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Marine Current Energy Conversion

Resource and Technology

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Abstract

Research in the area of energy conversion from marine currents has been carried out at the Division of Electricity for several years. The focus has been to develop a simple and robust system for converting 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 that is designed to match the characteristics of the resource. During this thesis work a prototype of such a variable speed generator, rated at 5 kW at 10 rpm, has been constructed to validate previous finite element simulations. Experiments show that the generator is well balanced and that there is reasonable agreement between measurements and corresponding simulations, both at the nominal operating point and at variable speed and variable load operation from 2–16 rpm. It is shown that the generator can accommodate operation at fixed tip speed ratio with different fixed pitch vertical axis turbines in current velocities of 0.5–2.5 m/s. The generator has also been tested under diode rectifier operation where it has been interconnected with a second generator on a common DC-bus similar to how several units could be connected in offshore operation.

The conditions for marine current energy conversion in Norway have been investigated based on available data in pilot books and published literature. During this review work more than 100 sites have been identified as interesting with an estimated total theoretical resource—i.e. the kinetic energy in the undisturbed flow—of approximately 17 TWh. However, due to uncertainties regarding data from pilot books, and the fact that the methodology used to obtain this theoretical value is sensitive to errors in the input data, this assessment should only be seen as a rough indication of the size and characteristics of the resource in Norwegian waters. Furthermore, the literature review reveals that the theoretical resource is likely to be a poor indicator of how much energy can be extracted at a site. The review also shows that further work, both measurements and simulations, is required to reach a more reliable estimate of the extractable resource.

To Therese

List of Papers

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

I   **Grabbe, M.**, Lalander, E., Lundin, S. & Leijon, M. (2008) A review of the tidal current energy resource in Norway. Submitted to *Renewable and Sustainable Energy Reviews*, October 24th 2008.

II Yuen, K., Nilsson, K., **Grabbe, M.** & Leijon, M. (2007) Experimental setup: Low speed permanent magnet generator for marine current power conversion. Reviewed conference paper, published in *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*, San Diego, USA.

III Nilsson, K., **Grabbe, M.**, Yuen, K. & Leijon, M. (2007) A direct drive generator for marine current energy conversion—first experimental results. Reviewed conference paper, published in *Proceedings of the 7th European Wave and Tidal Energy Conference*, Porto, Portugal.

IV 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.

V   Stålberg, M., Svensson, O., Boström, C., **Grabbe, M.**, Bülow, F. & Leijon, M. (2008) Laboratory Testing of a Marine Substation for Wave Power. Submitted to *IEEE Transactions on Power Delivery*, November 4th 2008.

VI Yuen, K., Thomas, K., **Grabbe, M.**, Deglaire, P., Bouquerel, M., Österberg, D. & Leijon, M. (2008) Matching a permanent magnet synchronous generator to a fixed pitch vertical axis turbine for marine current energy conversion. Accepted for publication in *IEEE Journal of Oceanic Engineering* as of Novemeber 4th 2008.

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

VII A low speed speed permanent magnetized generator for marine current energy conversion. *Oral presentation by Katarina Yuen and the author at the 1st International PhD Symposium on Offshore Renewable Energy, INORE 2007, 1st of June, Trondheim, Norway.*

VIII Lundin, S., **Grabbe, M.**, Yuen, K. & Leijon, M. (2008) A design study of marine current turbine-generator combinations. Submitted to *The 28th International Conference on Ocean, Offshore and Arctic Engineering*, December 8th 2008.

Contents

Nomenclature and abbreviations

A	m^2	Area
B	T	Magnetic flux density
c	–	Number of parallel current circuits
c_b	m	Chord length
C_P	–	Power coefficient
D_{si}	m	Inner diameter of the stator
E_i	V	No load voltage
f	Hz	Frequency
f_w	–	Winding factor
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^3	Eddy current loss
$P_{hysteresis}$	W/m^3	Hysteresis loss
q	–	Number of stator slots per pole and phase
R	Ω	Resistance
U_{rms}	V	RMS phase voltage
v	m/s	Velocity
Φ	Wb	Magnetic flux
λ	–	Tip speed ratio
Ω	rad/s	Angular velocity
ρ	kg/m^3	Density
σ	–	Turbine solidity

AC	Alternating Current
DC	Direct Current
DNL	Den Norske Los
HAT	Highest Astronomical Tide
HWL	Highest Water Level
LAT	Lowest Astronomical Tide
LWL	Lowest Water Level
MCEC	Marine Current Energy Converter
MMSS	Mean Maximum Spring Speed
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

Throughout history, humankind has found innovative ways of utilizing different 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 [1], one can only hope that the recent surge of interest in renewable resources such as wave energy and marine current energy will 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 ground grain throughout the Middle Ages [2]. More recently, they have also been used to generate electricity, for instance in the 240 MW tidal barrage at La Rance [3–5]. 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 [6–9].

