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# Hydro-Kinetic Energy Conversion

*Resource and Technology*

MÅRTEN GRABBE



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#### **Abstract**

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The kinetic energy present in tidal currents and other water courses has long been appreciated as a vast resource of renewable energy. The work presented in this doctoral thesis is devoted to both the characteristics of the hydro-kinetic resource and the technology for energy conversion.

An assessment of the tidal energy resource in Norwegian waters has been carried out based on available data in pilot books. More than 100 sites have been identified as interesting with a total estimated theoretical resource—i.e. the kinetic energy in the undisturbed flow—in the range of 17 TWh. A second study was performed to analyse the velocity distributions presented by tidal currents, regulated rivers and unregulated rivers. The focus is on the possible degree of utilization (or capacity factor), the fraction of converted energy and the ratio of maximum to rated velocity, all of which are believed to be important characteristics of the resource affecting the economic viability of a hydro-kinetic energy converter.

The concept for hydro-kinetic energy conversion studied in this thesis comprises a vertical axis turbine coupled to a directly driven permanent magnet generator. One such cable wound laboratory generator has been constructed and an experimental setup for deployment in the river Dalälven has been finalized as part of this thesis work. It has been shown, through simulations and experiments, that the generator design at hand can meet the system requirements in the expected range of operation. Experience from winding the prototype generators suggests that improvements of the stator slot geometry can be implemented and, according to simulations, decrease the stator weight by 11% and decrease the load angle by 17%. The decrease in load angle opens the possibility to reduce the amount of permanent magnetic material in the design.

*Keywords:* Tidal energy, renewable energy, vertical axis turbine, permanent magnet generator, resource assessment

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*To Therese & Winston*



# List of Papers

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

- I **Grabbe, M.**, Lalander, E., Lundin, S. & Leijon, M. (2009) A review of the tidal current energy resource in Norway. *Renewable and Sustainable Energy Reviews*, 13(8):1898–1909.
- II Lalander, E., **Grabbe, M.** & Leijon, M. (2013) On the velocity distribution for hydro-kinetic energy conversion from tidal currents and rivers. Accepted with revisions, *Journal of Renewable and Sustainable Energy*, February 2013.
- III Thomas, K., **Grabbe, M.**, Yuen, K. & Leijon, M. (2008) A low-speed generator for energy conversion from marine currents—experimental validation of simulations. *Proc. IMechE Part A: Journal of Power and Energy*, 222(4):381–388.
- IV Yuen, K., Thomas, K., **Grabbe, M.**, Deglaire, P., Bouquerel, M., Österberg, D. & Leijon, M. (2009) Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion. *IEEE Journal of Oceanic Engineering* 34(1):24–31.
- V Thomas, K., **Grabbe, M.**, Yuen, K. & Leijon, M. (2012) A permanent magnet generator for energy conversion from marine currents: No load and load experiments. *ISRN Renewable Energy*, Article ID 489379, doi:10.5402/2012/489379.
- VI **Grabbe, M.**, Eriksson, S. & Leijon, M. (2013) Detailed study of the stator slot geometry of a cable wound synchronous generator. Submitted to *Renewable Energy*, February 2013.
- VII **Grabbe, M.**, Yuen, K., Goude, A., Lalander, E. & Leijon, M. (2009) Design of an experimental setup for hydro-kinetic energy conversion. *International Journal on Hydropower & Dams*, 15(5):112–116.
- VIII **Grabbe, M.**, Yuen, K., Apelfröjd, S. & Leijon, M. (2013) Efficiency of a directly driven generator for hydro-kinetic energy conversion. *In Manuscript*.

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The author has also contributed to the following papers not included in the thesis.

- IX Baránková, H., Bárdos, L., Bergkvist, M., Waters, R., **Grabbe, M.** & Leijon, M. (2009) Coatings for renewable energy. *Proc. of the 52nd Annual Tech. Conf. of SVC*, May 2009, Santa Clara, USA.
- X Lundin, S., **Grabbe, M.**, Yuen, K. & Leijon, M. (2009) A design study of marine current turbine-generator combinations. *Proceedings of the 28th International Conference on Ocean, Offshore and Arctic Engineering*, May 31 to June 5 2009, Honolulu, Hawaii.
- XI Nilsson, K., **Grabbe, M.**, Yuen, K. & Leijon, M. (2007) A direct drive generator for marine current energy conversion—first experimental results. *Proceedings of the 7th European Wave and Tidal Energy Conference*, September 2007, Porto, Portugal.
- XII Rahm, M., Svensson, O., Boström, C., **Grabbe, M.**, Bülow, F. & Leijon, M. (2009) Laboratory experimental verification of a marine substation. *Proceedings of the 8th European Wave and Tidal Energy Conference*, September 2009, Uppsala, Sweden.
- XIII Rahm, M., Svensson, O., Boström, C., **Grabbe, M.**, Bülow, F. & Leijon, M. (2010) Offshore underwater substation for wave energy converter arrays. *IET Renewable Power Generation*, 4(6):602–612.
- XIV Yuen, K., Nilsson, K., **Grabbe, M.** & Leijon, M. (2007) Experimental setup: Low speed permanent magnet generator for marine current power conversion. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*, June 2007, San Diego, USA.
- XV Yuen, K., Lundin, S., **Grabbe, M.**, Goude, A., Lalander, E. & Leijon, M. (2011) The Söderfors project: Construction of an experimental hydrokinetic power station. *Proceedings of the 9th European Wave and Tidal Energy Conference*, September 2011, Southampton, UK.

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# Nomenclature and abbreviations

$\alpha$	–	Degree of utilization
$A$	m <sup>2</sup>	Area
$B$	T	Magnetic flux density
$\beta$	–	Velocity factor
$c$	–	Number of parallel current circuits
$c_b$	m	Chord length
$C_P$	–	Power coefficient
$D_{si}$	m	Inner diameter of the stator
$d_{c-a}$	mm	Distance from cable to air gap
$d_{c-c}$	mm	Distance between cables
$d_{c-s}$	mm	Distance between cable and stator
$E_c$	Wh	Converted energy
$E_i$	V	No load voltage
$E_w$	Wh	Kinetic energy in the water
$f$	Hz	Frequency
$f_w$	–	Winding factor
$H$	m	Tidal height
$I$	A	Armature current
$l_{br}$	m	Axial length of the stator
$N$	–	Number of turns
$N_b$	–	Number of blades
$n_s$	–	Number of conductors per slot
$p$	–	Number of pole pairs
$P$	W	Power
$P_{Cu}$	W	Copper losses
$P_{eddy}$	W/m <sup>3</sup>	Eddy current loss
$P_{hysteresis}$	W/m <sup>3</sup>	Hysteresis loss
$q$	–	Number of stator slots per pole and phase
$Q$	m <sup>3</sup> /s	River discharge

$R$	$\Omega$	Resistance
$r$	m	Turbine radius
$U_{rms}$	V	RMS phase voltage
$v$	m/s	Velocity
$w_{waist}$	mm	Width of waist in stator slot
$w_{slot}$	mm	Stator slot opening width
$\Phi$	Wb	Magnetic flux
$\phi$	h	Tidal phase shift
$\lambda$	–	Tip speed ratio
$\Omega$	rad/s	Angular velocity
$\rho$	kg/m <sup>3</sup>	Density
$\sigma$	–	Turbine solidity
AC	Alternating Current	
ADCP	Acoustic Doppler Current Profiler	
DC	Direct Current	
DNL	Den Norske Los	
HAT	Highest Astronomical Tide	
HWL	Highest Water Level	
IR	Infrared light	
LAT	Lowest Astronomical Tide	
LWL	Lowest Water Level	
MMSS	Mean Maximum Spring Speed	
NACA	National Advisory Committee for Aeronautics	
PM	Permanent Magnet	
PMSG	Permanent Magnet Synchronous Generator	
PVC	A polymer, Polyvinyl Chloride	
RMS	Root Mean Square	
SG	Synchronous Generator	

# 1. Introduction

## 1.1 Background

In light of the increasing energy demand from an ever growing population and a new-found awareness of the many environmental issues connected to our energy consumption, the road towards a sustainable and reliable energy supply is frequently discussed by journalists, politicians, industrialists and researchers alike. In spite of the many proposed alternatives, however, a clear solution to these issues still seems to elude us in practice, but as I hope this thesis will show, marine current energy may be a part of the solution.

Throughout history, humankind has found innovative ways of utilizing various energy resources in nature, ranging from ancient water wheels and wind mills to modern hydro power plants and wind turbines. Today, when it seems likely that we need a mix of different energy conversion technologies to secure a sustainable energy supply, one can only hope that the recent surge of interest in renewable resources such as wave energy and marine current energy will eventually lead to economically and environmentally viable technologies for electricity generation.

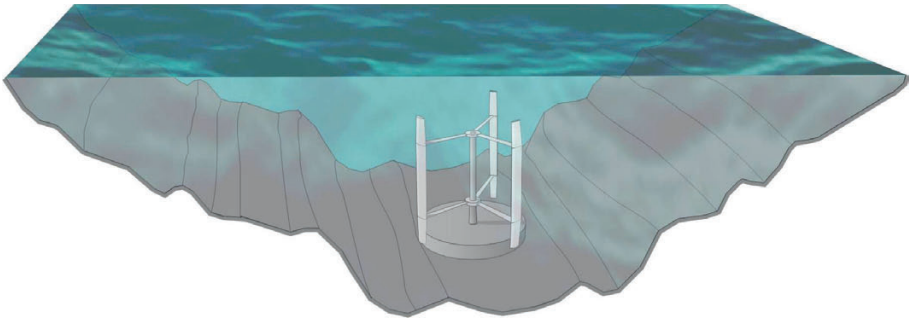
Tides have long been appreciated as a vast energy resource and they were used in tidal mills to grind grain throughout the Middle Ages [1]. More recently, they have also been used to generate electricity, for instance in the 240 MW tidal barrage on the estuary of the River Rance in Brittany, France [2–4]. Tidal currents, however, are still more or less an untapped energy source even though several marine current turbine prototypes have been tested offshore in the last few years [5–8].

Many of the prototypes that have been deployed offshore more or less resemble conventional wind energy converters in that they are equipped with a horizontal axis turbine coupled to a gearbox and a generator. A slightly different approach to energy conversion from marine currents has been taken at the Division of Electricity at Uppsala University. The concept is based on a vertical axis turbine connected directly to a permanent magnet synchronous generator (PMSG).

In the following, I would like to briefly describe the energy conversion system studied, to explain where this thesis fits into the larger picture, and to give the outline of the thesis.

## 1.2 The energy conversion system studied

Research in the area of energy conversion from marine currents has been carried out at the Division of Electricity since Mats Leijon was appointed Professor of Electricity at Uppsala University in 2000. From the start of the project, focus has been on developing a simple and robust system designed to convert the kinetic energy in freely flowing water to electricity. The concept is based on a vertical axis turbine directly coupled to a permanent magnet synchronous generator. The system is intended to be placed on the seabed or riverbed where it would be protected from storm surges and floating debris. An illustration of the system is presented in Fig. 1.1.



*Figure 1.1:* The turbine and generator placed on the seabed in a narrow watercourse (illustration by Karin Thomas).

The functionality and survivability of a system operating in an underwater environment demand simplicity and robustness. Once the turbine and generator are deployed offshore, it is likely that any maintenance operation would be both difficult and expensive. Thus, the intention has been to design the system from a holistic viewpoint, aiming at minimizing the number of moving parts that could require maintenance rather than sub-optimizing parts of the system. For instance by using a directly driven generator the gearbox can be excluded. Furthermore, as permanent magnets are used, no separate excitation system with slip rings and carbon brushes is needed. The vertical axis turbine is omnidirectional in the horizontal plane, so no yaw mechanism is required to align the turbine with the water current at the turn of the tide. The turbine blades have fixed pitch avoiding any blade pitch mechanism that could fail or need maintenance.

Such design choices, however, will shift several engineering problems from the mechanical side to the electrical side of the design. The generator will have to be able to electrically start, control and brake the turbine in the expected range of operation. The generator will thus be operated at variable speed and the terminal voltage will vary in both amplitude and frequency along with changes in the flow velocity. Hence the output from the generator has to be rectified and inverted before the generator is connected to the grid.

### 1.3 Scope of thesis

The overarching aim of the research project is to design a sustainable and economically viable system for harnessing the renewable energy in tidal currents and rivers. The first step towards that goal was to investigate how a generator could be designed to suit the characteristics of the resource and to meet the system requirements as described above. The means to do this was initially finite element-based simulations regarding the electromagnetic design of the generator. These efforts led to several publications on directly driven generators in the range of 1–160 kVA [9–15] as well as two doctoral theses, namely those of Ph.D. Erik Segergren [16] and Ph.D. Karin Thomas [17].

When I joined the research group, the time had come to build a first prototype of such a generator to allow for validation of previous simulations and to gain experience for possible future offshore experiments. From that day on, much of my time has been spent in the laboratory building experimental setups and performing experiments.

Working with the first prototype was a good experience that gave the research group confidence to move forward with deployment of a hydro-kinetic energy converter. Leaving the safety of the laboratory environment, however, soon proved to be a strenuous challenge. Much effort was directed at finding a suitable test site, securing funding, acquiring the necessary permits, maintaining a good relationship with local authorities and informing the locals of our activities, all time consuming activities that are not principally engineering science, but nonetheless an oftentimes appreciated topic of discussion with other research groups at conferences and an indispensable part of successfully utilizing the hydro-kinetic resource.

Finally a suitable site was found in the river Dalälven at Söderfors and the practical work of realizing a complete unit for in-stream experiments could begin. Much of the design and the construction work has been a collaborative effort within the research group. My colleague Emilia Lalander was in charge of characterizing the site through Acoustic Doppler Current Profiler (ADCP) measurements and simulations, as presented in her licentiate thesis [18]. Based on the velocities at the site, Ph.D. Anders Goude performed the hydrodynamic design of the turbine as a part of his research work. Ph.D. Katarina Yuen constructed and tested the control and measurement system to be used in the experimental setup [19]. Much of the mechanical design has been done by Anders Nilsson while Staffan Lundin has been responsible for the work on-site. I was once again responsible for finalizing the generator, testing the machine in the laboratory and making it ready for deployment.

The experimental station was ready for deployment in the summer of 2012. However, an unusually rainy summer resulted in unusually high discharge in the river that lasted throughout the autumn. At the time of writing, we are still awaiting the right weather conditions to deploy the turbine.

Concurrent with the experimental work, my continuous desire to reach a better understanding of the hydro-kinetic resource has resulted in two papers regarding the resource characteristics. Firstly, a resource assessment for Nor-

wegian waters has been carried out and secondly, a study of the velocity distribution from tidal currents and rivers has been performed.

## 1.4 Outline of thesis

This compilation thesis is based on eight research articles in the area of hydro-kinetic energy conversion. The introductory chapters of the thesis serves to give a context and a summary of the appended papers.

Part I of the thesis gives a general introduction to marine currents as a renewable energy resource. It also summarizes the findings in Papers I and II, including a closer look at what is currently known about the resource in Norwegian waters and a more in-depth analysis of the velocity distribution of tidal currents and rivers.

Part II deals with the technology for hydro-kinetic energy conversion with emphasis on my own work in generator design and construction. A short theoretical background to the tools and methods used for the design and construction of the prototype generators is presented in Chapter 6. The design and the experiments with the two prototypes are discussed in Chapters 7 and 8, respectively. The experimental results are discussed in Chapter 9, reflecting the work with the laboratory prototype generator presented in Papers III–VI and the Söderfors project as presented in Papers VII–VIII.

Conclusions and suggested future work are given in Chapters 10 and 11 respectively. The author's contribution to each of the appended papers is presented in Chapter 12 together with a short summary of the papers. For the interested reader, a Swedish summary of this thesis is given in Chapter 13.

## Part I:

### Resource

This part of the thesis is intended to be an introduction to the area of hydro-kinetic energy conversion with focus on the resource characteristics. Short summaries of the resource assessment carried out in Paper I and the study on velocity distributions presented in Paper II are also included here.





## 2. Marine current energy resource

### 2.1 Resource characteristics

Hydro-kinetic energy conversion concerns, as the term implies, electricity generation from the kinetic energy in freely flowing water. The term *marine current energy* is also often used to indicate that any kind of water current can be included in the resource, be it tidal currents, rivers or other ocean currents driven for instance by thermal gradients or differences in salinity.

So what would constitute a good site for hydro-kinetic energy conversion? A clear-cut answer to that question is perhaps not so easily given. Several site specific characteristics of the resource have to be considered, such as depth, seabed material, turbulence and wave climate to name a few, as well as adherent issues such as distance to nearest grid connection and conflicts with other users. Simply put, it is a complex question and it is easier explain where to start looking; one would be looking for sites where the currents are strong, such as a narrow sound, a strait, an estuary, around a headland or in a river.

The kinetic power  $P$  in a flowing fluid through a given cross-section  $A$  is strongly dependent on the velocity, and can be expressed as

$$P = \frac{1}{2} \rho A v^3, \quad (2.1)$$

where  $\rho$  is the mass density of the fluid and  $v$  is the velocity of the fluid through the cross-sectional area  $A$ . One may conclude that energy conversion from marine currents is interesting even for relatively low velocities, as water is much denser than air. However, the higher density also means that any marine current turbine will have to withstand strong forces. It should come as no surprise that many early marine current turbine prototypes resemble sturdy wind turbines.

