rotational speed and losses are evaluated. The iron losses in the generator are smaller than the copper losses at rated operation, and are dependent on the generator frequency. If the rotational speed is of the same order of magnitude for the experiments they can be assumed to be equal in size and not included in the analysis of the power losses.

**Startup power and energy**

This section presents the investigation of the power and energy needed for starting a 7.5 kW VACT in Paper III. The startup time and energy is investigated for a range of input power at three water speeds. The upstream ADCP measurement is used to estimate the undisturbed power in the water. The startup system uses the BLDC motor based control with a hysteresis current controller. When the startup system injects power to the generator the turbine starts to slowly rotate. The startup is considered finished when the rotational speed makes a jump to the free-spin velocity. 10 startups are conducted for each water speed and input power setting, and the average value is used for analysis. The losses considered are the copper losses in the transmission line and generator winding, the frictional losses are assumed to give a constant torque of 32 Nm and the iron losses are assumed to give a constant torque of 180 Nm.
Grid connection
The grid connection system described in section 2.2 is tested and the results are presented in Paper IV. The startup, power extraction from the generator and power injection to the grid is tested. The startup sequence is operated until the turbine is absorbing enough power to rotate without help of the startup system. Then power is extracted from the generator and dissipated into the emergency load ("DC chopper"). Then power is injected to the grid. The set points for the current reference from the generator are changed during grid operation to investigate the stability of the grid connection. The focus is on the stability of the DC bus voltage and the power flow in the system. The system is compared with the simulations in [49] and the laboratory tests in [50]. The system installed at the site is slightly modified from the simulated and laboratory tested setup. The setup in the lab boosts the grid voltage to 400 V using the grid converter during startup, but here the converter is run as a passive rectifier. In the lab setup the reference voltage of the DC bus is set to 400 V before grid connection, in the setup at the experimental site the reference voltage is set to 425 V.

3.2 Turbine performance measurements and simulations

Power coefficient of the turbine
The power coefficient curve is obtained from 21 measurement points and presented in Paper V. AC load operation during 30 minutes is conducted for a range of fixed resistances and water speeds. The power extracted by the turbine is calculated with Eq. 2.6 and the water speed measurement from the upstream ADCP. The electrical losses are the power dissipated in the load, transmission lines and generator windings. The power is calculated using the measured resistances and current. The iron losses and mechanical losses are estimated to be 180\omega.

Validating a coupled simulation model
Paper VI presents a coupled model of an electrical system with an hydrodynamic free vortex model. The model of the electrical system is implemented in Simulink and the vortex model is imported to Simulink as a function with rotational speed and water speed as inputs, and calculates the turbine torque as output.

A description of the two-dimensional free vortex method implemented is presented in [9,36,37]. The vortex method has been validated for wind turbine applications in [36,37]. The accuracy of the force calculation model decreases as the angle of attack increases, meaning that the accuracy of the simulation model can be expected to decrease for low tip speed ratios of the turbine, corresponding to high angles of attack. The losses arising from the struts on
the turbine are not properly modeled in the two-dimensional vortex model. A correction model has been applied to account for these losses, described in Paper VI. It simplifies the drag force generated from the struts to a coefficient times the square of the rotational speed. The coefficient can be determined through experiments.

The electrical model is implemented in Simulink using the `powergui` blocks. Since the hydrodynamic model and electrical model update at different time steps, a variable step solver has been used to maximize simulation speed and retain solver accuracy. The generator is modeled as a Permanent Magnet Synchronous Generator with the flux linkage, stator resistance and armature inductance from Table 2.1. The generator produces voltages and currents from the torque output of the vortex code. The power produced by the generator can then be connected either to a fixed resistive three phase AC-load, or a DC-load. The DC-load is modeled after the experimental setup described in section 2.2 and evaluated in Paper II. The parameters of the DC-load model components are listed in Table 3.1 and the Simulink model can be seen in Fig. 3.1.

First the generator and turbine models are calibrated separately. The simulated no-load generator voltage is calibrated by comparing with experimental data of no-load operation of the generator. The losses of the generator are calibrated by comparing with experimental data of AC load. A fixed torque is used as input to the generator model that results in the same rotational speed for the generator as in the experiment. The power in, and voltage over the load is evaluated.

The combined iron, frictional and bearing losses are estimated to give a constant torque of 350 Nm. The loss is implemented as a torque loss in the calculation of torque output from the turbine. The drag losses of the turbine are estimated to give a torque dependent on the rotational speed squared, times a constant. The constant is experimentally determined by allowing the turbine to rotate without any load to determine its free-spin velocity. The turbine is then simulated using this rotational velocity, and the constant has been adapted to make the simulation model give zero torque at the free-spin velocity.

The combined generator and turbine models are validated by comparing with the experimentally obtained; power coefficient curve in Paper V, free-

<table>
<thead>
<tr>
<th>Table 3.1. Passive rectifier and DC load component values in Simulink</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC load parameters</td>
</tr>
<tr>
<td>Rectifier on-resistance 1 mΩ</td>
</tr>
<tr>
<td>Rectifier forward voltage drop 0 V</td>
</tr>
<tr>
<td>IGBT on-resistance 0.1 mΩ</td>
</tr>
<tr>
<td>IGBT forward voltage drop 1 V</td>
</tr>
<tr>
<td>Snubber resistance 47 kΩ</td>
</tr>
<tr>
<td>Snubber capacitance 470 nF</td>
</tr>
</tbody>
</table>
spin RPM and TSR, and with DC-load Target voltage operation for a sequence of changes in target voltage reference. Note that in the obtained $C_p$-curve, the power extracted by the turbine is estimated with Eq. 2.6 and by assuming that the power from the iron losses and mechanical losses in the generator are $180\omega$ plus the electrical power dissipated in the load. It has later been determined that the losses are closer to $350\omega$. Hence the calculated performance does is lower than what can be the expected hydrodynamic performance of the turbine. The results from the paper are used to compare with the simulated $C_p$-curve and referred to as the $C_{p_{turbine}}$.

The target DC voltage model is evaluated on how well it can emulate step responses of the dc bus voltage and rotational speed for a change in $\lambda$. The rise time, overshoot of the rotational speed as well as the DC bus voltage are analyzed.