Many of the prototypes that have been deployed offshore more or less resemble modern 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). The idea of using vertical axis turbines for marine current energy conversion has been proposed before. In some cases the turbine is ducted [10], uses helical blades [11–13], uses a blade pitch mechanism [7, 14, 15] or is combined with a Savonius rotor improve the starting torque [16]. In this case, however, the turbine studied is a fixed pitch vertical axis turbine with straight blades. Material concerning direct drive generators for marine current energy conversion is less abundant, although a few interesting generator topologies have been proposed recently [17, 18].

Over the years, several postgraduate students have worked on this project, and hopefully many more will continue the work in the years to come. In the following, I would like to describe the energy conversion system studied in the project, 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 in 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 into 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 bottom of the ocean or a river where it would be protected from storm surges and strong waves. An illustration of the system is presented in Fig. 1.1.
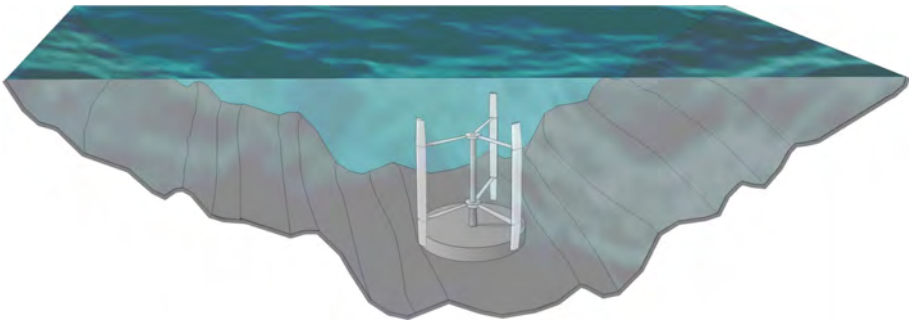

Figure 1.1: The turbine and generator placed on the seabed in a narrow watercourse (illustration by Karin Thomas).

The functionality and survivability of a system operating in an underwater environment demands simplicity and robustness. Once the turbine and generator are deployed offshore, it is likely that any maintenance operation would be both difficult and rather expensive. Thus, the intention has been to design the system from a holistic viewpoint, aiming at minimizing the number of moving parts that could need maintenance rather than suboptimizing parts of the system. With a direct-drive 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 needed 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.

As the generator will be operated at variable speed the terminal voltage will be varying in both amplitude and frequency along with changes in the marine current velocity. Thus the output from the generator has to be rectified and inverted before the generator is connected to the grid.

1.3   Scope of thesis

Previous work within the project has led to several publications on generators in the range of 1–160 kVA [19–25] as well as two doctoral theses, namely those of Ph.D. Erik Segergren [26] and Ph.D. Karin Thomas [27]. The starting point was to investigate how a direct drive PMSG 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.

At the start of this licentiate work, the time had come to build a first prototype of such a generator to allow for comparison with previous simulations and to gain experience for possible future offshore experiments. Much of the design and construction work has been a collaborative effort within the research group and this has already led to a licentiate thesis by Katarina Yuen [28]. At the same time, there has been an ongoing effort to reach a better understanding of the characteristics of the resource. This has been attempted by means of an extensive literature review carried out alongside the construction of the prototype generator. From the review it appears that the resource in Norway is not fully covered in international resource assessments. Hence, a resource assessment for Norwegian waters has been carried out.

1.4   Outline of thesis

The thesis is based on six papers in the area of marine current energy conversion. The first part of the thesis serves to give a context and a summary of the appended papers.

In Chapter 2, a general introduction to marine currents as a renewable energy resource is given, followed by a closer look at what is currently known about the resource in Norwegian waters. A more in-depth analysis of the resource in Norway is presented in Paper I.

A short theoretical background to the design and construction of the prototype generator is presented in Chapter 3 followed by a summary of the actual construction work in Chapter 4. The experimental results from the prototype generator are discussed in Chapter 5. Conclusions and suggested future work are given in Chapter 6 and 7 respectively.

The author's contribution to each of the appended papers is presented in Chapter 8 together with a short summary of the papers. For the interested reader, a Swedish summary of this thesis is given in Chapter 9.

2. Marine current energy resource

This chapter is intended to be an introduction to the area of marine current energy conversion with focus on the resource characteristics. A short summary of the resource assessment carried out in Paper I regarding Norway is also included here.

2.1 Resource characteristics

Marine current energy conversion concerns electricity generation from the kinetic energy in freely flowing water. This differentiates marine current energy conversion from traditional hydro power where the amount of energy extracted from a river is dependent on the head between the reservoir and the water level below the dam. A similar approach can in fact be used for tidal power in areas with high tides. In that case, a barrage can be constructed in a narrow bay or estuary to utilize the head between low and high water. Another way to generate electricity from water would then be to convert the kinetic energy of the flowing water similar to the way a wind turbine would extract energy from the wind. In that case, a dam or reservoir is not necessary; rather one would be looking for sites where the currents are strong, such as a narrow sound, strait, estuary, around a headland or in a river.