As long as one imagines a single turbine at a site with a cross-sectional area much larger than that of the turbine, one would be tempted to extend the comparison with wind power where the theoretically derived maximum for energy extraction, known as the Betz limit, is 59% of the kinetic energy in the free flow. However, at a good wind site there is usually nothing that would block the flow on the sides of the turbine or above it. This means that one can expect a wind turbine to have a relatively small effect on the overall wind conditions and the wind speed is likely to recuperate at a certain distance behind the turbine. For a marine current turbine placed in a narrow channel on the other hand, the flow will be restricted by the sides of the channel as well as by the open boundary at the surface. Thus, the assumptions made by Betz

in deriving the theoretical value for a wind turbine is not valid in the case of a restricted channel flow. In any case, it should be clear that the fraction of the kinetic energy that can be extracted is site dependent. This makes it difficult to perform (and to evaluate) general resource assessments for marine current energy that try to take many sites into account by applying the same method for all the sites.

There are several characteristics of marine currents that make them attractive as an energy source. Marine currents, especially tidal currents, are largely predictable. As an energy source they also offer a potentially high degree of utilization, something which could have a strong impact on the economic viability of any renewable energy project [20, 21].

Limited rated velocity of each device gives smaller difference in power production between spring and neap and thus also a higher degree of utilization [22]. Hence the predictable nature of the resource combined with a limited power of each device could be beneficial for management of power delivery in the case of a large scale marine current turbine farm. In some places the tide is phase shifted along the coastline, which means that several marine current turbine farms could be geographically located to even out the aggregated output over the tidal cycle. This has for instance been shown to be the case around the British Isles [22, 23].

## 2.2 Resource assessments

A growing interest in renewable energy during the late 1990s and early twenty-first century led to the publication of several tidal energy resource assessments oftentimes prepared by private consultants, for instance [24–31]. The purpose of most of these assessments was to give a rough estimate of the size of the resource to aid in strategic decision making rather than trying to understand the process of energy extraction and characterizing different sites accurately. Furthermore, the focus was mainly on tidal currents, so for instance unregulated rivers were usually not included in these assessments.

Unfortunately, there is still little data from tidal currents collected for the purpose of assessing the resource. Hence most of the above mentioned resource assessments are desktop studies based on secondary material collected for other purposes than investigating the tidal resource. Due to the large number of sites included, it is understandable that a methodology that is quick and easy to use for all sites is preferable. For these reasons the kinetic energy in the undisturbed flow has in many cases been used as a measure of the extractable resource, regardless of the local bathymetry, something which has been shown to be incorrect [32, 33]. For a more in-depth review of previous international resource assessments, see [34].

The resource is sometimes described as theoretical, extractable (or available), technical or economical. One would assume that the theoretical resource is the kinetic energy in the undisturbed flow, that the extractable resource is the maximum amount of energy that can be physically extracted from a hydro-



Figure 2.1: Two of the turbines deployed in New York City’s East River. The diameter of the turbine is 5 m (used with permission).

dynamic point of view, and that the technical and economical resource would then be evaluated in terms of certain technical and economical constraints. This is, however, not always the case which makes it difficult to compare different assessments.

In [24–26, 30] certain selection criteria are used for determining which sites should be included in the assessment. For instance in [30], the sites considered are those with a depth of 20 m or more, as that is thought to be the minimum depth required for a commercial size marine current turbine unit. Hence, one could argue that assumptions about the *technology* have been included in the *theoretical* resource. Interestingly enough, what seems to stand as the world’s first grid-connected array of marine current turbines<sup>1</sup>—installed in the East River in New York—did not require a depth of 20 m, see Fig. 2.1. This goes to show the pitfalls and difficulties in making a thorough and consistent resource assessment as well as the problem of interpreting the numbers given in already existing assessments.

The question then remains how to correctly assess the extractable marine current energy resource. There is seemingly no clear answer to that as of yet. Even a suggested standard for resource assessments published as recently as 2009 [35] indicates that one should look into the latest research publications for guidance regarding how to measure and describe aspects of the resource such as turbulence. To complicate the situation even further, the hydro-kinetic resource is highly dependent on the geographical location of the turbine. This could become an issue during the approval process of marine current energy projects, since the available resource could change dramatically by just shifting the turbine position a relatively short distance. A similar situation can be seen in rivers, where it is important to position the turbine where the thalweg is stable [36, 37].

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<sup>1</sup> <http://www.verdantpower.com>

Regardless of these hurdles, one could always turn to numerical modelling of interesting sites to investigate the kinetic energy in the undisturbed flow as well as how the situation would change when the turbines are in place. This would require input data that is not always readily available, and it would also require a lot of effort even for a single site. The results from such an approach are, however, very useful, see for instance [38, 39].

Another approach would be to perform long term velocity measurements at the potential turbine site, preferably with an ADCP, aiming to achieve both high spatial resolution (i.e. an indication of where to place the turbine) and high temporal resolution (i.e. to estimate the velocity distribution). ADCP measurements are well documented and often used in oceanography and by the offshore industry, and more recently discussed how to be utilized in determining the hydro-kinetic resource [40–44]. ADCP measurements are, however, expensive and a simpler approach is preferable for site-screening in order for smaller hydro-kinetic projects to be economically feasible [45].

Assessing hundreds of sites with either of those approaches would be a daunting task. In the last couple of years, however, academic work looking into energy extraction from sites with a characteristic geometry have begun to surface and could in time prove to give some sort of guidelines of how to estimate the extractable resource. Examples of this would be models for a simple uniform channel [46, 47], a channel with varying cross section linking two large bodies of water [33] and a channel connecting a bay to a large basin [32, 48, 49]. From this research it is clear that the extractable resource is site dependent and not always simply proportional to the kinetic energy in the undisturbed flow.

### 3. A review of the resource in Norway

Much work has been carried out in Norway regarding both offshore technology and oceanography. Looking at marine current energy in Norway, the knowledge in offshore technology has been put to use in a few prototypes (most notably a 300 kW prototype from Hammerfest Strøm AS<sup>1</sup>), but surprisingly little has been published regarding the tidal resource in Norwegian waters in the perspective of energy conversion.

The long Norwegian coastline is strongly affected by the tide and all the narrow fjords and sounds make for many sites that could be interesting for marine current energy conversion. The tidal amplitude is limited in the south of Norway but increases further to the north, see Fig. 3.1. Sites with a high tidal current velocity can be found from Bodø all the way up to Vardø, see Fig. 3.2. Several well known sites with strong currents can be found around the Lofoten islands, for instance the Moskenstraumen [50] and Saltstraumen [51].

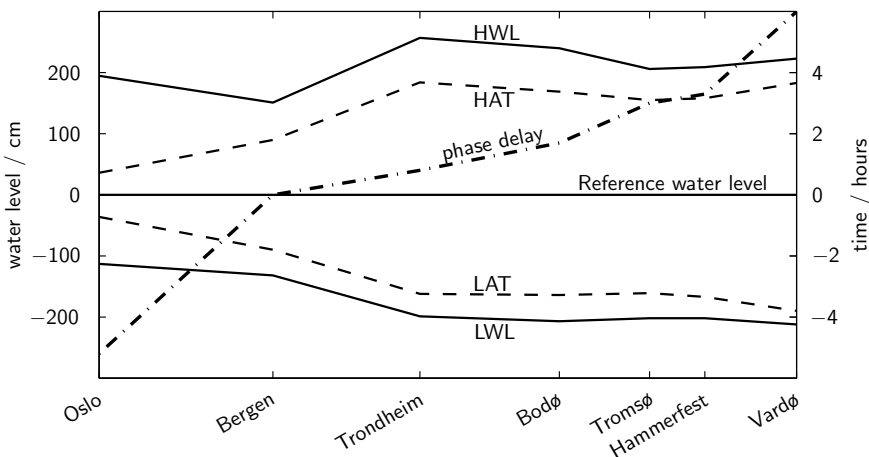


Figure 3.1: The sea level is shown as Highest and Lowest Water Level (HWL/LWL) and Highest and Lowest Astronomical Tide (HAT/LAT) compared to the mean water level in cm. The phase lag of the tidal wave along the coastline is shown in hours where time for high water is taken as zero in Bergen (data from DNL [52], prepared by Emilia Lalander).

In recent years, two resource assessments have been presented regarding the tidal resource in Norway [53, 54]. A review of these two assessments has been carried out in Paper I and complemented with a comparative study based on available data. What follows is essentially a brief summary of Paper I.

<sup>1</sup><http://www.hammerfeststrom.com> – accessed February 2013

### 3.1 Available data

Norwegian universities have a rich history of research within oceanography. In many cases though, the research has been focused on other issues than tidal energy resource assessments, such as prediction of surface currents to aid in navigation [55], studying the circulation in fjords [51] or drift of particles such as cod eggs [56]. Hence the two resource assessments [53, 54], as well as the comparative study in Paper I, are mainly based on current velocities found in a Norwegian pilot book called *Den Norske Los (DNL)* [52, 57–62]. Mean depth and width for each site are taken from digital sea charts<sup>2</sup>.

### 3.2 Methodology

The methodology used in [53] and this comparative study is very easy to use but also sensitive to errors in the current velocity data as the cube of the velocity is used to estimate the kinetic energy. The methodology as such is not new and a similar approach has been taken in [26, 27] and is further discussed in [8, 63]. Some of the steps and main assumptions included in the analysis are given here.

- *Current velocities from DNL.* The current velocities from DNL are included in the model as mean maximum spring speed (MMSS), even though it is not always clear from DNL if this is the case or not. Furthermore, it is not always explained in DNL how or where at a site the velocity has been measured or estimated. This can result in large relative errors in the estimated resource.
- *Width and mean depth from digital sea charts.* All sites are modelled as having a rectangular cross section based on width and mean depth as seen on digital sea charts. The bottom friction is included by means of a one-tenth velocity profile and friction against the sides of the channel is neglected. There are two noticeable problems with this approach: firstly, using the same velocity across the whole cross section is most likely an over estimation of the resource, as the velocity is usually decreased close to the borders of the channel, and secondly, the cross section area for each site is chosen as the smallest cross section, while the velocity along a channel varies with the cross section and it is not given in DNL exactly where at a site that the velocity has been measured.
- *The currents are assumed to vary sinusoidally.* The tidal currents are assumed to vary sinusoidally over a semi-diurnal tidal cycle of 12.5 hours with a spring/neap period of 29 days.
- *Annual energy yield.* The theoretical resource at a site is calculated based on certain characteristics of the tidal currents. In this case, the same values as in [53] have been chosen to allow for comparison. The neap current velocity is set to 79.6% of the spring tide current velocity, the ebb tide velocity is assumed to be 90.0% of the flood tide velocity and finally the

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<sup>2</sup>The Norwegian Coastal Administration – <http://kart2.kystverket.no>

Table 3.1: *The number of sites and calculated resource as presented in the three different resource assessments (Table 1 from Paper I).*

	[53]	[54]	Present study
No. of sites	12	22	104
Theoretical resource	2.3 TWh	–	17 TWh
Extractable resource	0.23–1.1 TWh	–	–
Technical resource	0.18–0.89 TWh	> 1 TWh	–
Economical resource	0.16–0.82 TWh	< 1 TWh	–

second tide velocity during the day is assumed to be 93.6% of the first tide during the day. Furthermore, the difference in tidal amplitude from spring to neap is assumed to vary linearly over the 29 day period. Other values of these parameters would of course also give a different theoretical resource.

As seen above, the methodology used is very simple and also very sensitive to relative errors. Hence, the comparative study presented here and in Paper I should only be seen as a rough indication of the size and characteristics of the resource based on data presented in DNL.

### 3.3 Comparison of assessments

Based on the data and methodology described above 12 sites were assessed in [53], 24 sites in [54], and 104 sites in this comparative study (see Table 3.1). In this comparative study, only the theoretical resource has been included due to the difficulties of correctly assessing the extractable resource based on the available data and methodologies as discussed in section 2.2. Based on this data and the parameters used to calculate the resource, this yields a theoretical resource of roughly 17 TWh for the 104 sites included in the study. This can be compared to a technical and economical resource estimated to the order of 1 TWh in [53, 54].

All the sites have been organized according to velocity and depth in Table 3.2. Not surprisingly, deep sites with a high velocity contribute significantly to the total resource in all the three assessments. However, it is also interesting to see that there are quite a few smaller sites that could be viable to use for marine current energy conversion. It is also important to remember that none of the three assessments have considered conflicts with other users. Furthermore, there might be interesting sites that are not mentioned in DNL and thus not included in the assessments. All of the 104 sites included in this comparative study can be found in parts five and six of DNL [61, 62], which cover the area from Rørvik to the Russian border in the north, see Fig. 3.2.

Table 3.2: A comparison of how the resource is distributed among different velocity and mean depth intervals in the three resource assessments. The number of sites is given for each interval followed by the contribution to the total resource as a percentage (Table 2 from Paper I).

No. of sites with	[53]	[54]	Present study
MMSS above 3 m/s	3 (41%)	4 (6%)	28 (68%)
MMSS of 2–3 m/s	9 (59%)	11 (79%)	39 (26%)
MMSS below 2 m/s	–	9 (15%)	37 (6%)
mean depth of more than 40 m	1 (24%)	11 (85%)	15 (59%)
mean depth of 20–40 m	5 (52%)	11 (13%)	17 (28%)
mean depth of less than 20 m	6 (24%)	2 (2%)	72 (13%)



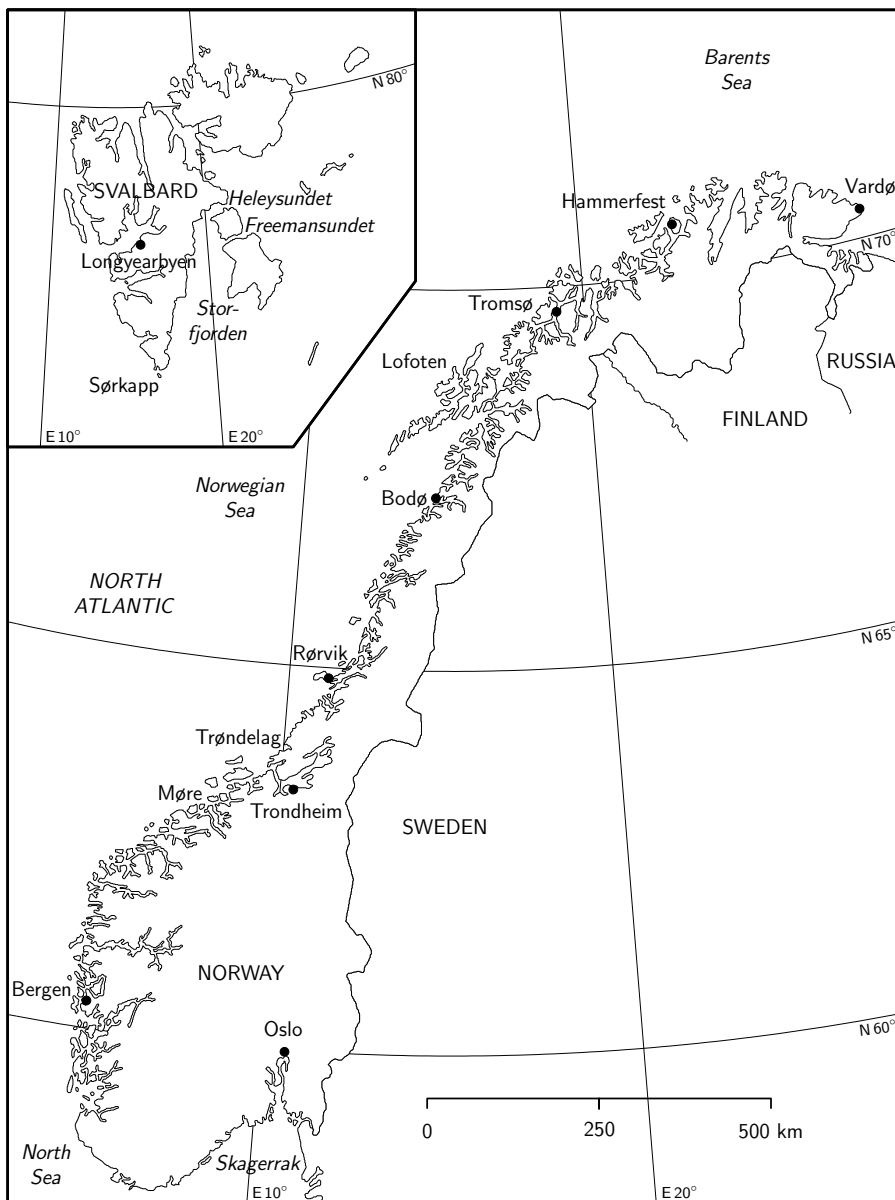


Figure 3.2: A map of the Norwegian coastline including Svalbard (picture prepared by Staffan Lundin, Fig. 1 from Paper I).



## 4. On the velocity distribution

One of the more interesting and challenging aspects, from an engineering point of view, of utilizing hydro-kinetic energy is that we are left with little or no possibility to control the resource; rather we have to find a technically and economically viable solution based on the characteristics of the resource. If the focus of the previously discussed study on the Norwegian resource, as well as that of many other resource assessments, was mainly the size of the resource (be it theoretical or extractable), the focus in Paper II is on the temporal variations of the velocity.