**Impact of blade pitch angle on turbine performance**

The purpose of these experiments is to obtain data on how the blade pitch angle impacts the power coefficient of the turbine. The experimental data are compared with numerical simulation results using the vortex filament model and the actuator line model, presented in Paper VII.

Free-spin operation and AC-load experiments of the turbine will be recorded for a range of water speeds for each pitch angle. The free-spin rotational speed will be used to estimate which pitch angle results in the lowest drag losses. The load experiments will be used to plot the $C_p$-curve for each pitch angle. The power capture and tip speed ratio is calculated for each experiment. The power extracted is calculated as the average value of the sum of the power in the load, power losses in the transmission line and generator windings, and the iron, seal and frictional losses. The iron, seal and frictional losses are estimated to be $350\omega$, from Paper VI. The power absorbed by the turbine is

\[
-p_1 = \frac{1}{2} \rho A C_{p_{turbine}} \left( \frac{V_{water}}{\Omega} \right)^3
\]

\[
V_{ABC} \quad I_{ABC}
\]

**Figure 3.1.** The Simulink model with the *vortex simulation* block that imports the vortex code as a function. The *DC load with rectifier* block has been replaced with three resistors for the AC-load simulations. Adapted from Fig. 3 in Paper VI.
estimated using Eq. 2.2 and the measured water speed. The power coefficient for each water speed is calculated using Eq. 2.4. The TSR of each experiment is calculated using Eq. 2.3 and the average of the measured water speed and rotational speed.

3.3 Estimating the water speed at the turbine

It can be noted in Fig. 4.7 that the water speed measured by the upstream and downstream ADCP is not the same when the turbine is not rotating. This is a result of the fact that the cross-sectional area changes along the river. The volumetric flow rate in cubic meter per second, $Q$, is the flow velocity times the area $\Rightarrow Q = v \cdot A$. Since there is no added flow between the two ADCPs, when the area is increased, the flow velocity is reduced. The turbine is placed between the two ADCPs, so the speed of the water at the point of the turbine is not measured. In Paper II, the undisturbed water velocity at the turbine is estimated by assuming that the turbine is placed half way between the two ADCPs, and that the water speed decreases linearly between the two devices. The water velocity at the upstream and downstream ADCPs was recorded with a frequency of 0.1 Hz, without the turbine operating, for one week in November 2014. A histogram of the fraction between the upstream and downstream measurements is shown in Fig. 3.2. The average value of the fraction, in Paper II called the correction factor, $c$, was 1.090, so the undisturbed water speed at the turbine can be estimated by

$$v_{turbine} = 0.9587 \cdot v_{upstream} \quad (3.1)$$

For most of the Papers in this thesis, the upstream velocity measurement has been used for estimating the velocity at the turbine. Sometimes the correction

![Figure 3.2](image-url)
factor has been omitted in the estimation of the water speed at the turbine, if the accuracy of the water speed measurement was of low priority.

3.4 Marine currents to power desalination

A case study of marine current converters placed in the Western Indian Ocean outside the coast of South Africa is presented in Paper VI. The goal is to supply an intermediate population size, 5000 people, with freshwater.

The SWRO plant is assumed to need 4 kWh per produced cubic meter of freshwater and that one person needs 20 liters [55] of freshwater per day. Waterspeed data is collected from [56] where the resource at 4 sites from North East London, South Africa are investigated. The top plot in Fig. 8 in [56] is used as input to 10 marine current converters. The measured water speeds have been interpolated with 100 steps between the data points. If the water speed is lower than 1.0 m/s the turbine cannot produce a net positive hydrodynamic torque. The limit is based on experience from the Söderfors experimental site, where the converter could extract power from 0.85-0.95 m/s. If the water speed is higher than 2 m/s the loads on the struts and blades are too high, and the turbine has to be shut down.

Using water speed data and eq. 2.7, the output power from any number of marine converter can be estimated. First, the efficiency of the system has to be estimated; the power output of each converter without power electronics nor transmission cable, is estimated using the results in Table 3 in Paper II, to be 19 % of the power in the undisturbed water. The incident water direction angle affects the power coefficient for the turbine. Numerical simulations of the impact of spacing (distance between turbine centers) between turbines and incident water angle are presented in [26]. The reduction of power coefficient as a function of incident angle is plotted in Fig. 2 in [26] and can be used to estimate the power output from an array of turbines placed side by side. The power electronics components are assumed to have an efficiency of 90 %. The power transmission losses from the marine current converter to the SWRO plant are estimated assuming a 1 km sea cable with resistance 0.01 Ω/km. For a transmission voltage of 400 V the losses will be around 3 %. The expression for the power output from the converters in Eq. 2.7 can now be extended to

\[ P_{\text{converters}} \approx N_{\text{MCC}} \cdot 0.19 \cdot 0.9 \cdot 0.97 \cdot c_{\text{incident}} \cdot v^3 \]  

(3.2)

where \( c_{\text{incident}} \) is the reduction of power coefficient as a result of incident water angle.
4. The Söderfors Experimental Site and Converter Deployment

Paper I describes the deployment of the turbine and generator and the first results of power extraction from the turbine. The generator and electrical system was constructed at Ångström laboratory in Uppsala and then transported to Söderfors. A cabin was placed on-shore that houses the electrical system, including power control and measurement equipment. The turbine blades were attached to the converter on location, about 300 m from the experimental site. Then the entire converter unit was transported on a trailer to the bridge for deployment, see Fig. 4.1.

![Converter Unit on Trailer](image)

_Figure 4.1. The converter unit on a trailer, nearby the experimental site, before transporting it to the river._

The deployment was carried out on March 7th 2013. The turbine and generator was lowered into the water using a crane standing on the bridge. The turbine, generator and its tripod foundation weighs almost 12 tonnes. Three-phase power and data cables from the generator were connected prior to deployment. The data cables send information from the Hall sensors and camera placed inside the generator housing. In Fig. 4.2, one can see several members of the project aligning the turbine with the ropes, and making sure that the cables are not entangled.
Figure 4.2. (a) Making sure that the cables from the generator do not get entangled somewhere while the converter unit gets lowered into the water. (b) The converter about to be submerged. Fig. 4 from Paper I, photo by Uppsala University.