The term *marine currents* as used here includes any kind of water currents, be it tidal currents, unregulated rivers or other ocean currents driven for instance by thermal gradients or differences in salinity. The power P in a flowing fluid through a given cross-section A can be expressed as

$$P = \frac{1}{2}\rho A v^3 \tag{2.1}$$

where ρ is the density of the fluid and v is the velocity of the fluid through the cross-section A. Thus, as water is much denser than air, energy conversion from marine currents is interesting even for relatively low velocities. As long as one imagines a single turbine at a site with a cross section much larger than that of the turbine, one would be tempted to draw comparisons 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 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 most likely not suitable in the case of a marine current turbine in a restricted channel. For instance, if too many turbines are placed in a narrow strait between two islands, the blockage effect could decrease the upstream velocity significantly or divert parts of the flow around the other side of the island instead of past the turbines. A different situation would occur if the turbines were to be placed in a river where the flow is constricted and more or less forced to flow past the turbines.

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. One could, of course, try to characterize all the sites and put them into different categories, but at present the necessary data and methods to do this are often not readily available. The difference in velocity before and after the turbines are deployed should also most likely be incorporated into the design process of the actual marine current energy converter (MCEC). As has been shown for a site close to a headland, the velocity in the simulated MCEC farm is clearly lower than that of the undisturbed flow [29].

There are several characteristics of marine currents that make them attractive as an energy source. Marine currents, especially tidal currents, are to a large extent predictable and less intermittent than for instance the wind and the sun. 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 [30]. Limited output power of each device gives smaller difference in power production between spring and neap and thus also a higher degree of utilization [31]. 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 MCEC farm. In some places the tide is phase shifted along the coastline, which means that several MCEC 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 [31, 32].

A MCEC should be emission free during normal operation. The total emissions during the life cycle of a MCEC are expected to be at a similar level as that of a wind turbine or a wave energy converter [33]. As an example, the carbon intensity of the Seagen marine current turbine [6, 34] has been found to be comparable to that of a wind turbine in a life cycle assessment [35]. 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.

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 [36–42]. 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 [43, 44]. For a more in-depth review of previous international resource assessments, see [45].

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 hydrodynamic 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 [36–38, 42] certain selection criteria are used for determining which sites should be included in the assessment. For instance in [42], 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[1]—installed in the East River in New York—does 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. However, 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

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[1]http://www.verdantpower.com – accessed November 2008

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).

effort even for a single site. Thus, assessing hundreds of sites with such an approach is a daunting task. In the last couple of years, 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 [44] and a channel connecting a bay to a large basin [43, 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.

2.3   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[2]), 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. 2.2. Sites with a high tidal current velocity can be found from Bodø all the way up to Vardø, see Fig. 2.3. Several well known sites with strong currents can be found around the Lofoten islands, for instance the Moskenstraumen [50] and Saltstraumen [51].

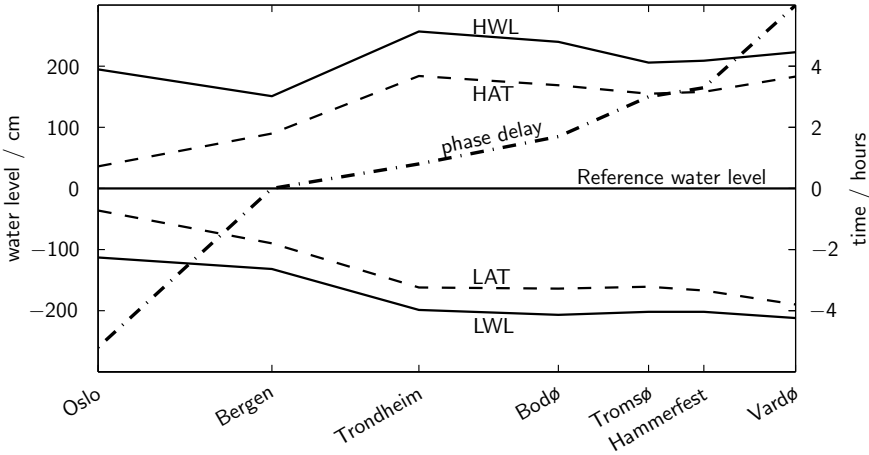[2]http://www.hammerfeststrom.com – accessed November 2008

Figure 2.2: 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]. As presented in Paper I, a review of these two assessments and the tidal resource in Norway has been carried out and complemented with an assessment based on available data. The data and methodology for this comparative study will be briefly presented here.

2.3.1 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 is taken from digital sea charts[3].

2.3.2 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 [38, 39] and is further discussed

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[3]The Norwegian Coastal Administration – http://kart2.kystverket.no

in [9, 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 estimate 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% of the flood tide velocity and finally the 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.