The velocity distribution gives important information on how to design the system. As mentioned previously, one important aspect is the degree of utilization, or capacity factor,  $\alpha$ , which is defined as the ratio of annually converted energy delivered to the electric grid,  $E_c$ , to the rated power of the device,  $P_{rate}$ , times the number of hours in a year, or as

$$\alpha = \frac{E_c}{P_{rate} \cdot 8760} \cdot 100. \quad (4.1)$$

The degree of utilization is thus dependent on both the nature of the resource and our engineering choices. One recent example is where Walkington and Burrows [64] modelled four possible marine current turbine farms along the UK West Coast. The turbines at two of the sites performed quite well according to simulations, achieving a degree of utilization of 44% and 55% respectively. The two other farms only reached 5% and 16% respectively. This, however, does not necessarily mean that the two latter sites are not suitable for energy conversion, it is rather an indication that turbines with a lower rated velocity would likely have been a better choice for those particular sites.

A high degree of utilization alone is naturally not the be-all and end-all in determining if a site is suitable or not, as it can be achieved for any continuous velocity distribution by simply lowering the rated velocity of the turbine. However, by doing so, one also decreases the amount of converted energy (and thus the expected revenue from the installation) while the turbine would still have to withstand the maximum velocity at the site. Then, again from an engineering perspective, a site with a velocity distribution that offers a high degree of utilization while maintaining a low ratio between maximum velocity and rated velocity would seem promising. In that context, the degree of utilization can be a viable tool for comparing different sites.

The velocity distribution of a number of tidal sites with different tidal regimes and of both regulated and unregulated rivers are compared in Paper II, and a brief summary of the study will be given here. Comparing

velocity distributions may raise some more far-reaching questions, one question being if the relation between mean velocity and maximum velocity is found to be, in general, large for the resource at hand. That could prove to be an obstacle, technically and economically, to utilizing the resource. Another concern would be if there were found to be great differences in the velocity distribution between different sites, which could make it harder to find a technical solution suitable for the majority of the sites.

A proper analysis of those questions is a daunting task, far outside the scope of this thesis, and it would require long data sets of high temporal resolution at the exact site of the turbine to begin with. To the best of the author's knowledge, such data is not abundant and a simpler approach has been taken here as a first step. Time series of the velocity have been created based on the limited available data, and the velocities has been normalized in order to compare the shape of the velocity distributions at a number of sites. Hence, the possible degree of utilization and ratio of maximum velocity to rated velocity could still be analysed, but the absolute velocities and power could not be meaningfully analysed as the available measurements are not necessarily performed at the best location for a turbine.

## 4.1 Methodology

This section presents the data and the methods used to construct the required one-year-series of velocity data to analyse the degree of utilization for tidal currents and rivers. Different methods has been used for tidal currents, regulated rivers and unregulated rivers due to the available data for the three cases.

### 4.1.1 Tidal sites

Tidal sites were chosen so as to include different tidal regimes, based on sites highlighted by Hardisty [65] to be of interest for hydro-kinetic energy conversion in North America. Among the many sites mentioned by Hardisty, the sites where tidal height and velocity measurements were available were included in this study. Tidal height data were acquired from the Center for Operational Oceanographic Products & Services (CO-OPS) at the U.S. National Oceanic and Atmospheric Administration (NOAA) [66], and velocity data were taken from the C-MIST database at the NOAA's webpage [66, 67]. The time resolution for the tidal height data was one measurement per hour. Further details on the collected velocity series such as length of measurement, depth at measurement site and other information are presented in more detail in Paper II.

At least a one-year record of velocity data is required for a proper analysis of the possible degree of utilization. The available ADCP measurements, however, were rarely more than a month at most. Thus a one-year velocity series had to be constructed by correlating the available velocity measurements with the tidal height.

Firstly, as is common practice, the bins of velocity data affected by interference close to the surface were removed, and bins with bad velocity data were also removed. Then the tidal height, denoted as  $H$ , was correlated with the measured velocities,  $U_{T,meas}$ , according to  $U_{T,meas} \propto H(\phi)$  where  $\phi$  is the phase shift in time measured in hours. Index  $T$  indicates the tidal regime data. The value of  $\phi$  giving the best correlation was used. The correlation coefficients for the tidal sites are presented in Table 4.1. The tidal height data were then calibrated with the velocity in order to find an approximate velocity series for the whole year,  $U_T$ , according to

$$U_T = H(\phi) \cdot A + B \approx U_{T,meas}, \quad (4.2)$$

where  $A$  and  $B$  were adjusted until the best fit was found. Sites with data showing a low correlation were omitted from the analysis. The results of the correlation and calibration are shown in Table 4.1. The resulting histograms for three different sites are shown in Fig. 4.1.

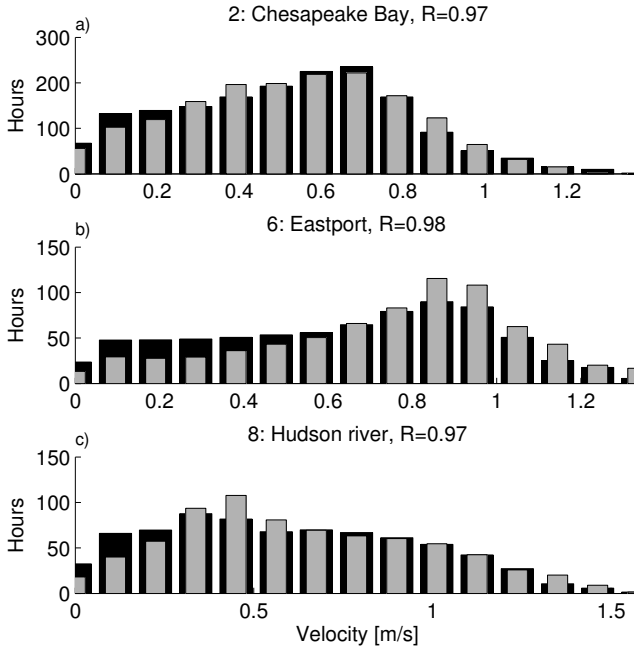


Figure 4.1: Histogram of three selected tidal sites with measured velocity in black and calculated velocity in grey (Fig. 7 in Paper II).

#### 4.1.2 Regulated rivers

Discharge data for rivers is often available, whereas the velocity at a river site seldom is known. Two separate approaches for regulated and unregulated

Table 4.1: *The parameter values of A and B from Eq. 4.2, the correlated  $\phi$ -values and the correlation coefficients for the tidal sites. Names in italic were not used in the later calculations due to the low correlation or short measurement time (Table 2 from Paper II).*

	Site	A [1/s]	B [m/s]	$\phi$ [h]	R	R <sup>2</sup>
1	Chesapeake bay, VA	1.3	0.1	0.0	0.91	0.83
2	Chesapeake bay, VA	2.1	0.0	-4.8	0.97	0.94
–	<i>Buzzards Bay, MA</i>	3.7	-0.1	2.3	0.83	0.68
3	Cook Inlet, AK	0.5	-0.1	3.7	0.92	0.85
4	Cook Inlet, AK	0.5	0.5	4.0	0.87	0.76
5	Cook Inlet, AK	0.7	0.0	2.2	0.93	0.87
–	<i>Cook Inlet, AK</i>	0.5	0.4	1.9	0.82	0.68
6	Eastport, ME	0.4	0.0	-2.9	0.98	0.96
7	Eastport, ME	0.2	0.0	3.9	0.96	0.91
8	Hudson river, NY	1.4	-0.2	0.4	0.97	0.95
9	Chesapeake, VA	1.3	0.1	2.7	0.91	0.84
–	<i>San Fransisc. Bay</i>	0.7	0.0	-3.2	0.85	0.73
–	<i>San Fransisc. Bay</i>	1.7	0.4	2.3	0.98	0.95

ivers have been taken in this study to acquire an approximate relationship between discharge and velocity at a number of sites.

Regulated river sites are here defined as sites with a reservoir downstream that controls the water level in the river. Thus, with only small changes in the water level compared to the depth at the site, the velocity can be assumed to be linearly dependent on the discharge.

Discharge data measured at daily intervals for twelve years were acquired from the Swedish Meteorological and Hydrological Office (SMHI) for a number of regulated Swedish rivers. Vattenfall AB provided discharge data measured at hourly intervals from Söderfors in the river Dalälven for the years 2003–2008. Measurements with a bottom-mounted 600 kHz ADCP were conducted at the site for 26 days in April–May 2010. The ADCP was deployed in the middle of the river, and the measurements were set to 3 minute intervals with a depth resolution of 1 m.

The measured velocity was found to be linearly dependent on the discharge with a correlation coefficient (R) of 0.94, see Fig. 4.2. The assumption of a linear relationship was then used at the remaining sites (but with a normalised value for the velocity due to the lack of actual velocity data) according to

$$U_{Rn} = \frac{Q_R}{\overline{Q_R}}, \quad (4.3)$$

where the  $\overline{Q_R}$  is the total mean of the data. Index  $R$  indicates that the data are from regulated rivers and index  $n$  that the data is normalised. The resulting histogram for two of the sites can be seen in Fig. 4.3.

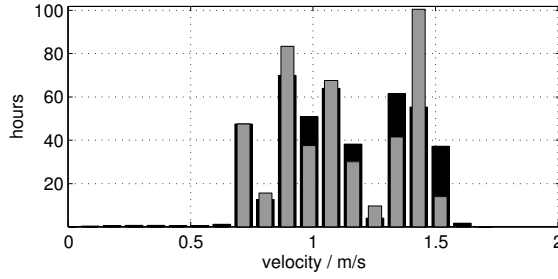


Figure 4.2: Histogram of measured velocity (black) and calculated velocity from discharge (grey) with a correlation coefficient of 0.94. The Y-axis shows the number of hours (Fig. 1 from Paper II).

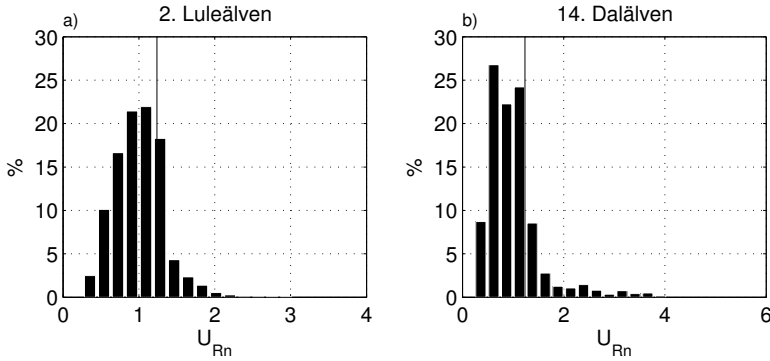


Figure 4.3: Histogram of the velocity ( $Q_R/\overline{Q_R}$ ) for two selected regulated rivers. The vertical lines indicate  $U_{opt}$  for each site (Fig. 2 from Paper II).

#### 4.1.3 Unregulated rivers

In unregulated rivers the water level may vary with discharge, resulting in a non-linear relationship between discharge and velocity. The correlation between measured velocity and discharge was established for a few river sites in Alaska in a technical report from 2008 [68]. The same relationship have been used for further analysis of the data in this study. A more detailed study of one of the sites (Kvichak river) in [68] has recently been published [69]. The log-relationship between the velocity and the discharge available in the two reports, however, gives similar results regarding the capacity factor.

Many years of discharge data could be retrieved from the USGS [70] and annual variation in the hydro-kinetic resource could thus be studied. Both the discharge and the calculated velocity distribution are presented for two sites in Fig. 4.4 to show their logarithmic relationship.

#### 4.1.4 Data analysis

The length of the velocity series for rivers depend on how many years of discharge data that was available, as discussed previously, whereas only one-year

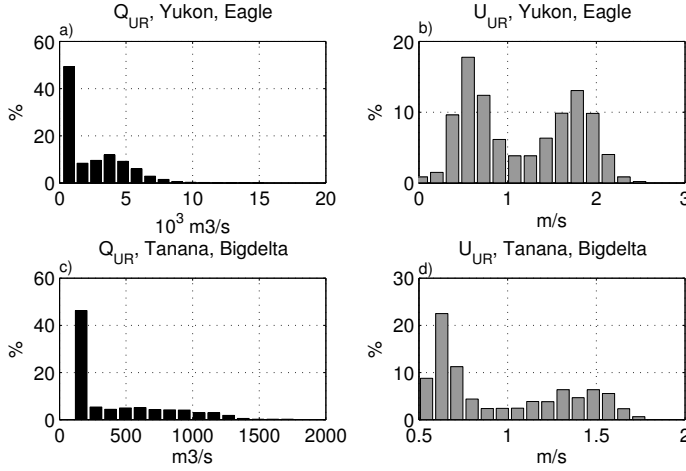


Figure 4.4: Histogram of the discharge distribution (a and c) and the velocity distribution (b and d) for two of the unregulated rivers. The Y-axis show percentage of time (Fig. 5 from Paper II).

velocity series were used for tidal sites. The average of the yearly maximum ( $\overline{U_{max}}$ ) has been used for the river sites and the yearly maximum has been used for tidal sites. Data for extreme conditions, i.e. the 100-year occurring velocity or storm surges, were not available for this analysis. To allow for comparison of the different regimes,  $\overline{U_{max}}$  and  $U_{max}$  were divided by the mean value.

To analyse the fraction of converted energy and degree of utilization it is necessary to know the velocity distribution, the turbine power coefficient and to choose the rated velocity of the turbine. In this case, two turbines with different rated velocity have been used to highlight the importance of choosing a suitable rated velocity and what impact that might have on the degree of utilization.

A  $C_P$ -curve from modern wind turbine [71] has been used as starting point and the rated velocity has been chosen according to two methods. In Method I, the turbine is assumed to be designed to have its maximum  $C_P$  occurring at the optimal velocity ( $U_{opt}$ ) of the site. In Method II, the turbine is instead assumed to have its rated velocity ( $U_{rate}$ ) coinciding with the optimal velocity of the site. The resulting  $C_P$ -curves for both methods are illustrated in Fig. 4.5.

The rated velocity is thus not set to a specific value, instead it is chosen based on the velocity distribution at each site. The intention is that Method I should correspond to a high rated velocity (and hence low degree of utilization) and that Method II should correspond to a relatively low rated velocity. In most cases, a reasonable design point might lie somewhere in between the two methods.

The velocity distribution was used to calculate the kinetic energy per square meter in the freely flowing water,  $E_w/A_t$ , using



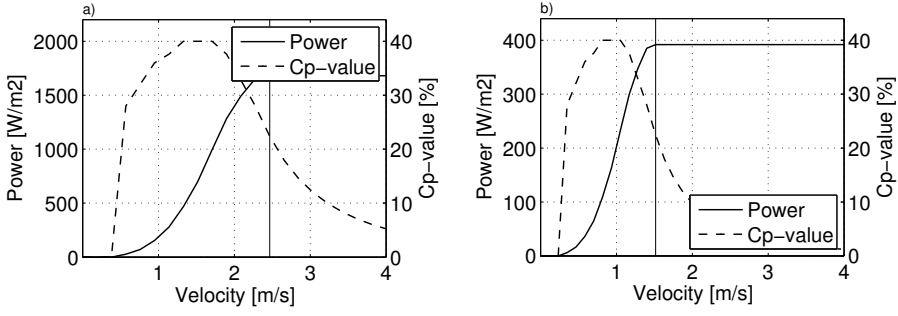


Figure 4.5: The  $C_p$ -curves for Method I (a) and Method II (b) that were used in the calculations. The vertical line shows the rated velocity.  $U_{opt}$  is 1.5 m/s in both figures (Fig. 8 from Paper II).

$$E_{w,i}/A_t = \frac{1}{2} \rho U_i^3 N_i \cdot 8760 \quad [\text{Wh/m}^2] \quad (4.4)$$

where  $A_t$  is the turbine cross sectional area,  $N_i$  is the annual incidence of each velocity segment and  $i$  is the index of each velocity segment. The velocity giving the highest value of  $E_w$  is defined as the optimal velocity,  $U_{opt}$ .

The converted energy can then be calculated as

$$E_c/A_t = \sum E_{w,i}/A_t C_{P,i} \quad [\text{Wh/m}^2], \quad (4.5)$$

where  $C_P$  is the power coefficient of the turbine. Thus, the degree of utilization,  $\alpha$ , can be evaluated as

$$\alpha = \frac{E_c/A_t}{P_{rate}/A_t \cdot 8760} \cdot 100, \quad (4.6)$$

where  $P_{rate}$  is the rated power of the turbine. The different sites have also been compared by looking at the ratios  $U_{rate}/\bar{U}$ ,  $U_{max}/U_{rate}$  and  $E_c/E_w$ .

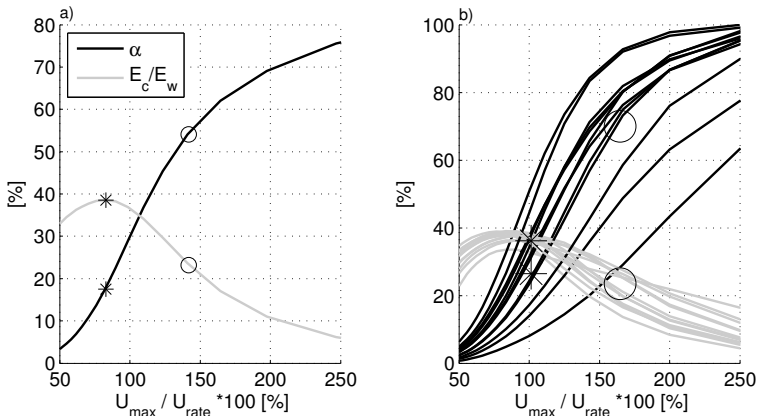
## 4.2 Results and discussion

The main results are presented in Table 4.2. It should be noted, as mentioned earlier, that the intention with this study is to look at the various velocity distributions that tidal currents and rivers may present, rather than characterising a certain site or a certain technology. The sites at hand are therefore not necessarily suitable for deployment of hydro-kinetic turbines pertaining to e.g. location, depth or velocity. With that said, the results regarding tidal currents could, however, be considered rather general as both diurnal, semi-diurnal and mixed tidal regimes were included. It may be more difficult to draw general

conclusions based on the analysed river sites, due to differences in precipitation and run-off in different parts of world.