The cables are wrapped in a yellow plastic tube for protection against obstacles that can be pushed away from the turbine during operation. To prevent the cables from moving along the bottom of the river, the divers also placed sand bags on top of the cables. The power cables are roughly 50 m long and guided along one of the bridge pillars to a small electrical enclosure, see Fig. 4.3. In the enclosure, there is a manual short-circuit connection that can be applied to act as a parking brake for the generator. The short-circuit is the only control of the device when it is not in operation, i.e. there are no mechanical brakes or

Figure 4.3. (a) The power and data cables from the generator are connected to a small enclosure on the bridge before rerouting to the measurement cabin. (b) The small enclosure houses a computer, marked in green, and a manual three-phase short-circuit used as a parking brake, marked in red.
safety measures. There is a second short-circuit in the cabin for redundancy. Since the cables from the enclosure to the cabin adds resistance to the circuit, the second short-circuit has a lower braking capability than the first.

On the same day, three ADCPs were installed at the site. Two of them measure the vertical velocity profile, one upstream, and one downstream, both about 15 m from the converter. Each ADCP unit was mounted on a metal structure and placed on the bottom of the river using the crane, see Fig. 4.4.

![Figure 4.4. (a) Schematic of the ADCP unit (b) mounting one of the ADCPs, for measuring the vertical velocity profile, on its foundation (c) an ADCP being deployed in the river using the crane.](image)

The last ADCP was mounted on one of the bridge pillars for measuring the horizontal velocity profile. Fig. 4.5 shows a view from the bridge after the deployment and the layout of the placement of the converter and ADCPs relative to the bridge. Two orange buoys were attached to the foundation of the

![Figure 4.5. (a) A view from the bridge, after the successful deployment. The two orange buoys on the surface mark the placement of the converter for boats passing in the river. (b) The layout of the devices placed in the river. Adapted from Fig. 4 in Paper I.](image)
converter to mark the placement of the turbine in the river.

Figures 4.6 and 4.7 show the first results presented in Paper I. The line-to-line voltages and currents from the generator were recorded during fixed AC load experiments. The load was 2.5 $\Omega$ per phase, at an upstream average velocity of 1.14 m/s resulting in a rotational speed of 12.7 RPM, equivalent to 11.8 Hz, and delivering $I_{RMS} = 23.7$ A at $V_{LLRMS} = 103$ V. The initial results indicated that the converter was operating as expected.

![Figure 4.6. Line-to-line RMS voltage and RMS current during fixed AC load operation. Adapted from Fig. 6 in Paper I.](image1)

Fig. 4.7 shows the water velocity measured before (blue line) and after (green line) the turbine when the turbine was standing still and during operation (the grey areas). During operation, the water speed at the downstream decreases significantly, verifying that the downstream ADCP is placed as intended, in the wake of the turbine.

![Figure 4.7. Measured upstream and downstream velocity during operation fixed AC load operation. Adapted from Fig. 7 in Paper I.](image2)
5. Experimental Results of Power Control

This chapter describes the experimental results from Papers II, III and IV.

5.1 DC bus voltage control

Experimental data comparing three control methods are presented in Paper II. The methods are three phase resistive AC load, fixed PWM DC-load and target DC voltage control (in the paper called constant DC). The power in the water is estimated using the measurement from the upstream ADCP and the correction factor from equation 3.1. A statistical analysis of the water speed revealed that the variance was equal for the three cases, but the average water velocity was higher for the fixed PWM case. A histogram of the rotational speed is shown in Fig. 5.1 and the results are summarized in Table 5.1. A statistical analysis of the rotational speed revealed that the variance for the three cases was not the same, and that the mean was the same for the target voltage and the fixed PWM. The target voltage control reduced the variance with a factor of 3.5 compared with the AC-load case. The variance in the rotational speed of the target voltage control is about 4.2 % of the mean value.

Table 5.1. Rotational speed of the turbine for the three load cases. Calculated average $\lambda$ from average water speed and average RPM. Table 2 from Paper II.

<table>
<thead>
<tr>
<th>Load case</th>
<th>AC</th>
<th>Fixed PWM</th>
<th>Target voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average RPM</td>
<td>15.35</td>
<td>15.68</td>
<td>15.65</td>
</tr>
<tr>
<td>Variance</td>
<td>2.34</td>
<td>2.11</td>
<td>0.65</td>
</tr>
<tr>
<td>Average $\lambda$</td>
<td>3.61</td>
<td>3.65</td>
<td>3.67</td>
</tr>
</tbody>
</table>

The amplitude of the currents in the generator in the AC-load case are the highest, see Fig. 5.2. The DC-load cases have a very pronounced third harmonic arising from the rectification. The extracted power, RMS-current from the generator and system efficiency, listed in Table 5.2, show that the cost of reducing the variation of rotational speed is higher losses. That in turn results in a lower average power extracted in the load. The system efficiency $\eta$ is around 19 % for all three cases. Note that the system efficiency accounts for the active power extracted from the turbine, i.e. the power delivered to the generator windings, transmission lines and load.
5.2 Startup power and energy

This section presents the investigation of the power and energy needed to start the turbine, described in Paper III. The three water speeds used for the experiments are below the rating of the device; 0.98 m/s, 1.04 m/s and 1.16 m/s. The startup time in relation to BLDC power is shown in Fig. 5.3. The startup time is more dependent on the BLDC power setting than the water speed. At
Table 5.2. Measured resistances, calculated RMS current in each phase, calculated power, $P_{\text{kinetic}}$, fraction of losses to $P_{\text{losses}} + P_{\text{load}}$, and system efficiency $\eta_{\text{system}}$. Adapted from Table 3 in Paper II.

<table>
<thead>
<tr>
<th>Load case Unit</th>
<th>AC</th>
<th>Fixed PWM</th>
<th>Target voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{load}}$ $\Omega$/phase</td>
<td>3.52</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>$i_{\text{RMS phase}}$ A</td>
<td>20.77</td>
<td>23.23</td>
<td>23.53</td>
</tr>
<tr>
<td>$P_{\text{load}}$ kW</td>
<td>4.60</td>
<td>4.55</td>
<td>4.44</td>
</tr>
<tr>
<td>$P_{\text{losses}}$ kW</td>
<td>0.56</td>
<td>0.70</td>
<td>0.72</td>
</tr>
<tr>
<td>$P_{\text{losses}}/(P_{\text{losses}} + P_{\text{load}})$ %</td>
<td>10.9</td>
<td>13.3</td>
<td>13.9</td>
</tr>
<tr>
<td>Mean $P_{\text{kinetic}}$ kW</td>
<td>27.44</td>
<td>28.15</td>
<td>27.78</td>
</tr>
<tr>
<td>$\eta_{\text{system}}$ -</td>
<td>0.188</td>
<td>0.187</td>
<td>0.186</td>
</tr>
</tbody>
</table>

Figure 5.3. Time to start the turbine vs average BLDC output power of the startup, for three water speeds. Adapted from Fig. 7 in Paper III.

low water speed there is a bigger difference in startup time since the input power is mostly feeding the losses.