2.3.3   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 2.1). 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

Table 2.1: *The number of sites and calculated resource as presented in the three different resource assessments.*

	[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	–

Table 2.2: *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.*

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%)

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 2.2. 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 possible 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. 2.3.
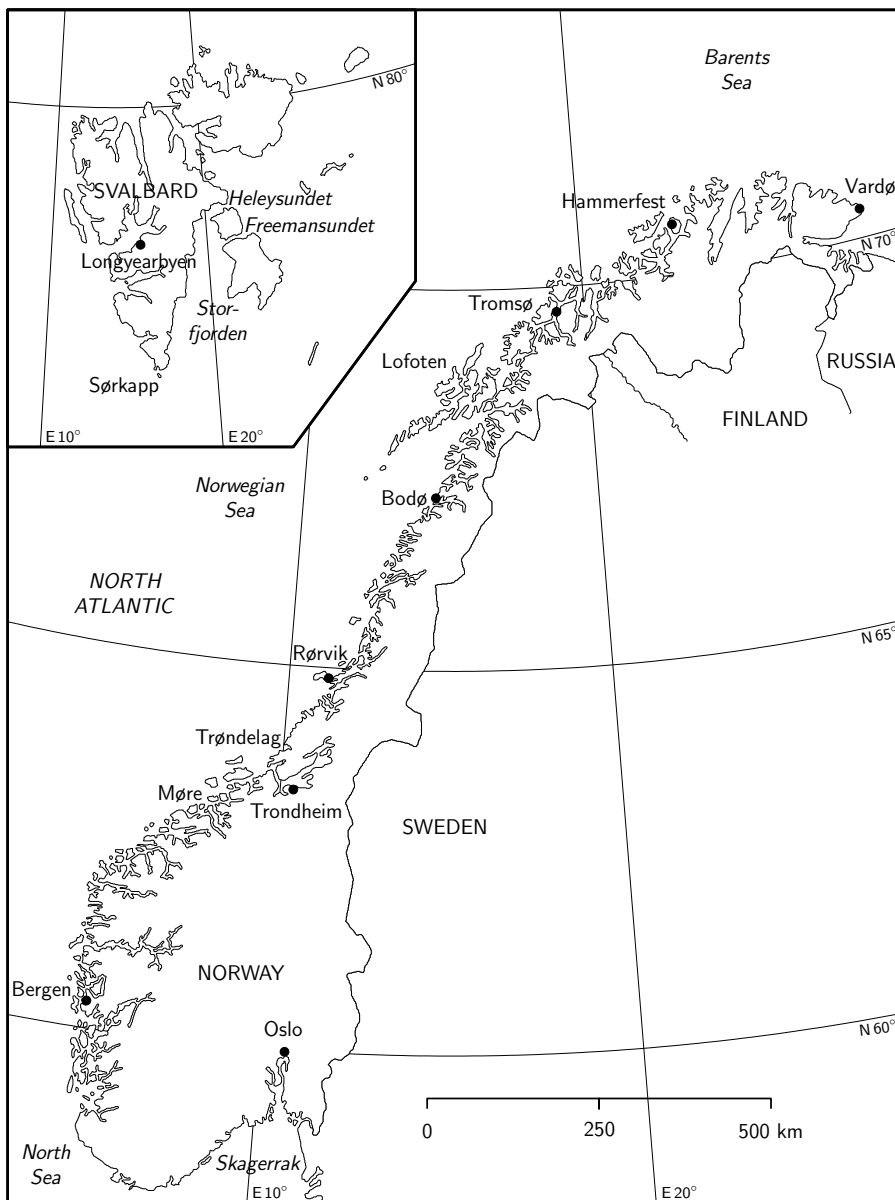
Figure 2.3: A map of the Norwegian coastline including Svalbard (picture prepared by Staffan Lundin).

3. 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. More information about the finite element simulations of the generator can be found in Paper IV, and the turbine-generator interaction is further described in Paper VI. For a more in-depth description of these subjects, the reader may look into some of the excellent textbooks available, for instance [64] regarding electrical machines, [65] for finite element simulations of electrical machines, and [66] regarding vertical axis turbines.

3.1 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 Φ as

$$E_i = -N \frac{d\Phi}{dt}. \tag{3.1}$$

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 in the generator. The dependence of the RMS phase voltage, U_{rms}, on the generator design is given by

$$U_{rms} = \frac{2\pi}{\sqrt{2}} f p \frac{q n_s f_w}{c} B_\delta D_{si} l_{br}. \tag{3.2}$$

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_σ 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 [67]. 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

$$P_{Cu} = R I^2, \tag{3.3}$$

$$P_{hysteresis} = k_h B_{max}^2 f, \tag{3.4}$$

$$P_{eddy} = k_e \left(B_{max} f \right)^2, \tag{3.5}$$

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 3.4 and 3.5 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.

3.2 Turbine

The amount of kinetic energy that can be extracted by a turbine from a flowing fluid is often referred to as 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 equation 2.1 be expressed as

$$P_t = \frac{1}{2} C_P \rho A v^3. \tag{3.6}$$

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 λ and can be defined as

$$\lambda = \frac{\Omega r}{v}, \tag{3.7}$$

where v is the velocity of the fluid, Ω the angular velocity of the turbine and r is the turbine radius. For a certain tip speed ratio λ_{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. 3.1. 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 λ_{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 λ to limit the forces on the turbine. Such a choice of control method could also be motivated in terms of degree of utilization [31].