The results indicate that both tidal currents and rivers seem to offer a relatively high degree of utilization. There are of course several factors that could limit the degree of utilization in practise. For instance, weather related effects and other extreme conditions are not accounted for in this study. Furthermore, and perhaps more importantly, viable technical solutions for operation in the harsh offshore environment are of course a necessity. The study is further limited by the lack of long velocity measurements of high temporal resolution, and thus the results presented here shall be seen as an early indication and a topic for further research and discussion.

The degree of utilization for the two methods are presented in Table 4.2. For the river sites the average degree of utilization is presented together with the standard deviation as a measure of how large the variations could be between the years. As expected, a lower rated velocity leads to a greater degree of utilization at the cost of a decrease in converted energy. An example of how the degree of utilization will vary depending on the chosen rated velocity is presented Fig. 4.6 for the tidal site No. 6 (Eastport), and the regulated river site No. 2 (Luleälven). This also illustrates that one might consider choosing a lower rated velocity for the turbine to achieve a better degree of utilization at the cost of a small reduction in annually converted energy.



*Figure 4.6: The variation of the degree of utilization and  $E_c/E_w$  with different quotients of  $U_{max}/U_{rate}$  for the tidal site in Eastport (tidal site No. 6) (a) and the regulated river site Luleälven (regulated river site No. 2) (b). The asterisks show the rated velocity for Method I and the circles show the rated velocity for Method II. Note that all 12 years are shown for the river site and that the position of the asterisk and the circle correspond to the average value from the two methods.(Table 7 from Paper II)*

The degree of utilization, fraction of converted energy and ratio of maximum velocity to rated velocity are all important factors to consider while choosing a site for hydro-kinetic energy conversion. As seen in Table 4.2, a high degree of utilization is achievable for all sites, but sometimes at the cost of a relatively large increase in  $U_{max}/U_{rate}$ . To indicate this, the velocity factor

Table 4.2: Results for the calculation of the degree of utilisation using the two methods (Table 7 from Paper II) .

	Method I						Method II					
	$\frac{U_{rate}}{U}$	$\frac{U_{max}}{U_{rate}}$	$\alpha$ [%]		$\frac{E_c}{E_w}$ [%]		$\frac{U_{rate}}{U}$	$\frac{U_{max}}{U_{rate}}$	$\alpha$ [%]		$\frac{E_c}{E_w}$ [%]	
			mean	std	mean	std			mean	std	mean	std
<b>Reg. rivers</b>												
1. Luleälven	2.4	0.9	20	6	38	1	1.5	1.5	53	12	24	3
2. Luleälven	2.0	1.0	26	8	36	3	1.2	1.6	70	13	24	5
3. Luleälven	2.6	1.1	16	8	31	8	1.6	1.8	45	14	23	11
4. Skellefteälv	2.1	1.3	25	12	31	6	1.3	2.0	64	20	22	9
5. Umeälven	1.9	1.2	30	13	32	9	1.2	2.0	70	18	20	9
6. Umeälven	2.5	0.9	20	8	36	4	1.5	1.5	55	16	24	6
7. Ångermanä.	2.2	1.3	21	11	30	10	1.4	2.1	54	17	21	11
8. Ångermanä.	2.1	1.0	25	11	35	5	1.3	1.7	65	21	23	7
9. Ångermanä.	2.1	1.6	24	12	25	10	1.3	2.7	54	17	16	10
10. Indalsälven	2.1	1.1	28	9	34	7	1.3	1.8	63	14	19	6
11. Ljungan	2.8	1.1	14	11	29	9	1.7	1.9	35	19	24	12
12. Ljusnan	1.9	1.9	27	13	23	12	1.2	3.2	60	14	15	10
13. Ljusnan	2.2	1.8	20	10	26	11	1.4	2.9	53	15	19	11
14. Dalälven	2.0	1.2	25	13	29	9	1.2	2.0	61	17	20	10
15. Dalälven	2.0	1.3	27	14	28	9	1.2	2.1	62	18	19	10
16. Dalälven	2.3	0.9	22	13	34	7	1.4	1.5	54	17	23	10
17. Dalälven	2.0	1.3	25	13	29	9	1.3	2.1	60	17	20	10
18. Dalälven	2.7	0.7	15	7	38	1	1.7	1.2	46	15	29	6
<b>Average</b>	<b>2.2</b>	<b>1.2</b>	<b>23</b>	<b>11</b>	<b>31</b>	<b>7</b>	<b>1.4</b>	<b>2.0</b>	<b>57</b>	<b>16</b>	<b>21</b>	<b>9</b>
<b>Unreg. rivers</b>												
1. Yukon	2.6	0.7	17	3	39	0	1.6	1.2	48	4	25	3
2. Taku	2.6	0.8	18	2	39	0	1.6	1.2	50	4	25	2
3. Tanana	2.4	0.7	16	6	38	2	1.5	1.1	44	16	26	5
4. Kvichak	1.9	0.7	31	10	39	1	1.1	1.1	81	10	26	5
5. Yukon	3.1	0.7	15	4	38	1	1.9	1.2	38	5	24	4
<b>Average</b>	<b>2.5</b>	<b>0.7</b>	<b>19</b>	<b>5</b>	<b>39</b>	<b>1</b>	<b>1.5</b>	<b>1.2</b>	<b>52</b>	<b>8</b>	<b>25</b>	<b>4</b>
<b>Tidal sites</b>												
1. Chesapeake	2.9	1.0	15		37		1.8	1.7	41		24	
2. Chesapeake	2.6	1.0	18		37		1.6	1.7	48		23	
3. Cook Inlet	2.6	1.0	18		37		1.6	1.7	48		23	
4. Cook Inlet	2.8	0.9	16		38		1.7	1.5	44		24	
5. Cook Inlet	2.8	1.0	16		37		1.7	1.7	42		22	
6. Eastport	2.6	0.8	18		39		1.6	1.4	52		26	
7. Eastport	2.6	0.8	18		39		1.6	1.4	52		26	
8. Hudson r.	2.9	1.0	16		37		1.8	1.7	41		23	
9. Chesapeake	2.8	1.0	16		37		1.7	1.7	44		24	
<b>Average</b>	<b>2.7</b>	<b>1.0</b>	<b>17</b>		<b>37</b>		<b>1.7</b>	<b>1.6</b>	<b>45</b>		<b>24</b>	

$\beta_\alpha$ , has been defined as the ratio  $U_{max}/U_{rate}$  at the desired degree of utilization ( $\alpha$ ) at a particular site. In other words, if  $\beta_{45}=1.4$ , this would mean that the desired 45% degree of utilization is reached at a  $U_{max}/U_{rate}$  ratio of 1.4. With such a low velocity factor, this would seem to be a promising site. On the contrary, if  $\beta_{45}=3.2$ , the site might be more difficult to develop. The velocity factor could thus be used as an early indication if a site is suitable or not.

## Part II:

### Technology

This part of the thesis serves to give a general introduction to the technology for marine current energy conversion and a summary of the work related to the two prototype generators further described in Papers III–VI and Papers VII–VIII respectively.



## 5. Marine current energy technology

Research and development in the area of marine current energy conversion seem to have gained impetus over the last decade with several large scale prototypes deployed over a period of time at test sites such as the European Marine Energy Centre, or EMEC<sup>1</sup>. The goal is to deliver renewable electricity to the grid, and the common approach is to convert the kinetic energy in the freely flowing water with some arrangements of hydrofoils to generate torque that can drive an electric generator, in principle very similar to how a modern wind turbine operates.

A marine current turbine should be expected to be emission free during normal operation. The total emissions during the life cycle of a marine current turbine are expected to be at a similar level as that of a wind turbine or a wave energy converter [72]. As an example, the carbon intensity of the Seagen [5, 73] has been found to be comparable to that of a wind turbine [74] and a wave energy device [75] in life cycle assessments. This is of course also technology dependent; for instance, choice of material, production methods and deployment and decommissioning techniques will affect the emission levels during different stages of the turbine's life cycle. In short, marine current energy is a promising renewable resource; the challenge is to prove the design life-time in the harsh offshore environment.



*Figure 5.1: A picture of the 1 MW AR1000 series turbine by Atlantis Resource Corporation before deployment (used with permission).*

<sup>1</sup><http://www.emec.org.uk/>

Steady progress is being made and several prototypes are moving closer to a commercial stage of development. For instance Tidal Generation Ltd<sup>2</sup> and Marine Current Turbines Ltd<sup>3</sup> have been mentioned as leaders in certain aspects of development in the UK [76]. A few others with notable offshore experience are Atlantis Resource Corporation<sup>4</sup> whose AR1000 turbine is shown in Fig. 5.1, OpenHydro<sup>5</sup>, Verdant Power<sup>6</sup> and ANDRITZ HYDRO Hammerfest<sup>7</sup>. The technology could still be seen as emerging though, as there are currently various technical solutions being promoted with no single design emerging as a clear winner yet. Perhaps the situation can be illustrated by the many names and acronyms given to such energy converters. Different designs have been called tidal in-stream energy conversion (TISEC) technologies [8], tidal current energy extraction (TCEE) technologies [77], tidal current power generation (TCPG) [78], tidal energy conversion systems (TECS) [35], tidal stream turbines (TST) [79], ocean current turbines (OCT) [80], hydrokinetic conversion devices (HCD) [81], marine hydrokinetic (MHK) devices [82], kinetic hydropower systems (KHPS) [83], marine current energy converters (MCEC) [84], or more commonly simply hydro-kinetic turbines or marine current turbines.



*Figure 5.2: The TidGen Power System just prior to its deployment at Cobscook Bay, Maine (photo courtesy of Ocean Renewable Power Company, used with permission).*

The work presented in this thesis is focused on a system that comprises a straight bladed vertical axis turbine and a directly driven permanent magnet generator. The idea of using vertical axis turbines for marine current energy conversion has been proposed before. In some cases the turbine is ducted [85], uses helical blades [86–88], uses a blade pitch mechanism [6,89,90] or is combined with a Savonius rotor to improve the starting torque [91]. For instance

<sup>2</sup><http://www.tidalgeneration.co.uk>

<sup>3</sup><http://www.marineturbines.com>

<sup>4</sup><http://www.atlantisresourcescorporation.com>

<sup>5</sup><http://www.openhydro.com>

<sup>6</sup><http://verdantpower.com>

<sup>7</sup><http://www.hammerfeststrom.com>



the Kobold turbine [89] has been operated offshore mounted under a floating platform, and the Ocean Renewable Power Company<sup>8</sup> has tested their turbine-generator unit with two helical turbines in horizontal position coupled to the same generator, see Fig. 5.2. In this case, however, the turbine studied is a fixed pitch vertical axis turbine with straight blades. Such a turbine has previously been tested both in a towing tank [92] and in a river [93]. Material concerning direct drive generators for such a device is less abundant, although a few interesting generator topologies for marine current energy conversion have been proposed recently [94–97].

A system with a fixed pitch vertical axis turbine coupled to a directly driven PM generator avoids the need for blade pitch, yaw-mechanism, gearbox, mechanical brake and slip rings. However, such a design choice also demands that the generator can be controlled to accommodate fixed tip speed operation, as well as start and brake procedures, at the low rotational speeds expected in a marine setting. The work presented in the following chapters include the design and construction of two such cable wound prototype generators.

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<sup>8</sup><http://www.orpc.co>



## 6. Theory

The author has not taken part in developing the theory or the tools used for the generator and turbine simulations. However, for the benefit of the reader, a short description of the theory will be given to clarify the terminology used later on regarding the interactions between the turbine and generator during fixed tip speed ratio operation. For a more in-depth description of these subjects, the reader may look into some of the excellent textbooks available, for instance [98] regarding electrical machines, [99] for finite element simulations of electrical machines, and [100] regarding vertical axis turbines. The generator-turbine interaction is also discussed in more detail in Paper IV.

### 6.1 Generator

A synchronous generator is composed of two main parts, a rotating part (rotor) and a fixed part (stator). The rotor is equipped with magnets—permanent magnets or electromagnets—so the stator will experience an alternating magnetic flux when the rotor rotates. The stator winding links the variable magnetic flux so that a variable voltage is induced in the winding. According to Faraday’s law of induction the induced no load voltage  $E_i$  in a coil depends on the number of turns  $N$  in the coil and the time rate of change of the flux  $\Phi$  as

$$E_i = -N \frac{d\Phi}{dt}. \quad (6.1)$$

For a complete generator, the total induced voltage is the sum of the voltages in all the coils that make up the winding. The magnitude of the total voltage depends on how the coils are positioned in the machine relative to each other. The magnetic flux in the machine, in turn, depends on the geometrical and material properties of the generator. The dependence of the RMS phase voltage,  $U_{rms}$ , on the generator design is given by

$$U_{rms} = \frac{2\pi}{\sqrt{2}} f p \frac{q n_s f_w}{c} B_\delta D_{si} l_{br}. \quad (6.2)$$

This formula is commonly referred to as the Generator Designer’s formula. From this, one can see which parameters affect the design, where  $f$  is the rotor’s mechanical frequency,  $p$  is the number of pole pairs,  $q$  is the number of slots per pole and phase,  $n_s$  is the number of conductors per slot,  $f_w$  is the winding factor,  $c$  is the number of parallel current circuits,  $B_\delta$  is the magnetic

flux density in the air gap,  $D_{si}$  is the inner diameter of the stator, and  $l_{br}$  is the axial length of the stator.

In the case of a very low speed machine, for instance, the number of poles and the diameter can be increased to reach a certain voltage level. In practice, other requirements (structural mechanics, costs etc.) also have to be taken into consideration, which makes the design process a bit more complicated.

For a grid connected generator, the voltage and the frequency are set by the voltage and the frequency on the grid. For a variable speed machine, however, voltage and frequency can be seen as free design parameters as the generator output will be rectified and inverted before grid connection.

The generator discussed in this thesis has been designed with the aid of an in-house developed two-dimensional finite element method tool based on the program ACE [101]. The main input parameters are the desired power, voltage, and rotational speed. After a two-dimensional cross section geometry of the generator has been defined and all parts have been assigned material properties, the magnetic flux density is calculated and the axial length of the machine is computed to achieve the desired voltage level. From these results the generator performance can be evaluated.

A generator will always suffer from different mechanical and electromagnetic losses during operation. In a well designed low speed PM generator, it is probable that copper losses in the stator winding and iron losses in the stator core will be the main contributors to the total losses in the machine. The iron losses are in turn the sum of the hysteresis and eddy current losses. The losses can be expressed as

$$P_{Cu} = RI^2, \quad (6.3)$$

$$P_{hysteresis} = k_h B_{max}^2 f, \quad (6.4)$$

$$P_{eddy} = k_e (B_{max} f)^2, \quad (6.5)$$

where  $R$  is the stator winding resistance and  $I$  the armature current. The loss coefficients  $k_h$  and  $k_e$  describe material properties,  $B_{max}$  is the maximum value of the magnetic flux density and  $f$  is the frequency. Equations 6.4 and 6.5 do not fully account for all losses in the stator. Hence, an empirical correction factor of 1.5 has been used to account for the influence of manufacturing processes and flux rotation in parts of the stator. The magnetic flux density will not vary much during operation since permanent magnets are used. The armature current and frequency will however change during variable load and variable speed operation. Thus, the share of copper losses and iron losses can be expected to change among various points of operation in a variable speed system.

## 6.2 Turbine

The amount of kinetic energy that can be extracted by a turbine from a flowing fluid is often referred to in terms of its power coefficient  $C_P$ . Thus, the amount of power that the turbine can capture and convert to mechanical power on the turbine shaft can in accordance with Eq. 2.1 be expressed as

$$P_t = \frac{1}{2} C_P \rho A v^3. \quad (6.6)$$

The value of  $C_P$ , or how “efficient” the turbine is, depends on how the turbine blades move relative to the flowing fluid. The relative velocity between the turbine blades and the water is called tip speed ratio  $\lambda$  and can be defined as

$$\lambda = \frac{\Omega r}{v}, \quad (6.7)$$

where  $v$  is the velocity of the fluid,  $\Omega$  the angular velocity of the turbine and  $r$  is the turbine radius. For a certain tip speed ratio  $\lambda_{opt}$ , the power coefficient will reach its maximum value and hence the turbine will give the highest power capture. Depending on how the turbine is designed,  $C_P$  will vary with the tip speed ratio slightly differently. As an example, the characteristic power coefficient curves for two of the turbines used in Paper VI are shown in Fig. 6.1. It can be seen that the two turbines reach their maximum  $C_P^{max}$  at a tip speed ratio of 2.5 and 3, respectively.