The friction and iron losses, as seen in Fig. 5.4, stay in the region of 30 W and 170 W independent of BLDC power. The copper losses decrease with a longer startup time, and if the startup takes more than four seconds the iron losses start to dominate. For the lowest startup power, equivalent to about 1/34th of rated power of the turbine, the power mostly feed the losses in the system and the startup time is on average 10-15 s. For the highest startup power, equivalent to 1/7th of rated power, the startup time is reduced to below 2 s. Considering how the slope of the curve levels out at the end of the input power scale, increasing the startup power will not significantly reduce the startup time. This means that the BLDC power rating can be significantly lower than the power rating of the turbine and generator while still being able to maintain a short startup time.

Fig. 5.5 shows time at nominal production to generate the energy equivalent to the startup energy. A higher water speed decreases the amount of
time it takes on nominal power production to recover the startup energy. The higher the input power, the less impact on the energy retrieval time. For a high startup power, the water speed has the highest impact on the time it takes to recover the energy needed for startup. The time to recover the energy for startup is almost equal in size for the two lowest water speeds and high power, because the difference in power in the water flow is much smaller compared to \(1.16 \text{ m/s}\). For all water speeds and startup powers, the energy needed for startup is equivalent to less than \(1.2 \text{ s}\) of power production at \(C_{P_{max}}\). This result is comparable with an electrical starter system made for a 12 kW VAWT with H-rotor in [57], which found that \(3 \text{ s}\) on nominal power production was enough to recover the startup energy.

5.3 Grid connection

Paper IV presents experimental data of the grid connection system. The experiments were carried out on 2016-12-14. The upstream ADCP measurement is used to estimate the undisturbed power in the water. The measured water speeds were in the region of \(80 \%\) of the rated water speed, corresponding to \(50 \%\) of the rated power of the marine current converter. Fig. 5.6 shows the startup sequence for the generator. The DC link is charged to 328 V by the grid before the startup is activated. Since there is no boosting capability or voltage control of passive rectification, the voltage of the DC link drops as power is delivered to the generator. After a few seconds of startup operation, the turbine has reached a rotational speed close to the nominal frequency, at
which point the startup sequence is turned off. The startup time is comparable with the results found in the investigation of the startup power and energy in Fig. 5.3. The lack of rotational speed feedback results in an overshoot until a wake has been built up behind the turbine. The overshoot may expose the turbine blades to forces high enough to break connection between the struts and the blades, see [30]. The DC link is again charged to 328 V by the grid when the startup is turned off. Now there is no active control of the generator, it spins without a load connected.

Figure 5.5. Time it takes to produce the energy needed to start the turbine, for three water speeds. Adapted from Fig. 9 in Paper III.

Figure 5.6. The startup sequence of the generator. The DC link voltage, initially 328 V, is decreased as the grid supplies power to the generator to force the turbine to rotate. Once the turbine has reached a rotational speed close to the nominal frequency the startup is turned off and the DC link is again charged to 328 V by the grid. Adapted from Fig. 4 in Paper IV.
Fig. 5.7 shows the DC bus voltage, the power from the generator and the generator frequency when the current reference from the generator is set to an amplitude of 6 A. When the converter starts extracting power from the turbine the generator frequency is reduced. The oscillations in generator frequency is a result of the variation of power absorption by the turbine within each rotation of the turbine. Since the control system does not have any rotational speed feedback, the oscillations cannot be damped by the generator side converter. The DC link is charged to 424 V, with no overshoot. The simulations showed a small overshoot in DC bus voltage when the converters change the direction of the power flow, seen in Fig. 6c in [49]. In this setup, when the generator side converter is activated, the DC bus voltage is lower than what the active rectification will boost the voltage to, charging the DC bus without overshoot. A spike in amplitude of the initial extracted currents can be seen in Fig. 6 in Paper IV when the generator converter starts boosting the voltage to the DC bus. The spike correspond to an overshoot of 74 %, and then the currents reach a stable operating point after a bit more than one electrical period. The design choice of the DC bus voltage before boosting the voltage is a trade off between DC bus overshoot and initial power extracted.

\[ \text{Figure 5.7. The generator side converter starts extracting power from the turbine, the DC link is charged to 424 V and the generator frequency decreases (the grid side converter is not yet supplying the grid). Adapted from Fig. 5 in Paper IV.} \]

Fig. 5.8 shows the DC bus voltage, the power from the generator and power to the grid when the grid side converter starts injecting power to the grid. Before power injection to the grid, the power extracted from the generator is dissipated using the DC chopper. As power is injected The DC link smoothly discharges from 424 V to the set point of 400 V and reaches a stable operating point. The power extracted from the generator is not affected by the power injection to the grid. The initially high power injected to the grid is the excess energy stored in the DC bus at 424 V and discharging to 400 V. The discharge
occurs in 0.2 s where the grid converter injects up to four times more power to the grid than what is extracted from the generator. After the discharge, the power output of the grid converter follows the generator converter and the DC voltage is stable, just as in the laboratory tests in [50].

*Figure 5.8.* The grid side converter starts injecting power to the grid. Adapted from Fig. 7 in Paper IV.

After about 40 s of grid operation the grid side converter unexpectedly stops injecting power, and the power is instead dissipated in the DC chopper. Fig. 5.9 shows the DC bus voltage, power from the generator and power to the grid during the disconnect. The generator converter continues to extract power during and after the fault, and can be confirmed by looking at the generator currents in Fig. 5.10.