Another characteristic of a turbine is its solidity σ, 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 [66]

$$\sigma = \frac{N_b c_b}{2 \pi r}, \tag{3.8}$$

where N_b is the number of blades, c_b the average blade chord length and r the turbine radius. 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.
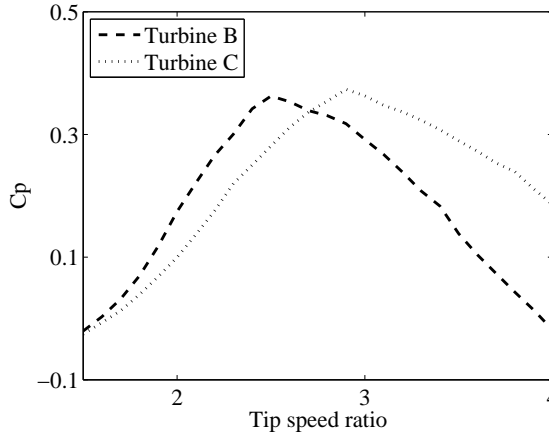
Figure 3.1: C_P–curves for two of the example turbines used in Paper VI.

3.3 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

$$\Omega = \frac{v\,\lambda_{opt}}{r}. \tag{3.9}$$

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 3.6, the input power to the generator will also be proportional to the rotational speed cubed, or Ω^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 Ω^3 according to

$$P_g = P_t \propto \Omega^3. \tag{3.10}$$

The power of the generator can be expressed as

$$P_g \propto UI. \tag{3.11}$$

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

$$I = \frac{U}{R} \Rightarrow P_g \propto \frac{U^2}{R}. \tag{3.12}$$

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

$$R \propto \frac{1}{\Omega} \qquad (3.13)$$

to maintain operation at λ_{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 3.3 – 3.5 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 direct drive generator under fixed tip speed ratio operation with a fixed pitch vertical axis turbine.

4. The prototype generator

In this chapter the design, construction and experiments regarding the direct-drive PMSG prototype will be discussed.

4.1   Design and construction

It was decided to build an experimental setup for a low speed permanent magnet generator to validate previous simulations. The prototype is 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. 4.1. 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 4.1). When the winding procedure was finished, the rotor could be lifted in place with the aid of an overhead crane (see Fig. 4.2).

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 plastic mould.
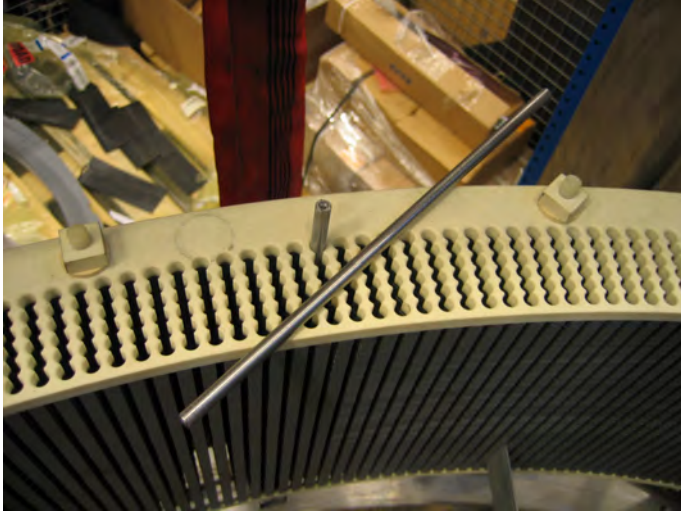
Figure 4.1: A few metal rods were put in the stator slots while stacking the stator sheet metal to maintain proper alignment.

Figure 4.2: The rotor is being lowered into the stator. The milled grooves for the magnets are clearly seen on the rotor ring.

In Fig. 4.3 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 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. 4.4. 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 4.1: *The initial design parameters compared to the actual prototype.*