During normal operation a high power capture is usually desired. It should be noted, however, that operation at  $\lambda_{opt}$  with the turbine does not necessarily equate to an optimal point of operation for the system as a whole. For instance, at high velocities it could be better to operate at a lower  $\lambda$  to limit the forces on the turbine. Such a choice of control method could also be motivated in terms of degree of utilization [22].

Another characteristic of a turbine is its solidity  $\sigma$ , i.e. the fraction of the area swept by the turbine that is taken up by the turbine blades. The solidity of a vertical axis turbine can be defined as [100]

$$\sigma = \frac{N_b c_b}{2 \pi r}, \quad (6.8)$$

where  $N_b$  is the number of blades and  $c_b$  the average blade chord length. Choosing a design value for the solidity is a trade off between several parameters. A lower solidity could for instance require less material and be more cost effective; on the other hand the structural integrity of the turbine might require a certain solidity.

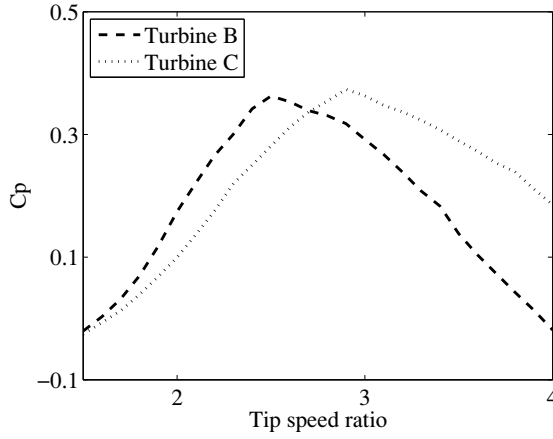


Figure 6.1:  $C_p$ -curves for two of the example turbines used (Fig. 8 in Paper IV).

### 6.3 Fixed tip speed ratio operation

To maintain  $C_p^{max}$  while the water current velocity varies, the turbine rotational speed should be controlled so that

$$\Omega = \frac{v \lambda_{opt}}{r}. \quad (6.9)$$

In other words, the rotational speed of the turbine should be increased as the water velocity increases. For a direct drive synchronous generator, the rotational speed of the generator will be the same as that of the turbine. Hence, as the power capture of the turbine is proportional to the cube of the velocity according to equation 6.6, the input power to the generator will also be proportional to the rotational speed cubed, or  $\Omega^3$ .

In order to get a rough idea of how the generator should be controlled to maintain fixed tip speed ratio operation of the turbine, let us assume that the generator is operated with a resistive load and neglect the losses within the generator. The power output of the generator should under these assumptions be equal to  $P_t$  and thus proportional to  $\Omega^3$  according to

$$P_g = P_t \propto \Omega^3. \quad (6.10)$$

The power of the generator can be expressed as

$$P_g \propto UI. \quad (6.11)$$

According to Ohm's law the current is proportional to the voltage divided by the resistance, which means that

$$I = \frac{U}{R} \Rightarrow P_g \propto \frac{U^2}{R}. \quad (6.12)$$

The voltage  $U$  is roughly proportional to  $\Omega$  in a generator and thus one can see that the resistive load should be varied as

$$R \propto \frac{1}{\Omega} \quad (6.13)$$

to maintain operation at  $\lambda_{opt}$ . In other words, the armature current should increase proportionally to the square of the rotational speed of the turbine during fixed tip speed ratio operation. According to equations 6.3 – 6.5 it is then clear that the iron losses will be relatively large at low velocities and copper losses will increase significantly at higher velocities. As mentioned previously, the generator will be connected to the grid via a rectifier and inverter to allow for variable speed operation. The reasoning above should however give a rough indication of the requirements put on a directly driven generator under fixed tip speed ratio operation with a fixed pitch vertical axis turbine.





## 7. The prototype generator

In this chapter the design, construction and experiments regarding the directly driven PMSG prototype will be discussed.

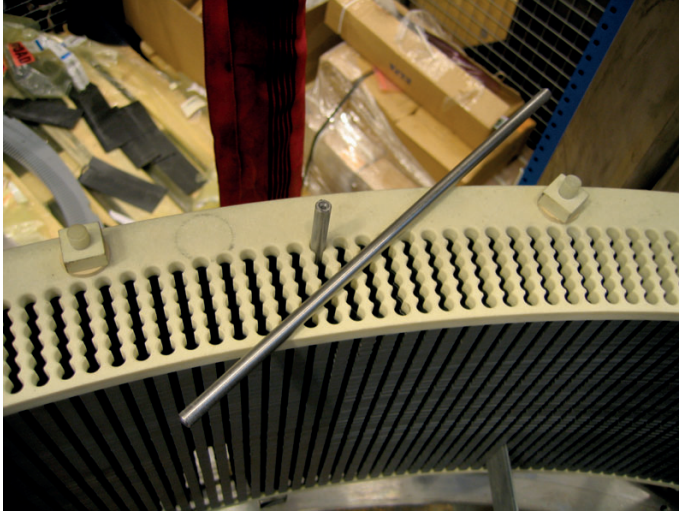
### 7.1 Design and construction

It was decided to build an experimental setup for a low speed permanent magnet generator to validate previous simulations. The first laboratory prototype was intended for variable speed operation and is equipped with 120 poles. According to the nominal design values, the generator is rated at 5 kW and 150 V at a rotational speed of 10 rpm.

The setup was only intended to be used in the laboratory; hence the mechanical requirements on the design could be kept seemingly simple. The stator had to be round, the rotor should be centred in the stator, the permanent magnets should be safely mounted and the whole setup should be able to operate in a range of rotational speeds corresponding to the expected situation in a tidal current. With that said, one could of course expect some practical issues along the way as the prototype in many ways is not a standard design.

After the different parts had been manufactured and delivered to the laboratory, the careful assembly could begin. After the stator support structure had been erected, the stator sheet metal could be stacked. Due to the low nominal frequency, 1 mm thick stator sheets could be used. To maintain proper alignment of the sheet metal, cylindrical metal rods were put in the stator slots at a few places, see Fig. 7.1. The result was satisfactory and the stator could be wound without complications. However, the end winding length was increased from the initial design value to ease the winding procedure (see Table 7.1). When the winding procedure was finished, the rotor could be lifted in place with the aid of an overhead crane (see Fig. 7.2).

The rotor was designed with milled grooves to keep the magnets in place. Before the rotor was magnetized, however, the frictional losses in the rotor bearings were measured to separate these losses from other losses in the machine. The time it took for the rotor to decelerate from 105% to 95% of nominal speed was measured. The frictional torque was found to be 2 Nm, or 0.04% of the nominal torque. According to the manufacturer's data, the frictional torque should be roughly 1.6 Nm. Such a low friction was taken as a sign that the alignment of the rotor shaft and the mounting of the bearings had gone according to plan. The magnets could then be mounted in the milled grooves using a bespoke plastic mould.



*Figure 7.1:* A few metal rods were put in the stator slots while stacking the stator sheet metal to maintain proper alignment.



*Figure 7.2:* The rotor is being lowered into the stator. The milled grooves for the magnets are clearly seen on the rotor ring.

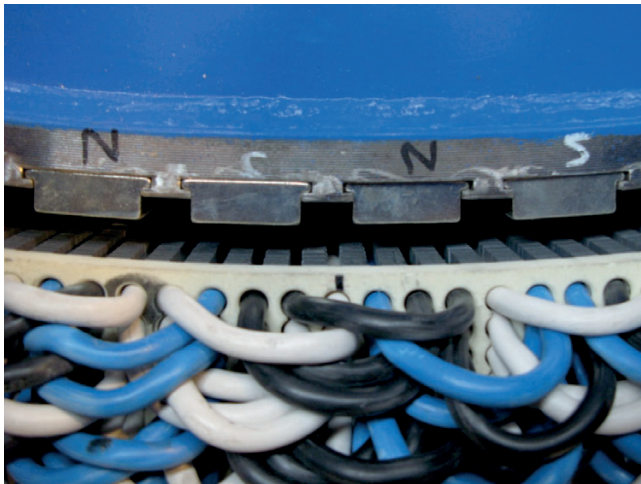
In Fig. 7.3, a photograph of the air gap can be seen together with the magnets inserted in the milled grooves and the three phase stator winding. The stator is wound with a commercially available PVC-insulated cable with a conductor cross section of  $16 \text{ mm}^2$ . Blue, white, and black insulation had been chosen for the three phases to avoid any confusion during the winding procedure. The finalized experimental setup is shown in Fig. 7.4. In the photograph the induction motor used to drive the generator can be seen tucked in under the generator. On the right hand, the motor drive and the computer used to collect data are also seen.

Table 7.1: *The initial design parameters compared to the actual prototype (Table 1 from Paper I).*

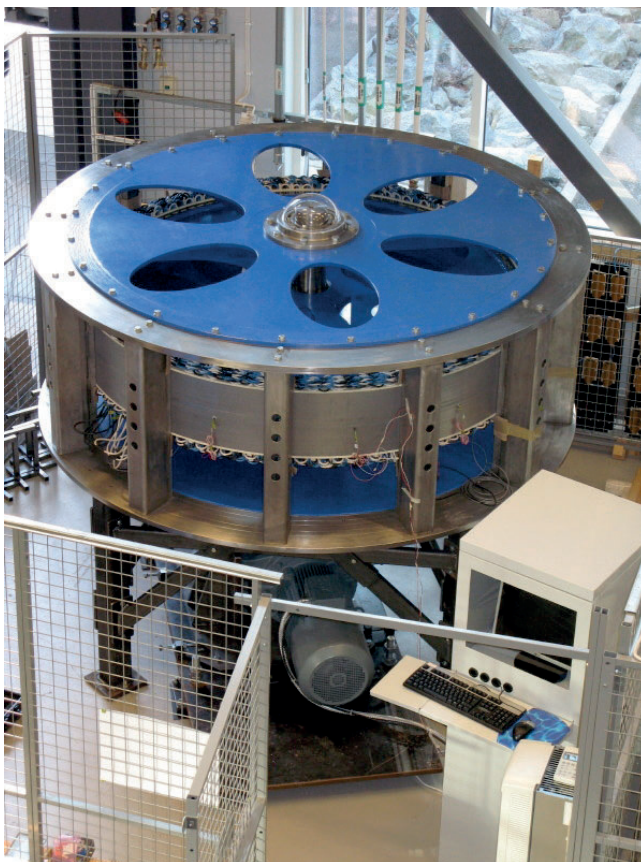
Generator parameter	Design stage	Actual prototype
Power	5 kW	5 kW
Voltage	150 V	150 V
Current density	1.2 A/mm <sup>2</sup>	1.2 A/mm <sup>2</sup>
Frequency	10 Hz	10 Hz
Nominal speed	10 rpm	10 rpm
Stator outer diameter	2000 mm	2000 mm
Stator inner diameter	1835 mm	1835 mm
Air gap	10 mm	10.5 mm
Slots per pole	7/5	7/5
Cables per slot	6	6
PM width	32 mm	32 mm
PM thickness	10 mm	13 mm
PM axial length	270 mm	4×68 mm (4 PM per pole)
Rotor ring thickness	10 mm	12–15 mm (mean 14.4 mm)
Stator axial length	270 mm	294 mm
Stacking factor	1	0.956
Coil end winding	80 mm	150 mm
Resistance per phase	0.48 $\Omega$	0.47 $\Omega$
Load	4.5 $\Omega$ per phase	4.44 $\Omega$ per phase

After the setup was finalized, it was clear that there were some small differences between the initial design and the constructed prototype (see Table 7.1) due to constructional inaccuracies and allowed tolerances. These small changes were incorporated in the simulation tool to allow for more accurate comparison between simulation and experiments.

Since there were some uncertainties regarding the issue of rotor position, it was decided to stack the stator sheet metal slightly higher than the axial length of the rotor to allow for small errors in the axial placement of the rotor. This decision—together with the fact that the stator sheet metal could not be stacked tightly enough to reach a stacking factor of one—meant that the stator axial length was slightly longer than the design value (294 mm compared to 270 mm). The rotor ring thickness turned out to be varying around the rotor. However, as the rotor ring is not close to magnetic saturation, this should not have any noticeable effect on the reluctance of the magnetic circuit.



*Figure 7.3: A photo of the air gap, permanent magnets, and stator winding (Fig. 5 from Paper I).*



*Figure 7.4: The experimental setup (Fig. 6 from Paper I).*

The motor drive system used to control the speed of the generator is based on a 30 kW frequency inverter from ABB and a 22 kW induction motor with a gearbox (gear ratio 89.89) from SEW Eurodrive. This allows for operation up to 67% above nominal speed and roughly twice the nominal torque. The generator is Y-connected to a resistive load<sup>1</sup>. The load can be varied by connecting the resistors in series and parallel.

In the end it was clear that the prototype met the design criteria: the stator was round within a tolerance of 0.1 mm, the rotor was well centered in the stator, and the magnets had been safely mounted. With the motor drive the generator could be operated from 0–16 rpm and the load could be varied both below and above rated load.

## 7.2 Experiments

Before the prototype generator was taken on its maiden run the resistance and inductance per phase of the winding were measured to 0.475  $\Omega$  and 11.5 mH respectively. As the generator was inaugurated, the first measurements were carried out just to see that the generator was well balanced and working as expected. The following equipment was used to measure the voltage and the current as well as the magnetic field in the air gap:

- Lecroy Wavesurfer 424 oscilloscope<sup>2</sup> with an accuracy of  $\pm (1.5\% + 0.5\%$  of full scale).
- Tektronix P2220 voltage probes (10x, 10 M $\Omega$ , 16 pF).
- Metrix MX240 universal power clamp<sup>3</sup> with an accuracy of 1%R + 8D, i.e. 1% of the measured value and  $\pm 8\%$  of the least significant digit.
- A Model 7010 Gauss/Tesla meter from F. W. Bell<sup>4</sup> with Hall probe to measure the magnetic field in the air gap.

After the joyous inauguration of the experimental setup all the differences between the initial design and the constructed prototype (as seen in Table 7.1) were incorporated into the simulation tool.

## 7.3 The stator slot geometry

While designing a prototype there are always a number of issues that are left unresolved, simply because the answer can only be found by actually building the prototype. One such case was the stator slot geometry of the first proto-

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<sup>1</sup>HS300 resistors from Arcool ([www.arcoolresistors.com](http://www.arcoolresistors.com)) and KS 300.6 heatsinks from Austerlitz Electronics ([www.austerlitz-electronic.de](http://www.austerlitz-electronic.de))

<sup>2</sup>[www.lecroy.com](http://www.lecroy.com)

<sup>3</sup>[www.chauvin-arnoux.com](http://www.chauvin-arnoux.com)

<sup>4</sup>[www.fwbell.com](http://www.fwbell.com)

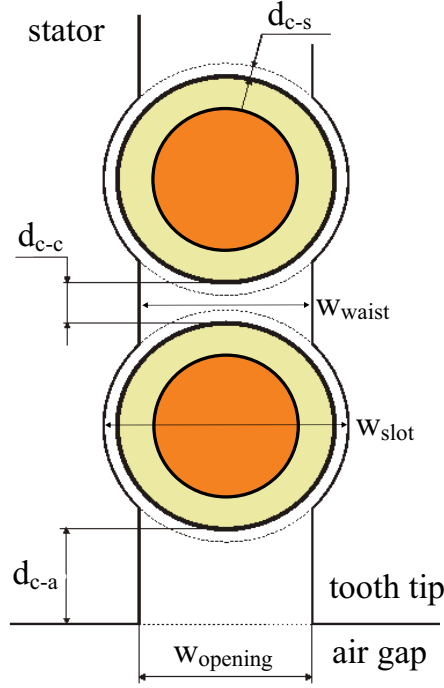


Figure 7.5: Geometry parameters of the studied stator slot (Fig. 2 from Paper VI).

type, where a too tight design could obstruct the winding procedure. Now, with practical experience, it can be concluded that the winding procedure was successful and that improvements to the stator slot geometry could be implemented in practice in future cable wound machines.

The cable wound design of the first prototype utilizes a single row six cables per slot. The cables are inserted axially rather than radially from the air gap. No slot wedges are used, instead the slot opening is small and a waist is introduced between each cable to keep them in place and to stop them from rubbing against each other during winding.

The stator slot geometry is studied by changing one parameter at a time. As can be seen in Fig. 7.5, there are four parameters that are changed: the distance between cable and air gap ( $d_{c-a}$ ), the distance between cables ( $d_{c-c}$ ), the distance between cable and stator ( $d_{c-s}$ ), and finally the waist ( $w_{waist}$ ) which is also referred to as the waist factor defined as the ratio of the waist to the slot width ( $w_{waist}/w_{slot}$ ).

The design of the first generator was used as reference geometry, and then one parameter at a time is changed to see how it influences the generator performance. All computations are performed at nominal load and speed. Based on experience from winding the first prototype, a new design is proposed that should be possible to implement in practice given that the stator sheets are stacked properly. The new design is compared to the reference machine in Section 9.4.



## 8. The Söderfors project

The Söderfors project is the research group's first attempt to operate the vertical axis turbine under real conditions in an aquatic setting. The primary goals with the experimental setup are proof of concept, validation of simulation tools and for experience. An important part of the project is to characterize the turbine in the flow conditions that a river may offer. Whilst the focus of this thesis is the generator, a brief overview of the site and the whole unit is presented to give the context in which the generator has been designed.

A suitable site was found where the river Dalälven flows through Söderfors. The site is situated 800 m downstream of an existing hydropower station and the channel is around 100 m wide with a depth of 6–7 m where the turbine shall be deployed, see Fig. 8.1



*Figure 8.1:* A view of the site in Söderfors. The turbine will be deployed downstream of the bridge with the aid of a crane.