*Figure 5.9.* The safety system unexpectedly stops the grid side converter from injecting power to the grid. Adapted from Fig. 9 in Paper IV.
The injected grid side currents quickly increase to 20 A where the safety system disconnects the grid converter. Before the grid is disconnected there is a drop in the DC link voltage. The generator converter quickly recharges the DC bus to 424 V once the grid converter is disconnected. Taking a closer look at the behavior of both the generator and grid side control variables before the disconnection in Fig. 5.11, the only variable that changes is the grid side $i_d$. The decrease in $i_d$ corresponds to an increase in reactive power injected to the grid. The DC bus voltage drops as the grid converter tries to inject more power to the grid than the generator can supply. Synchronization with the grid voltages is not lost during the disconnection, as can be seen by that the measured Line-to-Neutral voltage in phase A is in phase with the generated reference.
voltage, seen in Fig. 12 in Paper IV. Most likely the problem is associated with the $i_d$-current controller for the grid converter. Either the PI-parameters need further tuning to be adapted for the experimental site, or the cause could be integrator windup from the repeated change in current reference. Integrator windup can be solved by implementing an anti-windup scheme [58].

Fig. 5.12 shows the generator currents, voltages, power and DC bus voltage when the current reference for active power extraction from the generator is set to zero. As the current drops to zero there is a spike in generator voltage most likely caused by the big change in current through the inductance of the generator windings and filter. The spike in voltage results in a small peak of power discharge before dropping to zero with a small overshoot.

\[\text{Figure 5.12. The generator side current reference is set to zero, no more power is extracted from the generator. Adapted from Fig. 13 in Paper IV.}\]

For both the generator and grid side current controllers, the PI regulators are quite aggressively tuned. The response is fast, but the rapid change in current lead to voltage spikes due to the inductance of the filters on each side of the DC bus or to overshooting of currents that can cause unwanted power or voltage fluctuations. The difference in the set DC bus voltage before and after
the grid and generator side converters are activated lead to unwanted power and voltage fluctuations.
6. Experimental Results of Turbine Performance

This chapter describes the results from Papers V, VI and VII.

6.1 Power coefficient of the turbine

Paper V presents the performance of the turbine with $0^\circ$ pitch angle. The calculated power coefficient from 21 measurement points is plotted in Fig. 6.1. A third degree polynomial fit of the data shows that maximum $C_P$ is 0.26 at $\lambda=3.1$. $C_{P_{max}}$ of the turbine is lower than the expected 0.35 from the design, and peaks at a lower TSR. This is most likely caused by the unexpectedly high mechanical and hydrodynamic losses of the turbine.

![Figure 6.1](image-url)

*Figure 6.1.* Power coefficient measurements from flow speeds in the interval 1.2–1.4 m/s, plotted together with fitted curve of a third degree polynomial. Adapted from Fig. 3 in Paper V.

The 180 $\omega$ estimation of the iron and mechanical losses are lower than the actual losses. In Paper VI it has been shown that the losses are closer to 350 $\omega$. In Paper II, the water speed at the turbine was found to be a few percent lower than speed measured by the upstream ADCP. Hence the actual power coefficient curve can expected to be higher than the one plotted in Fig. 6.1.
6.2 Validating a coupled simulation model

Paper VI validates a model that couples a hydrodynamic model with an electrical model implemented in Simulink.

Calibrating the simulation model

The RMS line-to-line no-load voltage of the generator for six 30-minute experiments and the simulated voltage is shown in Fig. 4 in Paper VI. The no-load voltage showed an error less than 1% compared with experimental data. The generator losses were calibrated using six load cases at around 1.3 m/s with fixed AC-load ranging from 2.54Ω to 13.0Ω. The simulated and measured power in the load is plotted in Fig. 6.2 and the voltage over the load in Fig. 6.3.

![Figure 6.2.](image1.png)  
*Figure 6.2. Power in the AC-load for calibration of the generator model. Adapted from Fig. 4a in Paper VI.*

![Figure 6.3.](image2.png)  
*Figure 6.3. Generator line-to-line RMS-voltage for calibration of the generator model using AC-load operation. Adapted from Fig. 4b in Paper VI.*
The simulations agree well except at low rotational speed where the simulated power is 2.2 % lower and the simulated generator voltage is 2.6 % higher. This is most likely a result of the iron losses being overestimated at low electrical frequency.

To calibrate the drag losses of the turbine it was let to free-spin at 1.42 m/s for 30 minutes, and resulted in a rotational speed of 20.5 RPM. Drag losses of 1000 Nm gave zero torque from the turbine in the simulations. Together with the 350\(\omega\) power losses found in Paper VI, the hydrodynamic, electrical and mechanical torque giving losses dependent on the rotational speed are therefore estimated to be \(350 + 1000\omega^2\) Nm.

**Validating the AC-load model**
The calibrated model of the turbine and generator was simulated at free-spin operation for water speeds between 1.00 m/s and 1.50 m/s in steps of 0.10 m/s. The results are compared with experimental data recorded on 8 separate occasions where the turbine operated for 30 minutes without load. The simulation and experimental results are shown in Figures 6.4 and 6.5. The simulations agree well around the rating for the turbine, 1.35 m/s. The rotational speed is 0.8 % lower than the experiment at the rated water speed and 15.9 % higher at low water speed. TSR is 0.9 % lower around 1.35 m/s and 15.9 % higher at low water speed. At high and low water speed there is a clear difference in the predicted rotational speed and TSR operating point. The difference at low water speed can be explained by the loss of accuracy since the operating point is further away from the calibration point for the drag losses. At high water speed, there is a sudden drop in the measured rotational speed. The author has no explanation for the difference at high water speed other than something exterior affecting the performance of the turbine. On some occasions the turbine was showing unexpected behavior. It could be unusually difficult to start the turbine and unable to free-spin at water speeds where it can usually do so, with the problems disappearing the next day at the same water speed. These incidents have been written off as something exterior temporarily affecting the turbine, but could not be verified since there is no possibility to visually inspect the turbine before each experiment on site. The data from these experiments are not included in the analysis. This could explain the discrepancy of the two rotational speeds measured at just below 1.0 m/s.

The simulated power coefficient curve of the turbine is shown in Fig. 6.6 together with the experimental data from Paper V. Water speeds from 1.1 m/s to 1.5 m/s are simulated with AC loads from 1 \(\Omega\) to 9 \(\Omega\) at steps of 1 \(\Omega\). The simulation shows good agreement with the experimental results. The power capture of the turbine increases as the water speed increases, because the Reynolds number increases that in turn reduces the drag losses.
Figure 6.4. Simulated and experimentally measured rotational speed during free-spin operation of the turbine. Adapted from Fig. 5a in Paper VI.