Generator parameter	Design stage	Actual prototype
Power	5 kW	5 kW
Voltage	150 V	150 V
Current density	1.2 A/mm^2	1.2 A/mm^2
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 Ω	0.47 Ω
Load	4.5 Ω per phase	4.44 Ω 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 4.1) 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 the stator winding had to be completed before the rotor could be put in place, 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.
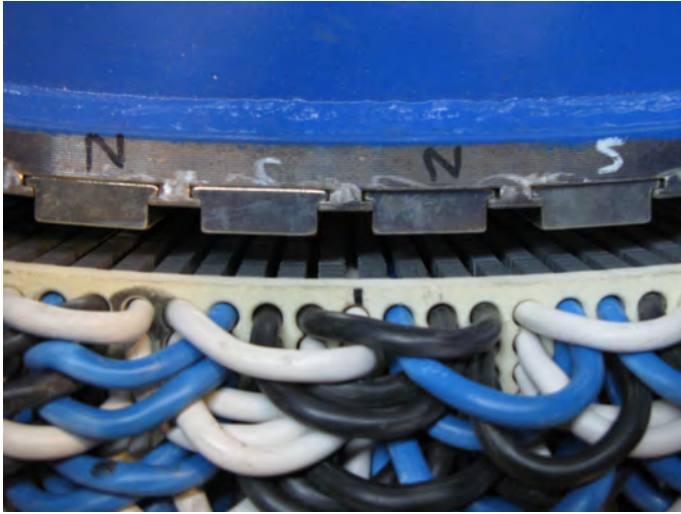
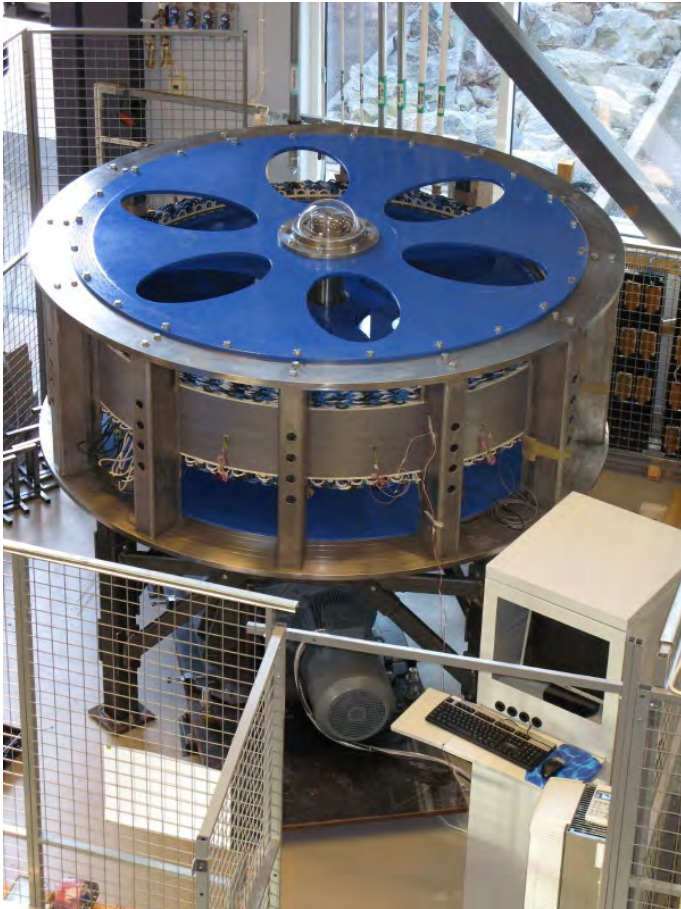*Figure 4.3:* A photo of the air gap, permanent magnets, and stator winding.

Figure 4.4: The experimental setup.

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 60% above nominal speed and roughly twice the nominal torque. The generator is Y-connected to a resistive load[1]. 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.

4.2   Experiments

Before the generator was taken on its maiden run the resistance and inductance per phase of the winding were measured to 0.475 Ω 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. These measurements are presented in Paper III and the equipment used was the following:

- A Tektronix TPS2014 four channel digital oscilloscope[2] with 8-bit resolution.
- Tektronix P2220 voltage probes (10x, 10 MΩ, 16 pF).
- Metrix MX240 universal power clamp[3] with an accuracy of 1%R + 8D, i.e. 1% of the measured value and ±8% of the least significant digit.

After the joyous inauguration of the experimental setup all the differences between the initial design and the constructed prototype (as seen in Table 4.1) were incorporated into the simulation tool. This explains the small differences between the results presented in Paper III and in Papers IV and VI. In the latter cases, the measurements were carried out with a Lecroy Wavesurfer 424 oscilloscope[4] with an accuracy of ± (1.5% + 0.5% of full scale). During the experiments presented in Paper V, a Semikron SKKD diode rectifier bridge was used to rectify the output of the generator and the Tektronix digital oscilloscope was once again used for measurements.

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[1]HS300 resistors from Arcool (www.arcoolresistors.com) and KS 300.6 heatsinks from Austerlitz Electronics (www.austerlitz-electronic.de)

[2]www.tek.com

[3]www.chauvin-arnoux.com

[4]www.lecroy.com

5. Results and discussion

In this chapter, some of the experimental results and simulations from the prototype generator are discussed based on the material presented in the appended papers.