Early on in the project, time was spent on securing the necessary permits and establishing good working relationships with the local and regional authorities. Hourly discharge data for the years 2004–2008 was acquired from the owner of the upstream hydro power plant (Vattenfall AB). Velocity measurements were carried out with an ADCP at the site to establish the annual velocity distribution (averaged over the five years of available data, see Fig. 8.2) and the velocity profile (averaged over 24 hours, see Fig. 8.3), which both are important for the design of the experimental station.

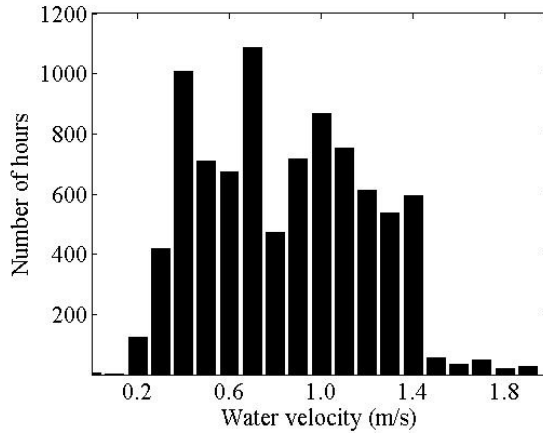


Figure 8.2: Annual velocity distribution based on five years of discharge data (Fig. 3 from Paper VII).

An illustration of the experimental station is shown in Fig. 8.4. The turbine utilizes five NACA 0021 blades with a cord length of 0.18 m. The turbine  $C_p$  is expected to be 0.35 at a tip speed ratio of 3.5. The conical lid on the generator housing also acts as turbine support. The whole unit is mounted on an adjustable tripod foundation. For more information on the site and the design of the turbine, please see Papers VII–VIII or [102].

## 8.1 Design and construction

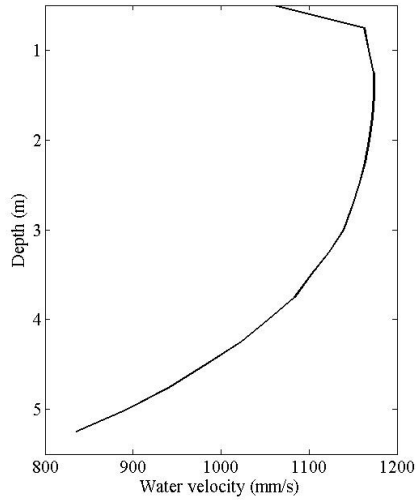
### 8.1.1 The generator

The electromagnetic design of the generator is largely based on the earlier laboratory prototype (see Chapter 7) adjusted to match the turbine performance for the flow velocities at the Söderfors site. Most of the work concerned mechanical integration of the generator, the turbine and the foundation. Sealing of the generator housing and inclusion of equipment for measurements and monitoring were also important parts of the design work. All the parts were designed to be machined at a local workshop and assembled by hand at the university.

The design ratings of the generator are 7.5 kW and 128 V at 15 rpm. It has 112 poles and is wound with a 5/4 fractional wave winding. The stator has an inner diameter of 1635 mm and the air gap is 7 mm.

The housing supports both the turbine shaft and the generator and is designed to be water tight. The stator frame is basically a thin metal ring, or steel tube, reinforced with beams and flanges (see Fig. 8.5, item 2). Firstly, the laser cut stator sheets (M800-100A) were stacked and secured (see Fig. 8.6) and the stator was wound with a standard 16 mm<sup>2</sup> cable (RK 16 450/750 V). The winding procedure was very similar to that of the first prototype. The ca-

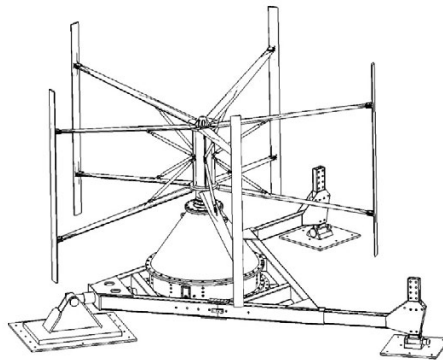




*Figure 8.3:* The velocity profile at the site based on 24 hour average of ADCP-measurements (Fig. 4 from Paper VII).

bles were cut in lengths suited for half a row. Starting in the bottom position of the slot, half of the cable was wound clock-wise and the other half counter clock-wise. Longer cables could probably be used in an automated winding procedure as discussed in [103] to limit the number of joints.

After winding, the stator section was fastened to the flat flanged bottom with standard o-rings for sealing. The un-magnetized rotor was then lowered into the stator (see Fig. 8.7) and the conical lid with the turbine bearing could be mounted. Thus, the rotor was secured and the generator could be tilted into horizontal position for magnetization and experiments. The generator was driven by the same equipment presented in Chapter 7, see Fig. 8.8.



*Figure 8.4:* The whole unit on the adjustable tripod foundation. Design by Anders Nilsson (from Paper VIII).

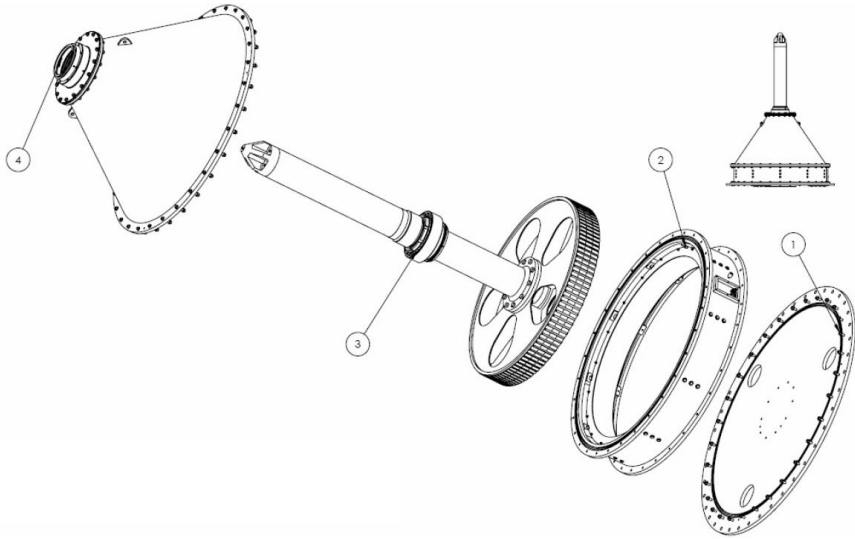


Figure 8.5: An exploded view drawing of the generator and housing with 1) the flat bottom flange with holes used for mounting magnets, 2) stator support, 3) rotor and shaft with bearings 4) lid and turbine support with sealing and bearing housing. Design by Anders Nilsson (from Paper VIII).

After the testing was completed, the sealing was mounted and filled with biodegradable grease (SKF LGGB 2) before a short test run. The holes in the flat flanged bottom were then permanently sealed and the generator was painted and transported to Söderfors to be mounted on the foundation.

### 8.1.2 Measurement system

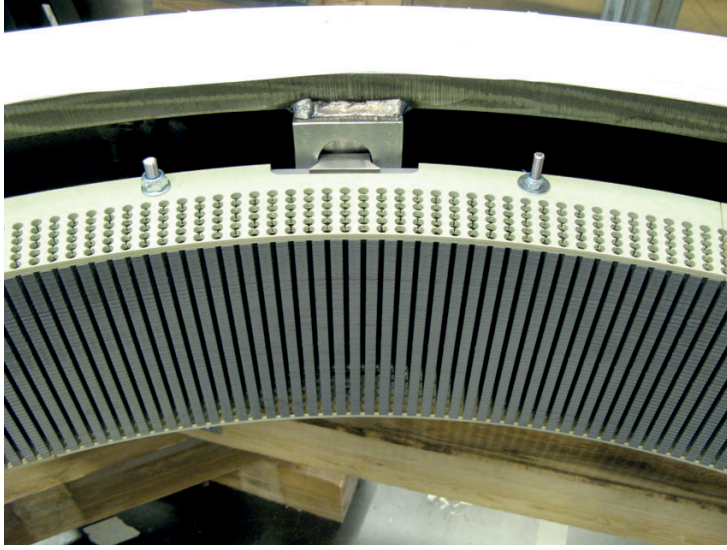
The control and measurement system of the Söderfors station is intended to operate the turbine at a designated tip speed ratio, and to handle start and brake procedures as well as collecting data for further analysis. For a more detailed description of the control system, see [19]. Although a separate system is used to drive and control the generator during these laboratory experiments, the measurement system of the Söderfors station is used to measure currents and voltages. Furthermore, frictional losses, torque and B-fields have also been measured as described below.

Currents are measured for each generator phase using HAL 100 and 200 current transducers from LEM<sup>1</sup>. Voltages from the generator and over the load are measured after voltage division. Three line-to-line voltages and one phase-to-neutral voltage are measured.

Measurement signals are acquired using a C-series module NI9205 from National Instruments<sup>2</sup> and a sampling rate of 2 kHz is used. The voltage signals were calibrated using an APPA 207 True RMS meter, which gave a scale

<sup>1</sup><http://www.lem.com> 2013-01-07

<sup>2</sup><http://www.ni.com> 2013-02-09



*Figure 8.6: The stator before winding (from Paper VIII).*

factor for each voltage division. The offset of the current transducers was set to be within  $\pm 0.018$  A.

Torque on the generator shaft was measured with a DF-30 torque sensor from Lorenz Messtechnik and the signal was transmitted to the NI 9205 module via a 2.4 GHz SG-link from MicroStrain.

Retardation tests were performed before the rotor was magnetized in order to establish the frictional losses. The rotational speed of the rotor was measured using an IR-sensor (Photologic OPB715) which detected the milled grooves in the rotor. A handheld gaussmeter (Lakeshore Model 410) with an accuracy of  $\pm 2\%$  of reading and  $\pm 0.1\%$  of full scale ( $\pm 2$  T) was used to measure the B-field in the air gap.

## 8.2 Experiments

Frictional losses were measured by accelerating the un-magnetized rotor manually to over 20 rpm and recording its deceleration in the expected range of operation (i.e. 5–15 rpm).

The B-field in the air gap was measured both during stand still and at nominal speed.

Two sets of experiments were performed using the motor-drive system seen in Fig. 8.8. In the first, the generator was operated at variable speed (2–16.7 rpm) against a purely resistive, Y-connected balanced three phase load. Different sets of  $1\ \Omega$  resistors (Vishay RPS 500 series) mounted on heat sinks were used to cover the expected range of power for fixed tip speed ratio operation of the vertical axis turbine. In the second set of experiments,



*Figure 8.7: The un-magnetized rotor in position (from Paper VIII).*

the generator was operated against a diode rectifier connected to the resistive load in parallel with a capacitor bank of 26.4 mF to more closely resemble the intended operation in Söderfors.



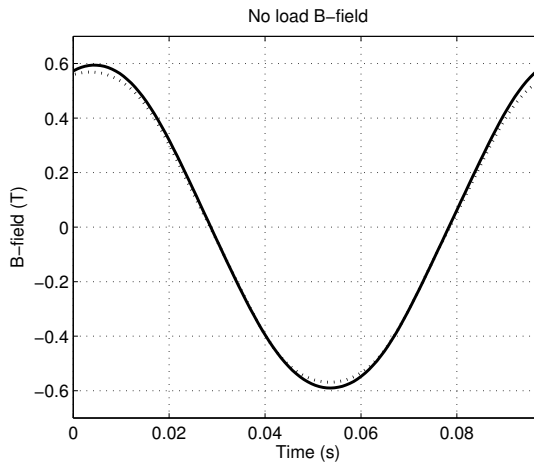
*Figure 8.8: The machine in horizontal position for laboratory experiments, connected to a motor drive system and a torque measuring system (from Paper VIII).*

## 9. Results and discussion

In this chapter, some of the experimental results and simulations are discussed based on the material presented in the appended Papers III–VIII.

### 9.1 Generator performance with resistive AC load

The first prototype generator was well balanced as expected. No-load tests were carried out at the nominal speed of 10 rpm. The normal component of the magnetic flux in the air gap was measured on a stator tooth and compared to simulated values taken 1 mm in front of a stator tooth to coincide with the position of the Hall probe (see Fig. 9.1). The voltage of one phase is compared to simulations in Fig. 9.2. It was found that the measured RMS value was lower than the simulated values, whereas the difference is smaller for peak-to-peak values. This can in part be explained by the harmonic content of the phase voltages. Under nominal load and speed conditions both experiments and simulations show only a negligible fifth harmonic. However, the third harmonic is larger in the simulations (6%) than in the measurements (2%). One possible explanation for the different harmonic content could be the T-shaped milled grooves that the magnets are positioned in (see Fig. 7.3). In the



*Figure 9.1:* The simulated (dotted line) and the measured (solid line) normal component of the B-field in the air gap at no load and nominal speed (from Paper V).

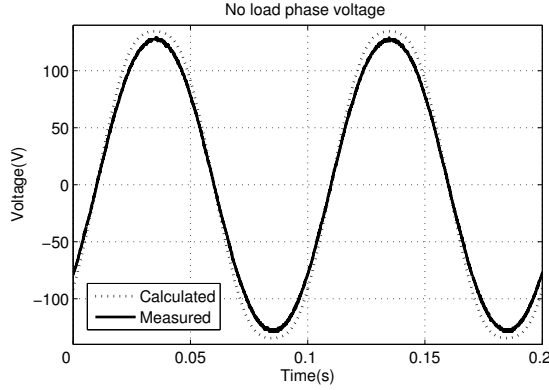


Figure 9.2: The no load phase voltage of one phase at the nominal speed of 10 rpm (Fig. 4 from Paper V).

simulation tool, the milled grooves are only modelled as rectangular grooves, which could give a slightly different field distribution.

As presented in Paper III and IV, the generator has also been tested experimentally under variable speed operation from 2–16 rpm with different resistive loads. The generator has been working satisfactorily under these conditions, and the phase voltage wave forms show reasonable agreement with simulations, both at very low speed and at the highest speed offered by the motor drive system used in the experimental setup (see Paper III).

In Fig. 9.3, the RMS values of the phase voltage are shown for variable speed operation with three different values of the resistive load. The deviations between measurements and simulations can in part be attributed to measurement uncertainties and differences in geometry and material properties between the constructed and the simulated generator. However, as the generator has a large diameter compared to its axial length, axial leakage is probably also a significant part of the difference between experiment and simulations.

## 9.2 Generator performance with turbines

In Paper IV, the performance of the first prototype generator has been evaluated under fixed tip speed ratio operation with three different hypothetical turbines. At this stage of the analysis, no consideration has been given to issues regarding structural mechanics of the turbines; they have merely been used to exemplify how the generator could be operated to match fixed TSR operation of the turbines. The three turbines A, B, and C were chosen to have different solidity and thus different optimum TSR (see Table 9.1), which means that they are likely to be suitable together with this particular generator at sites with somewhat different ranges of current velocities.

To simplify the comparison, the mechanical power on the turbine shaft is assumed to be the same as the mechanical power on the generator shaft (i.e.

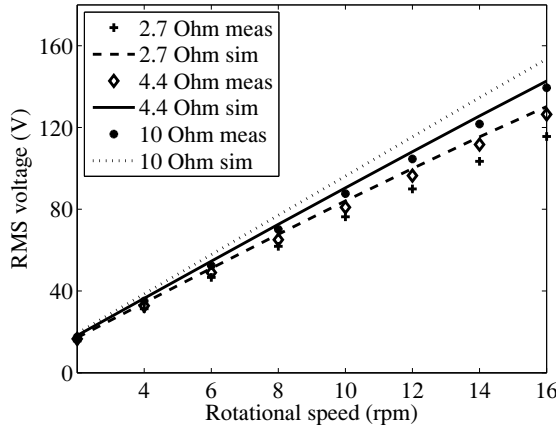


Figure 9.3: Measured and simulated values of  $U_{rms}$  for various speeds and loads (Fig. 6 from Paper IV).

Table 9.1: *Example turbines (Table 2 from Paper IV)*

Turbine	A	B	C
Radius (m)	2.5	3	3
Height (m)	1.6	3	3
$\lambda_{opt}$	1.7	2.5	3
$C_p$ (at $\lambda_{opt}$ )	0.35	0.35	0.35

frictional losses in bearings and seals are taken to be small and thus neglected). In Fig. 9.4, the power from the turbines is compared with the generator output and losses for four load cases from 4–16 rpm. As can be seen, the generator should be suitable for fixed tip speed ratio operation of all three turbines within this range of speeds.