Figure 6.5. Simulated and experimentally measured TSR during free-spin operation of the turbine. Adapted from Fig. 5b in Paper VI.

Figure 6.6. Simulated and experimentally measured $C_P$-curve. Adapted from Fig. 6a in Paper VI.
Validating the DC-load model

The target voltage model is validated with target DC voltage step responses. The experiment was carried out during 826 seconds of operation where the target dc voltage reference was changed with discrete steps and kept for a time period of at least one minute. The measured water speed was in the range of 1.10-1.25 m/s. At the lowest DC voltage setting in the experiment, the turbine reached a too low TSR for the turbine to absorb power, so it stopped. The sequence of DC voltage reference steps and measured water speed was used as input to the simulation. Most of the steps showed similar results. The first steps will be analyzed and the results that stands out. The step response of the first two steps in Target DC voltage show good agreement, and are shown in Figures 8 and 9 in Paper VI. For the second step it can be noted that the simulated rotational speed is lower than the experimental, see Fig. 6.7. The generator model overestimates the iron losses at low rotational speeds, causing more electrical power to be extracted from the generator, lowering the rotational speed. Taking a closer look at the rotational speed and the DC voltage during step one, it can be seen that the voltage reaches the set point value much faster than the rotational speed settles at the new operating point, shown in Fig. 6.8. When the target voltage is increased, the DC control will disconnect the load causing the generator to accelerate. When the load is disconnected, there is no voltage drop over the transmission cable so the full generator voltage will reach the DC load control that quickly charges the capacitor. When the target voltage is decreased, the voltage drop over the transmission line will be increased.

The sixth step is a big change in tip speed ratio from $\lambda=2.2$, passing $\lambda_{opt}$, up to $\lambda=3.9$, see Figures 6.9 and 6.10. Here the no-load voltage of the generator is lower than the target voltage, so the DC control has to wait for the generator to accelerate in order to generate a higher voltage. Once the target voltage has been reached the control system again extracts power, braking.

Figure 6.7. Simulated and experimentally measured rotational speed during the second step. Adapted from Fig. 9b in Paper VI.
the accelerating generator. Both the simulation and the experiment show an overshoot in rotational speed, but it is significantly higher in the simulation. The rotational speed is initially lower in the simulation so it needs more time to absorb the energy needed to reach the set point. Additionally, since the turbine starts at a lower rotational speed and accelerates freely, it will have a higher $\omega/dt$ when it reaches the voltage set point. The turbine will reach a higher rotational speed and this higher rotational energy takes longer time to release, resulting in a bigger overshoot. It has been shown in [31] that the forces on the turbine blades during runaway (overshoot related to free-spin of the turbine) can be up to 2.7 times the forces during nominal operation. It is therefore of great importance that the control system can brake the turbine at high rotational speeds. Increasing the magnitude of the DC load gives the control system a bigger load to brake the turbine with, and the overshoot could be reduced faster. However, controlling the rotational speed directly with a PI or PID regulator is a safer choice, since it can react faster to an overshoot or completely remove it if the regulator is tuned correctly.
**Figure 6.9.** Simulated and experimental step response of the DC bus voltage at step 6, at operation from low to high $\lambda$. Adapted from Fig. 11a in Paper VI.

**Figure 6.10.** Simulated and experimental step response of the rotational speed of the turbine at step 6, at operation from low to high $\lambda$. Adapted from Fig. 11b in Paper VI.
6.3 Impact of pitch angle on turbine performance

Paper VII presents experimental data and simulations on the impact of pitch angle on turbine performance. The experimental results from free-spin operation can be seen in Figures 6.11 and 6.12. The turbine with 0° pitch operates at a higher rotational speed for all water speeds except at low and and high speeds where it is similar in magnitude of the turbine with +3° pitch. The drag losses seem to be lower for the turbine with 0° pitch in operation at free-spin TSR.

![Figure 6.11](image)

*Figure 6.11.* Experimentally measured rotational speed at free-spin, for two pitch angles.

![Figure 6.12](image)

*Figure 6.12.* Experimentally measured TSR at free-spin, for two pitch angles.

The simulated and experimentally obtained $C_P$ curves can be seen in Fig. 6.13. Both simulations and the experimental data suggest that the 0° pitch have lower drag losses, and gives a higher maximum $C_P$ than +3°. The experimentally measured $C_P$ at +3° is 25 % lower than 0°. The vortex and ALM models both predict that -3° reduces the power capture more than +3°.
Figure 6.13. Simulated and experimentally measured $C_p$-curves, at different pitch angles.

In Fig. 6.14 it can be seen that both the ALM and vortex simulation predict that $+1^\circ$ results in the highest average $C_p$ of the turbine. Comparing the $C_p$ for $+3^\circ$ with $0^\circ$; The vortex model predicts 8.7 % lower, the ALM 3.2 % lower and the experiment 25.2 % lower $C_p$. Comparing the $C_p$ for $-3^\circ$ with $0^\circ$; The vortex model predicts 28.3 % lower and the ALM 10.1 % lower $C_p$. Comparing the $C_p$ for $+1^\circ$ with $0^\circ$; The vortex model predicts 1.6 % higher and the ALM 0.5 % higher $C_p$.

The results follow in line with the referenced literature for wind turbines, that a pitch angle of a few degrees can increase the average $C_p$.

Figure 6.14. Simulated and experimentally measured average $C_p$ as a function of pitch angle. Note that TSR is 3.4 for the ALM simulation and the experiment, and 3.2 for the vortex simulation.
7. Powering a Desalination Plant with Marine Current Energy

Paper VIII proposes a system based on the Söderfors turbine and generator together with the electrical system from Paper II, and presents a case study of marine current converters placed in the Western Indian Ocean outside the coast of South Africa. It is apparent from Fig. 7.1 that the proposed system cannot by itself continuously supply freshwater to any population size, since the water speed will for consecutive weeks be below the lowest limit for the converter. According to data from the case study site in Fig. 8 in [56], the incident water angles cover a range from \(-40^\circ\) to \(+40^\circ\). Using the power coefficient as a function of incident angles plot in Fig. 2 in [26], and to simplify the calculations, the power coefficient for the turbines in the case study are assumed to be decreased by 2\% for all angles. The reduction of power coefficient is included into equation 3.2 and gives

\[
P_{\text{converters}} \approx N_{\text{MCC}} \cdot 1706 \cdot v^3
\]

(7.1)

where \(N_{\text{MCC}}\) is the number of converters and \(v\) the water speed. Assuming that the desalination plant requires 4 kWh per cubic meter freshwater produced and the daily consumption of 20 L per day, the number of people supplied
with freshwater as a function of the number of converters and water speed can be expressed as

\[
N_{\text{freshwater}} = P_{\text{converters}} \frac{24 \cdot 7}{4000 \cdot 0.14} = 511.8 \cdot N_{\text{MCC}} \cdot v^3
\]  

(7.2)

Equations 7.1 and 7.2 together with the obtained water speed data are used to plot the power and number of people supplied with freshwater in Fig. 7.2. During 75% of the time the converter is producing power. When the converter is producing power, the SWRO plant is supplying a minimum of 5000 people, and at most almost 25 thousand people.