5.1 Generator performance with resistive AC load

Initial measurements of the no-load voltages show that the generator is well balanced and there is good agreement between measurements and simulations, see Fig. 5.1. As presented in Paper III, the RMS values of the no-load voltages for the three phases have been measured to 94.3 V, 94.6 V, and 94.8 V respectively at nominal speed. After these initial measurements, some small geometrical differences between the constructed generator and the model used for the design were incorporated into the simulation tool according to Table 2.2 and henceforth used in Papers IV and VI. As the generator is well balanced, only voltage and current from one phase will be shown in the following discussion.
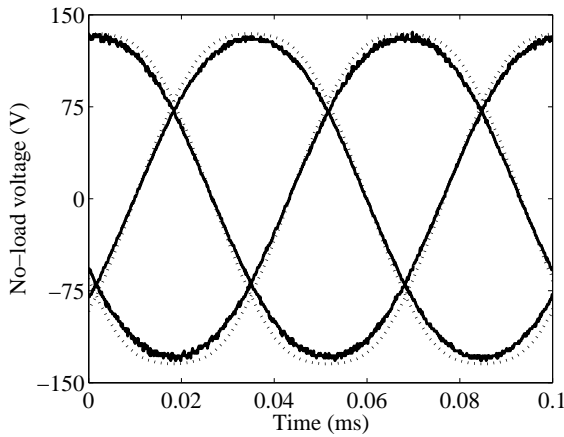

Figure 5.1: Initial measurements show that the three phases are well balanced at no-load. The dotted lines represent simulated values and the solid lines are measurements (from Paper III).

As presented in Papers IV and VI 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
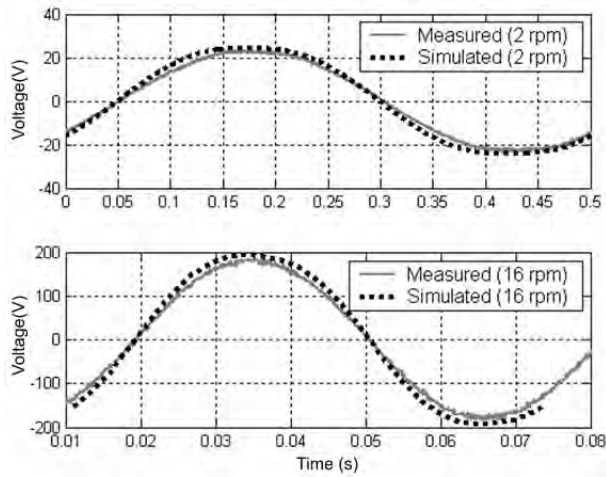
Figure 5.2: The generator was tested at nominal load over the full range of speed offered by the motor drive system. Here the voltage for 2 and 16 rpm is shown (from Paper IV).

simulations, both at very low speed and at the highest speed offered by the motor drive system used in the experimental setup (see Fig. 5.2).

In Fig. 5.3, the RMS values of the phase voltage are shown for variable speed operation with three different values of the resistive load. The measured RMS values are approximately 10% 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. 4.3). In the simulation tool, the milled grooves are only modelled as rectangular grooves, which could give a slightly different field distribution. Furthermore, deviations between measurements and simulations can in part also be attributed to measurement uncertainties and differences in geometry and material properties between the constructed and the simulated generator.
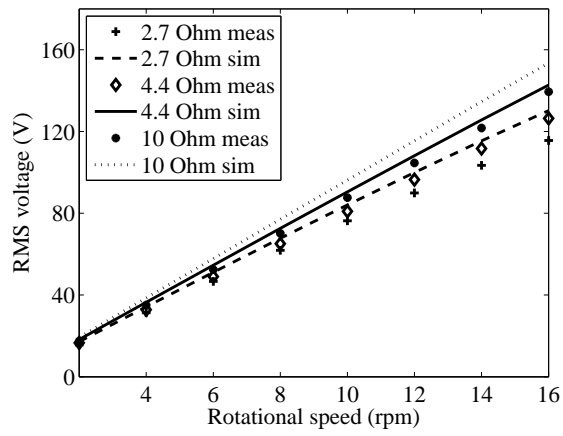
Figure 5.3: Measured and simulated values of U_{rms} for various speeds and loads (from Paper VI).

5.2 Generator performance with diode rectifier

As explained in Paper V, the marine current generator was used together with a PM wind energy generator [68] to test the functionality of a substation for interconnection and filtering of power from direct driven wave energy converters. At the same time this was also an opportunity to test the prototype generator under diode rectifier operation. During this experiment the generators were connected to a common DC-bus according to Fig. 5.4.
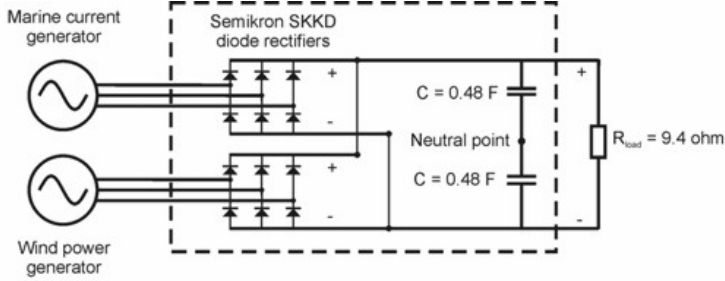

Figure 5.4: The electrical interconnection of the marine current generator and the wind energy generator during the experiments with the wave energy substation (from Paper V).