It is desirable to maintain good system efficiency over the expected range of operation. To do so, it is not self-evident that keeping the turbine at fixed tip speed ratio would also give the highest system efficiency in all situations, see for instance [19]. However, in this particular case the generator efficiency has been evaluated for fixed TSR operation for turbine A (Fig. 9.5) and turbine B (Fig. 9.6). It can be seen how iron losses tend to dominate at lower speeds as the power, and thus armature current, decreases. The copper losses, on the other hand, become significant at higher rotational speeds and power. The upper limit of fixed TSR operation for the generator would be reached as the heat from the copper losses comes close to the thermal limit of the chosen winding insulation. Where this limit would lie is not well known as it does not only depend on the generator, but also on the surrounding water temperature and how well the heat can be dissipated through the generator housing into the flowing water. For the prototype at hand, the thermal limit for for the

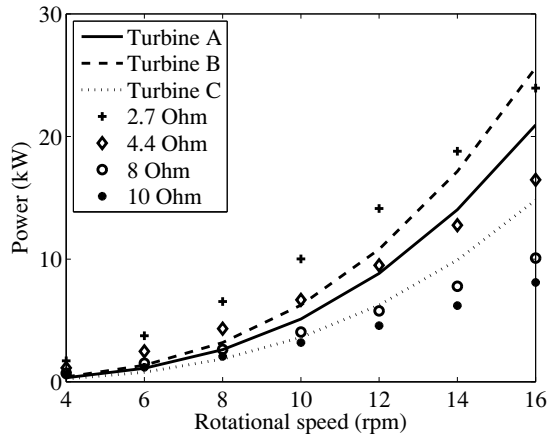


Figure 9.4: Power output from the three example turbines compared with generator power at different loads (Fig. 9 from Paper IV).

insulation material is  $70^{\circ}\text{C}$  for continuous operation, and it is expected to be reached when the current density is approximately  $4\text{ A/mm}^2$  or higher.

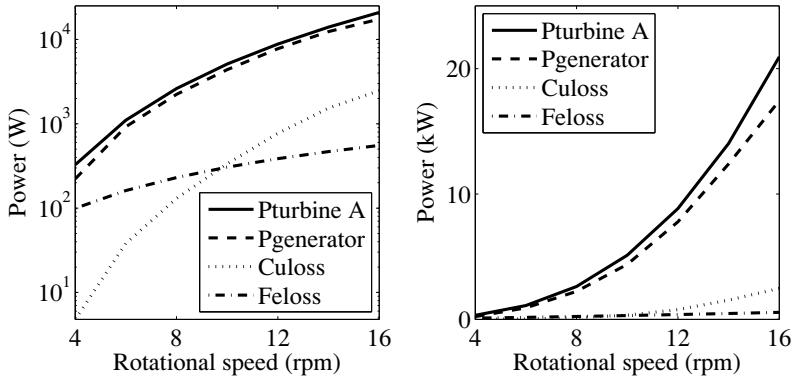


Figure 9.5: Generator performance with turbine A presented in logarithmic scale to the left and linear scale to the right (Fig. 10 from Paper IV).

To see more clearly which range of water current velocities would be suitable for such generator-turbine combinations, the generator efficiency as a function of current velocity is shown in Fig. 9.7 for fixed tip speed ratio operation with turbines A and B. It is seen that turbine A gives a high efficiency for current velocities up to  $2.5\text{ m/s}$ . Turbine B gives a better performance for lower velocities than turbine A and should be better suited for a site where the velocities seldom exceed  $1.5\text{ m/s}$ . Below  $1\text{ m/s}$  the efficiency decreases for both generator-turbine combinations, however turbine B can still be operated with reasonable efficiency down to  $0.5\text{ m/s}$ . For other water current velocities, a different combination of generator and turbine may be more suitable.



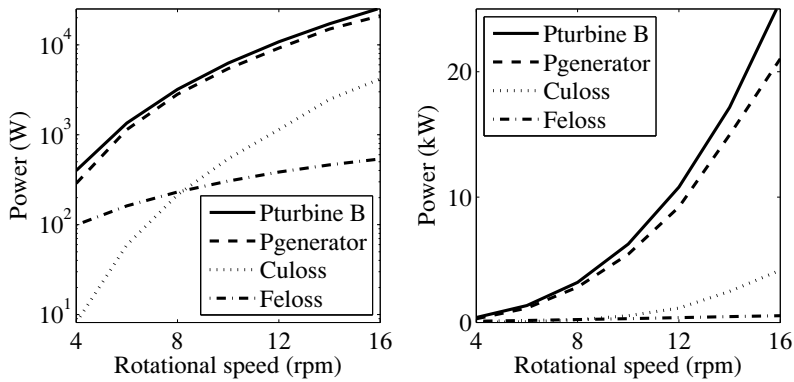


Figure 9.6: Generator performance with turbine B presented in logarithmic scale to the left and linear scale to the right (Fig. 12 from Paper IV).

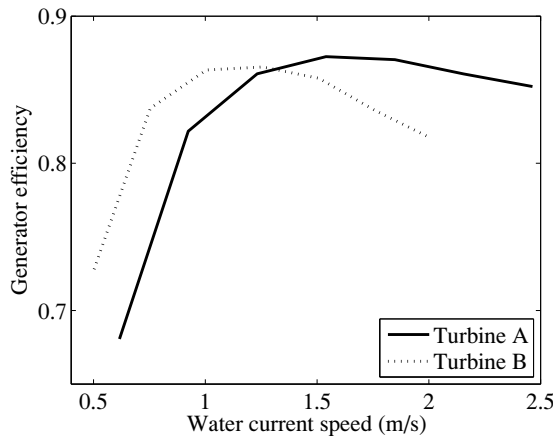


Figure 9.7: The generator efficiency as a function of rotational speed while under fixed tip speed ratio operation with turbines A and B (Fig. 14 from Paper IV).

In the actual marine environment, the generator should also have the capacity to decrease the rotational speed of the turbine at higher water velocities to limit the power absorbed and to avoid cavitation. If necessary, the generator and control system should also be able to electrically brake the turbine to a complete stand still at any water velocity expected at the site. The line voltage and efficiency of the generator at nominal speed and increasing load are shown in Fig. 9.8, indicating the generator can be used to control the turbine under various conditions while maintaining a good efficiency. To illustrate the brake capacity of the generator, the mechanical power on the shaft as the generator is connected to a dump load of  $1.5\Omega$  is compared the mechanical power of a turbine ( $C_P$  of 0.35, delivering 5 kW at 10 rpm in a water current of 1.5 m/s) running at a fixed TSR at increasing water velocities (see Fig. 9.9). It can be

seen that the generator safely brakes this particular turbine at velocities up to twice the nominal speed.

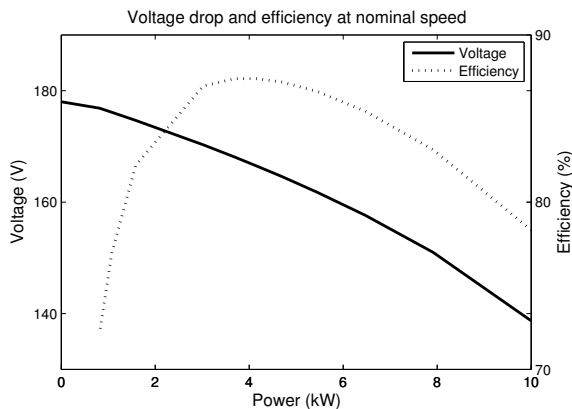


Figure 9.8: The generator line voltage and efficiency as a function of increasing power at nominal speed (Fig. 10 from Paper V).

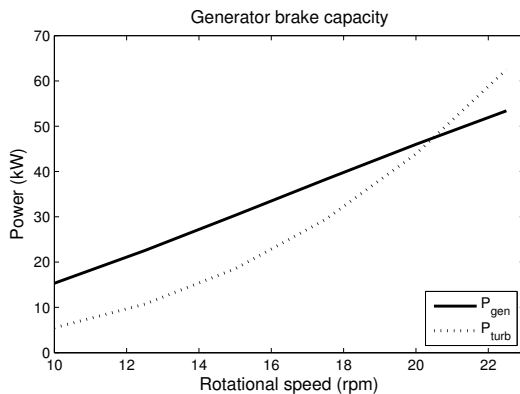


Figure 9.9: The mechanical power of a turbine and the generator. The turbine is operating at fixed TSR at increasing water velocities, and the generator is connected to a dump load of  $1.5 \Omega$  (Fig. 11 from Paper V).

### 9.3 The Söderfors generator

The generator for the Söderfors experimental station was tested in a laboratory setting before being transported to the site. The main aim was to measure the efficiency of the generator in the expected range of operation in order to better understand the turbine performance once in the water.

The frictional torque in the bearings was measured to 32 Nm and the air gap flux density was measured on several stator teeth at stand still to 0.66–0.68 T, slightly lower than the design value of 0.69 T.

The machine worked well during operation, although at a lower voltage level due to unexpected leakage flux at the top of the rotor, in turn resulting in higher copper losses and lower efficiency at the intended design point (7.5 kW at 15 rpm). Simulations predict the same no-load voltage as the experiments (138 V) with an effective length of 177 mm, 20 mm shorter than the stator stack length. This can to an large extent be explained by the leakage flux at the top of the rotor, see Fig. 9.10 for a graphical illustration of the situation. Furthermore, the simulations do not account for leakage due to each pole being made of three separate magnets or leakage due to equal rotor and stator stack length as discussed in [104].

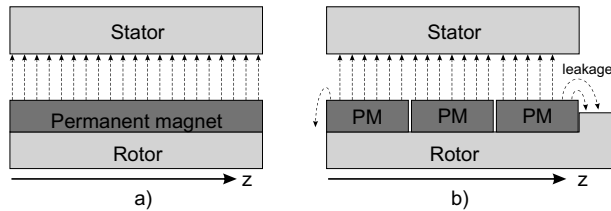


Figure 9.10: Artistic impression of the flux components created by the permanent magnets in a radial cross section of the machine. a) The simulated case with no leakage flux. b) The actual machine with significant leakage at the top of the rotor and three separate magnets per pole. The effective length is thus shorter than the stator stack length (Fig. 7 from Paper VIII).

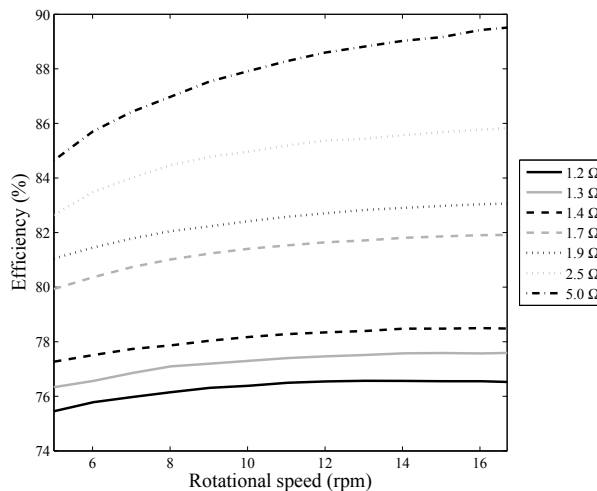


Figure 9.11: Measured efficiency during variable speed operation with different resistive loads (Fig. 8 from Paper VIII).

The measured efficiency in the range 5–16.7 rpm with a resistive load and with a rectifier is shown in Fig. 9.11 and 9.12 respectively. The generator is expected to operate in the presented range during fixed tip speed ratio operation of the turbine. It will operate at higher efficiency at at low speed and

low load, while to handle the quickly increasing power from the turbine at higher velocities the efficiency will drop off at higher rotational speed during fixed tip speed operation as discussed in [105]. To illustrate this, the measured voltage drop at constant rotational speed (15 rpm) and increasing power is shown in Fig. 9.13. As expected, the voltage and efficiency drop quicker as the generator output is rectified.

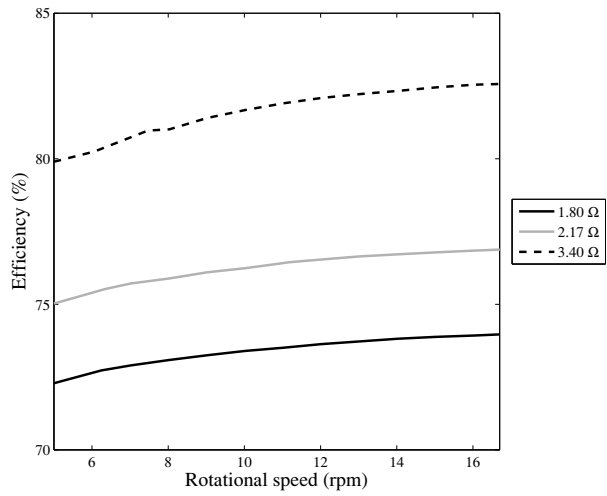


Figure 9.12: Measured efficiency during variable speed operation with rectifier and different resistive loads (Fig. 9 from Paper VIII).

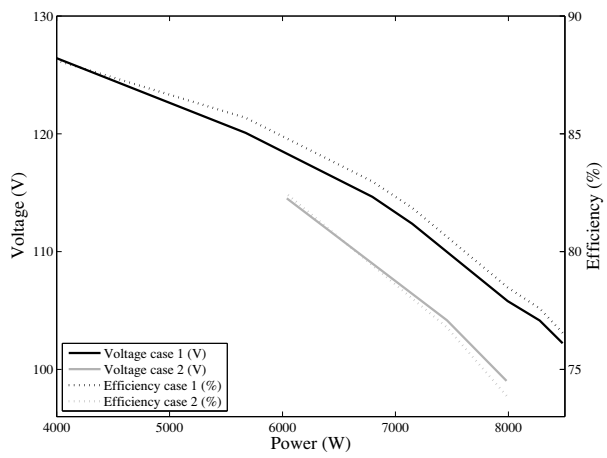


Figure 9.13: Comparison of the measured voltage drop and efficiency at nominal speed as a function of power output for the two cases, i.e. operation with increasing resistive load and with rectifier and increasing resistive load (from Paper VIII).

Table 9.2: *Stator slot geometry of the reference machine compared to the suggested improved geometry (Table 2 from Paper VI).*

Parameter	Reference	New design
Slot opening	4 mm	4 mm
Slot width ( $w_{slot}$ )	8 mm	7.6 mm
Waist width ( $w_{waist}$ )	6 mm	6.1 mm
Waist factor	0.75	0.8
Cable to cable ( $d_{c-c}$ )	2 mm	0.8 mm
Cable to air gap ( $d_{c-a}$ )	5.5 mm	1.3 mm
Cable to stator ( $d_{c-s}$ )	0.5 mm	0.3 mm
Cable diameter	7 mm	7 mm
Slot depth	58 mm	47.6 mm

Table 9.3: *Reference machine performance at its nominal operating point compared with the suggested improved design (Table 3 from Paper VI).*

Parameter	Reference	New design
Efficiency	86.4%	87.0%
B in stator tooth	1.69 T	1.57 T
Hysteresis losses in teeth	0.149 kW	0.128 kW
Eddy current losses in teeth	0.037 kW	0.032 kW
Total losses	0.785 kW	0.748 kW
Load angle	7.5°	6.2°
Stator weight	598 kg	532 kg

## 9.4 On the stator slot geometry

Utilizing cable winding presents the possibility to use new stator slot geometries not previously studied in great detail. First of all, it should be noted that no slot wedges are used in this design, instead the slot opening is small enough to hinder the armature winding from entering the air gap. As the stator is wound axially, however, the distance between cable and stator ( $d_{c-s}$ ) is important in practice. It is preferable to keep the gap between cable and stator small to keep the cables in place during operation and for a good thermal contact between the insulation and the stator steel. A *too* small gap, however, would cause problems during the winding procedure and cause unnecessary wear on the cables. Winding of the first prototype went smoothly with a gap of 0.5 mm, indicating that the gap could be decreased in practice as long as the stator sheets are stacked and aligned properly. The efficiency of the generator and the magnetic flux in the stator tooth are shown in Fig. 9.14 for varying  $d_{c-s}$ .

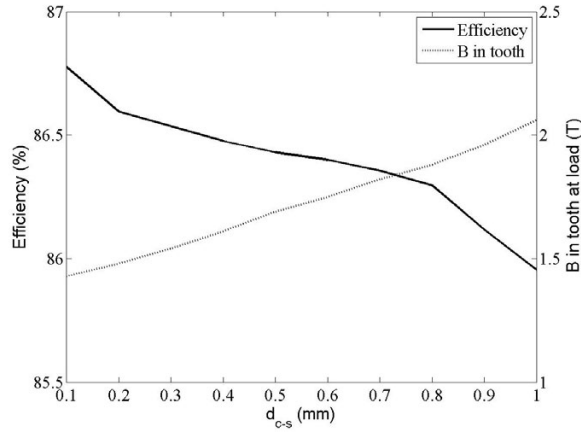


Figure 9.14: Efficiency and B-field in tooth at nominal load for varying distance between cable and stator (Fig. 6 from Paper VI).

Another important part of the stator slot geometry is the waist design. A small waist between each cable is necessary to keep the cable in place during operation and to stop the cables from rubbing against each other during winding. A small waist effectively keeps the cables in place, but it also enables leakage flux. It can clearly be seen in Fig. 9.15 that a smaller waist increase the leakage flux.

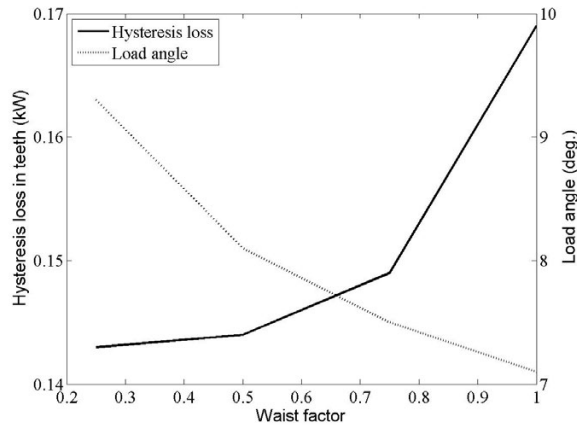


Figure 9.15: The hysteresis loss in the stator teeth and the load angle as a function of the waist factor (Fig. 3 from Paper VI).