A water storage tank system is considered in addition to the setup. 5000 people can be supplied with freshwater using a water storage with a capacity of 2800 m³, seen in Fig. 7.3. A rather large tank supply is needed since there are several weeks when the water speed is too low. The impact of water storage capacity and to what extent (in percent) it can supply a population size, is shown in Fig. 7.4. The difference in time between for how long a small and a large population size can be supplied with freshwater is relatively small. 1000 people can be supplied at 75% of the time without a tank, and 10000 people can be supplied for almost 55% of the time. Fig. 9 in Paper VIII shows that the maximum number of people the system can continuously supply freshwater for is \( \approx 5240 \) people with a storage capacity of 3100 m³. The limit of the number of people that can be supplied is set by the energy available for the marine current converter to extract. Note that the waterspeed data was collected during one year, and seasonal variation will affect the capability of the combined marine current converter and desalination plant. The choice of number of converters and capacity of storage has to be adapted to the needs and resource characteristics of each site.

\[
\text{Figure 7.2. Number of people supplied with freshwater and power supplied by the marine current converter to the desalination plant, every week during one year (without water storage). Fig. 6 from Paper VIII}
\]
**Figure 7.3.** Freshwater supplied to at minimum 5000 people per week using a tank with a capacity of 2800 m$^3$, during every week of the year. The blue line is people (thousands) supplied by the system, and the dashed red line is the water storage supply (m$^3$). Fig. 7 from Paper VIII.

**Figure 7.4.** Fraction of the time (%) a population size will be yearly supplied with freshwater, depending on the capacity of the water storage in addition to the desalination plant.
8. Conclusions

Experimental results from three different control methods are analyzed in Paper II. The target DC voltage control system was able to lower the variance in rotational speed, compared to fixed AC load and fixed PWM, at the cost of higher losses. Control of the turbine at high rotational speed is of great importance to ensure a safe operation of the turbine.

At nominal operation the converter has a rotational energy so low that any change in water speed quickly changes the rotational speed. This means that there is a very small buffer in terms of control of the turbine. Another result of the low rotational energy is that the startup sequence of the converter is very short. There is not enough time to build up a wake behind the turbine before the turbine has reached nominal operation. No wake at nominal operation means that if the turbine is left without control, it will accelerate to a rotational speed where the forces on the turbine blades and attachments are so high they risk damaging the turbine. One can conclude that a controlled startup is very important. The power and energy needed to start the turbine is investigated. It shows that the startup time is mostly dependent on input power, not on water speed. A startup input power of 1/7th of the rating of the converter is enough to start the machine within 2 seconds and the results suggest that a higher power would not significantly reduce the startup time or energy needed for startup. The energy needed to start the turbine is small in comparison to the power available for the converter to extract, less than 1.2 s of power production for all water speeds.

Experimental results of a grid connection system that features a back-to-back power converter has been presented. The design allows several turbines to be connected to one shared DC-bus. The startup and generator power extraction functionality behaved as expected. The system was able to change the power flow from the grid to the grid instantaneously. Some additional work on the PID for the current controller is needed to ensure stable operation.

The performance of a vertical axis current turbine is dependent on the blade pitch angle in relation to the relative water flow. The performance of the turbine with a 0° blade pitch angle has been investigated. Maximum power capture is found at tip-speed-ratio 3.1 and gives $C_{p_{\text{max}}}=0.26$. The performance is lower than expected, most likely caused by the unexpectedly high mechanical losses of the turbine. In hope of increasing the power capture, a +3° blade pitch angle has also been investigated. Results from both experiments and simulations suggest that the power coefficient is reduced by increasing the pitch from 0° to +3°. Results from simulations suggest that the peak power coefficient is at +1°. It should increase the power capture by 1-2 % compared with at 0°.
A simulation model that couples electrical and hydrodynamic models of a vertical axis marine current energy converter has been presented. The simulated power coefficient curve and steps of target dc voltage agree overall well with experimental data. The coupled model could be used to simulate the behavior of the converter system at water flow speeds that are not present at the experimental site.

A method to estimate the potential of a marine current powered desalination plant to supply freshwater is proposed. A case study from a region outside the coast of East London, South Africa, with water speeds in the interval 0.1-1.7 m/s is presented. The variations of water speed indicate that the converter only can supply the plant with power during 75% of the year. A system of ten converters, each modeled after the converter presented in this thesis, can supply at minimum 5000 and at maximum almost 25000 people. Using a water storage tank with a capacity of 2800 m² the population can be supplied all year around.
9. Future work

The lack of active startup control resulted in the turbine breaking twice. To prevent overshoot of the rotational speed during startup, to ensure the safety of the turbine, an active control must be implemented.

The experiments in this thesis have recorded data during 10 or 30 minutes. It would be interesting to do longer experiments with an autonomous drive of an MPPT to investigate the utilization factor for marine currents in a river using a vertical axis turbine.

For the grid connection, it would be interesting to investigate the injected power in terms of quality and current harmonics. The ride-though capability of the converter system during faults should be analyzed. The system is designed for several marine converter connected to one shared DC link, and tests were performed with one device. It would be interesting to conduct tests with several devices.

The turbine is a slow turning device, the angular kinetic energy is low, and extracts power at a high torque. During each revolution of the turbine, the torque varies with the incident angle of the water relative to the blade. The combination of high torque and low angular kinetic energy results in high torque fluctuations. To reduce the variations in torque, the blade number has been increased from the standard three blades used in vertical axis wind turbines. However, the variations in rotational speed during each revolution are still clearly visible. The resulting variations in rotational speed make the turbine drift away from the optimal tip-speed-ratio during each revolution, and may reduce the average power capture. A control system could be designed to follow the variations in torque to maximize the extracted power.

There is a lower limit to at what water speed the turbine will start to absorb power, called the cut-in speed. A hydrodynamic model of the the startup followed by an experimental investigation of the limit can help to evaluate the energy yield potential of a marine current site.

The influence of blade pitch angle on power coefficient for the turbine has been experimentally investigated for two pitch angles. Simulations suggest that the peak coefficient occurs between the two investigated angles. Experiments with smaller increments in pitch angle could be conducted to find the peak.
10. Summary of papers

In the following text the papers in the thesis are summarized and the author’s contribution is presented.

Paper I

The Söderfors Project: Experimental Hydrokinetic Power Station Deployment and First Results.
During 2013 an experimental hydrokinetic power station was deployed for in-stream experiments at a site in a river. This paper briefly describes the deployment process and reports some initial results from measurements made at the test site. The author participated in all of the experimental work and the deployment process.

Paper II

Experimental Results of a DC Bus Voltage Level Control for a Load-Controlled Marine Current Energy Converter.
This paper experimentally investigates three load control methods for the turbine. The three cases are; a fixed AC load, a fixed PWM DC load and a DC bus voltage control of a DC load. Experimental results show that the DC bus voltage control reduces the variation of rotational speed with a factor of 3.5. For all three cases, \( \lambda \) can be kept close to the expected \( \lambda_{\text{opt}} \). The author participated in all of the experimental work, analyzed the data together with the co-authors and wrote the paper.
Paper III

Power And Energy Needed For Starting A Vertical Axis Marine Current Turbine

This paper investigates the energy and power needed to at low speeds start the turbine electrically with a BrushLess DC (BLDC) motor, until the turbines gives a net positive torque to the generator. It is shown that the energy needed for startup is equivalent to less than 1.2 s of power production at maximum power capture of the turbine. The startup time is mostly dependent on BLDC power setting, not on water speed, and a BLDC power of 1/7th of rated power of the machine is enough to start the machine within 2 seconds. The author conducted the experiments, analyzed the data together with the co-authors and wrote the paper.

Paper IV

First Experimental Results of a Grid Connected Vertical Axis Marine Current Turbine using a Multilevel Power Converter

This conference paper presents the grid connection system and the first results. The startup of the turbine, power extraction and initial active power injection to the grid, at 50 % of rated power, operated as predicted by laboratory experiments and simulations. However, the grid converter experienced some issues mostly likely associated with the current controller. Further tuning of the PI regulators and the potential addition of an anti-windup could mitigate the control issue. The author conducted the experiments, analyzed the data together with the co-author and wrote the paper.

Paper V

Experimental Demonstration of Performance of a Vertical Axis Marine Current Turbine in a river

This paper presents an experimental study of the performance of the turbine. The performance of the turbine is comparable to that of vertical axis turbines designed for higher water speeds, demonstrating the viability of electricity generation in low speed (below 1.5 m/s) marine currents. The author participated in all of the experimental work and analyzed the data together with the co-authors.
Paper VI

Validation of a Coupled Electrical and Hydrodynamic Simulation Model For A Vertical Axis Marine Current Energy Converter.

A simulation model is validated that couples an electrical model in Simulink with a hydrodynamic vortex model by comparing with experimental data. The simulated results agree well experimental data except for low rotational speed where the accuracy of the calibration of the drag losses is reduced. The author designed the electrical simulation, conducted the experiments and wrote the majority paper.

Paper VII

Impact of Blade Pitch Angle on Turbine Performance of a Vertical Axis Current Turbine

The paper presents experimental and simulation results of the power capture of the turbine for different pitch angles. An ALM and a vortex model is applied for 3D simulations. Experimental and simulation results suggest that an angle of +0° gives higher $C_P$ than +3°. Both simulation models suggest that +1° gives a 1-2 % higher power output than +0°. The author conducted the experiments, analyzed the data together with the co-authors and wrote all parts in the paper except the description of the simulation models.

Paper VIII

Marine Current Energy Converters to Power a Reverse Osmosis Desalination Plant

This paper presents a method to estimate the potential for a marine current powered reverse osmosis desalination plant to supply freshwater to a population. It presents a case study in the coastal region outside South Africa in the Western Indian Ocean. The study finds that with the addition of a water storage tank with a capacity of 2800 m$^3$, the combined system can deliver freshwater to 5000 people all year around. The author provided the description and calculations relating to the marine current conversion unit and analyzed the results together with the co-authors.
11. Sammanfattning på svenska


Figure 11.1. Schematisk bild av strömkraftverket. Den har en vertikalaxlad turbin kopplad direkt till en generator med permanentmagneter.


Figure 11.2. Sjösättning av strömkraftverket i Dalälven i Söderfors. Foto Uppsala universitet.

Ett elektriskt system för att leverera el från strömkraftverket till nätet testas. Designen är byggd så att ett flertal strömkraftverk ska oberoende kunna kopplas till samma nätkoppling. Den visar lovande resultat.

Den typen av turbin som är vald i projektet är generellt inte självstartande. Uppstartsförloppet för turbinen har studerats genom att kolla på hur mycket effekt som behövs för att starta den och hur mycket energi som behövs i förhållande till den energin som kan utvinnas vid den vattenfarten presenteras. Slutsatsen är att den är väldigt liten oberoende av vilken effekt man levererar till den.


Bladen på turbinen är fixerade till en viss vinkel. Hur stor påverkan vinkeln har på turbinens effektupptagningsförmåga har studerats experimentellt för två olika vinklar. Utöver experimentet har resultaten backats up i samarbete med kollegor på avdelningen som genomfört hydrodynamiska 3D simuleringsar. Resultaten föreslår att man bör vinkla bladen lite i förhållande till startpositionen för att öka prestandan med 1-2%.
En simuleringsmodell som kopplar samman den elektriska biten med en hydrodynamisk modell har tagits fram. Den har validerats mot experimentella data från experimentstationen. Med hjälp av den kan man studera olika kontrollstrategier beroende på vattenfart, och få en noggrann beskrivning av hur turbinen skulle bete sig under såna förhållanden.
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