Based on experience from winding the the prototype generator, an improved stator slot geometry is proposed (see Table 9.2) that, according to simulations, would improve the generator performance (see Table 9.3). The efficiency would increase from 86.4% to 87.0% and the load angle would decrease from  $7.5^\circ$  to  $6.2^\circ$ . Perhaps more significantly, the stator weight would

be decreased by 11%, and the outer diameter would be decreased by 20.4 mm allowing for further savings on the support structure.

The decrease in load angle can be translated into either a decrease in magnetic material necessary to maintain the nominal design point of 150 V and 5 kW at a load angle of  $7.5^\circ$ , or an increase in power output at nominal voltage and nominal load angle. Simulations predict that the new design can reach the nominal design point utilizing 19% less permanent magnet material, or an 22% increase in electrical power output at nominal voltage and load angle.





**Part III:**

**Concluding remarks**



## 10. Conclusions

The subject of the present thesis is hydro-kinetic energy conversion from freely flowing water. Studies on both the resource and the technology have been performed and the following conclusions can be drawn.

An assessment of the tidal energy resource in Norway has been carried out based on available data in pilot books. More than 100 sites have been identified as interesting with a total estimated theoretical resource—i.e. the kinetic energy in the undisturbed flow—in the range of 17 TWh. However, due to the uncertainties connected to data from pilot books, and the fact that the methodology used to obtain this theoretical value is sensitive to relative errors, the assessment should only be seen as a rough indication of the size and characteristics of the resource in Norwegian waters.

The velocity distribution presented by tidal currents, unregulated rivers and regulated rivers has also been studied. The results indicate that a relatively high degree of utilization (around 50%) is achievable at most sites while the ratio of maximum velocity to rated velocity remains below two. Further velocity measurements of high temporal resolution are necessary to verify the results.

A laboratory prototype of a variable speed directly driven PM generator designed for the low velocities inherent to the hydro-kinetic resource has been constructed. Experiments show that the generator is well balanced and there is reasonable agreement between measurements and corresponding simulations, both at nominal load and under variable speed operation. It is shown that the generator can be controlled to accommodate fixed tip speed ratio operation and to brake the turbine in the expected range of operation.

An experimental setup comprising turbine, generator, foundation and control system has been finalized and is ready for deployment in the River Dal at Söderfors. The generator efficiency has been measured with both a resistive AC load and with a rectifier in the range of operation expected at the test site.

Practical experience from winding the first prototype generator suggests that improvements of the stator slot geometry can be implemented. Simulations predict that the proposed changes in the stator slot geometry would decrease the stator weight by 11% and decrease the load angle by 17%. The decrease in load angle opens the possibility to reduce the amount of permanent magnetic material in the design.



## 11. Future work

How to make the hydro-kinetic resource a valuable and sustainable part of our future energy system is not a question for engineering scientists alone. It has to be addressed by politicians, industrialists, environmental groups and device developers to name but a few.

Looking back at this thesis in the area of engineering science, however, it is clear that the work regarding the resource (Papers I and II) is limited by the availability of velocity measurements. It would be valuable to the field of research if more velocity measurements were performed and made publicly available. ADCP-measurements of high spatial and temporal resolution are not only important for estimating the potential energy yield, they are also important input parameters in the iterative process of improving the whole system in terms of reliability and efficiency.

The work leading up to this thesis has mainly been focused on the first step of such an iterative process, i.e. to deploy the first prototype and perform *in situ* experiments in an aquatic setting. The experimental station is finalized, but unfortunately not yet deployed. As soon as the weather conditions improve and the deployment can commence, there are numerous experiments to be performed. Two ADCPs are to be positioned upstream of the turbine, one in vertical position and one in horizontal position, to characterise the onset flow. Furthermore, one more ADCPs will be positioned downstream of the turbine to measure the wake propagation. Such measurements should lead to more realistic performance and loading predictions.



## 12. Summary of Papers

The work presented in this thesis is based on the following papers and the author's contribution to each paper is specified below.

### Paper I

#### **A review of the tidal current energy resource in Norway**

This is a review paper focusing on the possibility of utilizing tidal currents as an energy resource in Norway. Norway is well known both for her oil and offshore industry, and the academic work at Norwegian universities regarding oceanography has been extensive. However, surprisingly little work has been carried out regarding tidal currents as an energy resource. Hence closely related topics are also examined in order to shed some light on the tidal resource along the Norwegian coastline. Two published tidal energy resource assessments are reviewed and complemented with a desktop study based on data in pilot books. The argument is made that tidal energy could be an interesting option for Norway in terms of renewable energy. From the review it is also clear that more work, both measurements and simulations, are required for a better description of the extractable resource.

The author has collected background information and data needed to perform the review. The planning and interpretation have been done together with the co-authors. Concerning the writing, the author has been largely responsible for the introduction, the review of resource assessments, and the section on prototypes and experiments. *Published in Renewable and Sustainable Energy Reviews, 13(8):1898–1909, 2009.*

### Paper II

#### **On the velocity distribution for hydro-kinetic energy conversion from tidal currents and rivers**

In this paper the velocity distribution of a number of river sites and tidal currents are analysed. The focus is on the possible degree of utilization (or capacity factor), the fraction of converted energy and the ratio of maximum to rated velocity, all of which are believed to be important characteristics of the resource affecting the economic viability of a hydro-kinetic energy converter. The analysis suggests that choosing a rated velocity closer to the mean velocity at the site would, on average, result in a degree of utilization in the range of

50% while the ratio of maximum to rated velocity would still be around 2 or lower for both tidal currents, unregulated rivers and regulated rivers. This implies that the velocity distribution of both rivers and tidal currents is promising for kinetic energy conversion. These results, however, do not include weather related effects and the analysis could be improved if longer data sets of higher temporal resolution were available for all sites.

The author was the main instigator of the work and performed the literature review. The author also made minor contributions to the analysis and to the latter part of the writing process. *Accepted with revisions, Journal of Renewable and Sustainable Energy, 2013.*

## Paper III

### **A low-speed generator for energy conversion from marine currents—experimental validation of simulations**

This paper is devoted to discussing the road map from the conceptual stage of a direct drive generator suited to the nature of tidal currents towards design and construction of the first prototype. The design process and a number of practical issues encountered during the construction work are discussed. The argument is made that as such a generator is feasible, it is possible to eliminate several other mechanical components such as the gearbox and pitching mechanism. This could be crucial for the survivability of a marine current energy converter.

The author has taken part in the design and construction of the experimental setup and has made major contributions to the writing of the paper except for the section on theory and modelling details. *Published in Proc. IMechE Part A: Journal of Power and Energy, 222(4):381–388, 2008.*

## Paper IV

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

The aim of this paper is to evaluate the performance of the variable speed prototype generator in a system perspective, taking into account both the characteristics of a turbine and the natural variations in current velocities inherent to the resource. To achieve this, the prototype generator is tested under variable speed operation, at nominal load as well as above and below nominal load, and the measurements are found to be in agreement with the finite element based simulations. It is then evaluated how the generator could perform under fixed tip speed ratio operation with three different fixed pitch vertical axis turbines. It is shown that the generator can accommodate fixed tip speed ratio operation with different turbines in current velocities in the range of 0.5–2.5 m/s.



The author has been involved in preparing the equipment needed to perform the measurements. The author has also contributed to the writing process. *Published in IEEE Journal of Oceanic Engineering, 34(1):24–31, 2009.*

## Paper V

### **A permanent magnet generator for energy conversion from marine currents: No load and load experiments**

Empirical results from no load and nominal load experiments on the direct drive generator prototype are compared to finite element simulations of the generator. In both cases, the magnetic fields in the air gap are also compared to the corresponding simulations. Harmonic analysis of the measured phase voltages show only the presence of third harmonics. Simulations of variable speed operation suggests that the generator can be used to electrically control and brake the turbine in the intended range of operation.

The author participated in the design and construction of the experimental setup and performed a major revision of the paper. *Published in ISRN Renewable Energy, June 2012.*

## Paper VI

### **Detailed study of the stator slot geometry of a cable wound synchronous generator**

The stator slot design of a cable wound permanent magnet synchronous generator for hydro-kinetic energy conversion is studied using finite element (FE) simulations. Experience from the design and the construction of two prototypes are included to highlight the importance of changes on the millimetre scale in the stator slot geometry, and to discuss to what degree these changes can be implemented in practice. A new design is proposed and simulations predict an increase in efficiency, while the stator core weight and the load angle are decreased.

The author has written most of the paper. *Submitted to Renewable Energy, February 2013.*

## Paper VII

### **Design of an experimental setup for hydro-kinetic energy conversion**

The site of the Söderfors project in the River Dal is presented in this paper and an initial design of the experimental setup is proposed. The velocity distribution and velocity profile at the site are discussed based on ADCP measurements and hourly discharge data from the upstream hydropower plant. A simulated vertical axis turbine is combined with three generator designs, and

the efficiency and the annual energy production are presented for the three systems.

The work presented in the paper is clearly a collaborative effort of the whole research group involved in the Söderfors project. As first author and corresponding author, the author put forward the main structure of the paper and coordinated and edited the texts of the co-authors. *Published in International Journal on Hydropower & Dams, 15(5):112–116, 2009.*

## Paper VIII

### **Efficiency of a directly driven generator for hydro-kinetic energy conversion**

The design and construction of the direct drive generator to be used in the Söderfors prototype are discussed in this paper. The generator efficiency has been measured for the range of speed and power expected at the Söderfors site. To the best of the authors' knowledge, this is the first time a directly driven generator will be used in the low velocity range presented by rivers.

The author has worked with design and assembly of the experimental setup and written most of the paper. *In Manuscript, 2013.*

## 13. Svensk sammanfattning

Denna doktorsavhandling inom teknikvetenskap rör både resursen och tekniken för energiomvandling ur fritt strömmande vatten. Fritt strömmande vatten, såsom tidvattenströmmar, oreglerade älvar och andra havsströmmar, utgör en sedan länge känd källa för energi som hitintills är föga utnyttjad för generering av förnybar elenergi.

Det finns flertalet fördelaktiga aspekter hos fritt strömmande vatten som energikälla, exempelvis relativt hög energitäthet och möjlighet till god utnyttjandegrad. Dock måste tekniken klara den tuffa miljön ute till havs. Det finns även mycket som talar för att reparationer och underhållsarbete kan komma att bli relativt svårt och kostsamt ute till havs. Därför finns det anledning att tro att en enkel och robust teknisk lösning vore fördelaktigt ur ett helhetsperspektiv.

Forskningsområdet som sådant kan ännu anses vara relativt ungt och präglas av stor bredd, från oceanografi och hydrodynamik till mekanik och elektromagnetism, och en nära koppling mellan resursbeskrivningar och teknikutveckling förväntas vara gynnsamt för fortsatt utveckling. Som titeln antyder har denna avhandling inslag av både resursbeskrivning och teknikutveckling, där en inledande litteraturstudie visar att potentialen för förnybar energi från strömmande vatten ej är väl kartlagd i dagsläget. De data om strömmande vatten som finns tillhands är oftast inte insamlade för ändamålet att kartlägga potentialen. Dessutom saknas lättillgängliga metoder och modeller för att beräkna hur stor andel av den kinetiska energin som kan utvinnas och omvandlas. I samband med denna litteraturstudie utfördes även en mer ingående potentialbedömning för Norge. Utifrån data om tidvattenströmmar i *Den Norske Los* [52] har över 100 intressanta platser längs den norska kusten identifierats. Den samlade teoretiska resursen från dessa platser har mycket grovt uppskattats till 17 TWh. Hur stor del av den potentialen som kan tänkas utvinnas är i dagsläget svårt att avgöra. Dock går det att jämföra med två tidigare studier där man utifrån samma data undersökt 12 [53] respektive 24 platser [54] och funnit att den tekniska och ekonomiska potentialen på dessa platser skulle kunna vara omkring 1 TWh. Det bör dock noteras att alla tre studier är baserade på högst osäkra data. Vidare har ingen av de tre studierna tagit hänsyn till eventuella konflikter med andra näringsidkare eller avstånd till närmaste nätanslutning, faktorer som kan tänkas vara av vikt vid en eventuell exploatering av tidvattenresursen. Den utförda litteraturstudien visar att troligen både mer utförliga mätningar och omfattande numerisk modellering skulle krävas för att nå en bättre förståelse för resursen och dess respons på energiomvandling.

Som med många andra förnybara energikällor har vi ingen, eller mycket liten, möjlighet att styra när resursen är tillgänglig, dvs när vattnet strömmar och med vilken hastighet. För lämplig dimensionering av turbin och generator är det därför viktigt att veta vilken hastighetsfördelning som kan förväntas. Utifrån hastighetsfördelningen går det att välja lämplig nominell hastighet och effekt för turbinen samtidigt som det är känt vilken högsta hastighet utrustningen kan komma att utsättas för. Givetvis vore det fördelaktigt, tekniskt och ekonomiskt, med en hastighetsfördelning med liten skillnad mellan medelhastighet och maxhastighet eftersom det skulle resultera i en hög utnyttjandegrad samt förhållandevis låga maxlaster jämfört med nominella driftförhållanden. En studie har genomförts för att se vilken hastighetsfördelning, och därmed möjlig utnyttjandegrad, som tidvattenströmmar, oreglerade älvar och reglerade älvar kan tänkas erbjuda. Återigen bör noteras att studien begränsas av tillgängliga data för vattenhastigheter. Resultaten antyder dock att resursen erbjuder god utnyttjandegrad (omkring 50 %) samtidigt som kvoten mellan högsta hastighet och turbinens nominella hastighet i medeltal är 2 eller lägre.

Forskning kring tekniken för marin strömkraft har bedrivits vid Avdelningen för elektricitetslära vid Uppsala universitet sedan tidigt 2000-tal. Målet var redan från början att se till helheten och söka finna ett tekniskt och ekonomiskt hållbart sätt att generera förnybar el från strömmande vatten. Konceptet som togs fram, med avsikt att vara mekaniskt sett enkelt med få rörliga delar, bygger på en vertikalaxlad turbin kopplad direkt till en permanentmagnetiserad generator. Således undvikes flertalet komponenter som kan kräva underhåll, exempelvis växellåda och magnetiseringsutrustning för rotorpolerna. Genom att variera generatorns varvtal kan dessutom turbinen gå vid ett gynnsamt löptal och därmed upprätthålla en hög systemverkningsgrad inom det intervall av hastigheter som tidvattenströmmar och älvar erbjuder. Hela systemet är tänkt att stå på botten av havet eller ett vattendrag, skyddat från kraftiga vågor.

Under de första åren av projektet lades stor möda ned för att ta fram en elektromagnetisk design av en generator anpassad för de krav som ställs på det ovan omnämnda systemet. Vid starten av detta doktorsarbete fanns därmed en färdig elektromagnetisk design av generatoren och det var dags att ta steget från simuleringar till en första prototyp. Därför präglas denna avhandling av omfattande inslag av praktiskt ingenjörsarbete inför färdigställandet av prototypen och efterföljande experiment.

Den första prototypen har en kabellindad stator och en permanentmagnetiserad rotor med 120 poler. Generatorns märkvärden är 5 kVA och 150 V vid en nominell rotationshastighet av 10 varv per minut. Experimentuppställningen innefattar även ett drivsystem och en last som möjliggör drift i området upp till 16.7 varv per minut vid dellast såväl som vid överlast. De utförda experimenten stämmer väl överens med tidigare simuleringar inom området 2–16 varv per minut vid olika last. Simuleringar visar även att generatoren upprätthåller en verkningsgrad över 80 procent vid de hastigheter och laster som motsvarar optimal styrning av vertikalaxlade turbiner för strömningshastigheter i intervallet 0.5–2.5 m/s.

Som med de allra flesta prototyper finns det gott om utrymme för förbättringar. Praktiska erfarenheter från arbetet att bygga och linda statorn gav indikationer på att statorspårgeometrin kunde ändras, främst att kablarna kunde flyttas närmare varandra och att avståndet mellan kabel och stator kunde minskas, för att uppnå bättre prestanda utan att försvåra montage och lindning. Simuleringar visar att de föreslagna förändringarna i statorspårgeometrin kan minska statorvikten med 11 % samt minska maskinens lastvinkel med 17 %. Lägre lastvinkel kan i praktiken översättas till att mindre permanentmagneter behövs för att uppnå önskade prestanda.

Det naturliga steget efter tester i laboratoriet är förstås att sjösätta ett helt system och utföra experiment till havs. Efter mycket arbete fanns en lämplig plats för experiment i Dalälven vid Söderfors, och den senare hälften av detta doktorsarbete har syftat mot att genomföra experiment med en vertikalaxlad turbin och direkt driven generator under naturliga förhållanden. Huvudmålet är att undersöka hur turbinen fungerar under realistiska förhållanden, något som mycket litet information finns publicerad om. En viktig länk i det arbetet är att mäta det inkommande flödesfältet samt att mäta vakutbredningen efter turbinen. Som en del i det arbetet har också generatorns verkningsgrad uppmätts i det intervall av hastighet och effekt som kan förväntas i Dalälven. Experimentstationen var färdigställd för sjösättning i slutet av sommaren 2012, men det myckna regnandet ledde till ovanligt höga flöden i älven och sjösättningen fick skjutas på framtiden. I skrivande stund inväntas fortfarande väderförhållanden som kan tillåta sjösättning.



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