In Fig. 5.5, it is shown how the marine current generator delivers power to the common DC-bus, whereas the wind energy generator operates below the DC voltage and therefore does not deliver any power. In this particular case the marine current generator is operating at 7.7 Hz and delivering 2.3 kW to the DC-bus. The generator operated satisfactorily under variable speed operation with a diode rectifier and resistive load.
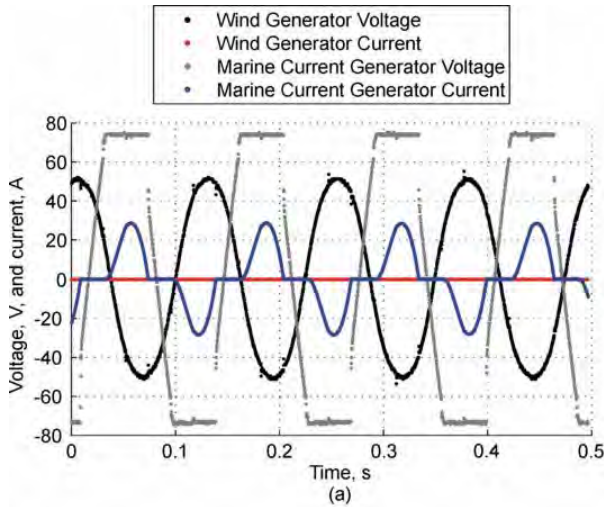

Figure 5.5: The marine current generator delivers power to the common DC-bus whereas the wind generator is operating below the DC voltage and does not deliver any power to the DC-bus (from Paper V).

Several more energy converters could be connected to the same DC-bus in a similar manner as discussed in [69]. This would require one diode rectifier bridge for each unit, but only one inverter and transformer to deliver power from all the energy converters on the common DC-bus to the grid. In the case of a marine current turbine farm, this could also be a cost effective way of operating the turbines at the same rotational speed. If one turbine would operate below the common DC voltage (i.e. too low rotational speed), no power would be extracted and thus the turbine could freely accelerate until it reached the set DC voltage.

5.3 Generator performance with turbines

In Paper VI the generator performance has been evaluated for 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 tip speed ratio operation of the turbines. The three turbines A, B, and C where chosen to have different solidity and thus different optimum tip speed ratio (see Table 5.1), which would mean that they are likely to be suitable together with this particular generator at sites with somewhat different ranges of current velocities.

Table 5.1: *Example turbines*

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

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. frictional losses in bearings and seals are taken to be small and thus neglected). The mechanical power on the generator shaft is thus equal to the sum of the electrical output from the generator and the electromagnetic losses within the generator. In Fig. 5.6, 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. However, in this particular case the generator efficiency has been evaluated for fixed tip speed ratio operation for turbine A (Fig. 5.7) and turbine B (Fig. 5.8).
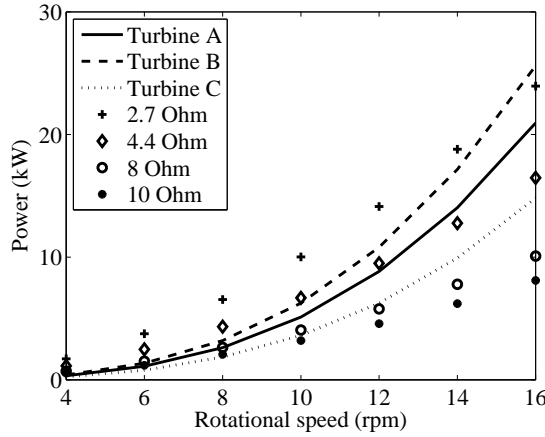
Figure 5.6: Power output from the three example turbines compared with generator power at different loads (from Paper VI).

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 tip speed ratio 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 from the generator through the generator housing and into the flowing water. For the prototype at hand, the thermal limit of 70°C for the insulation material is expected to be reached when the current density is approximately 4 A/mm^2.
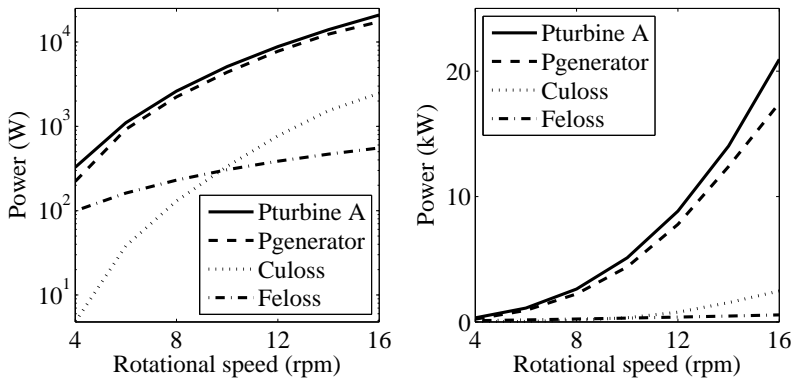

Figure 5.7: Generator performance with turbine A presented in logarithmic scale to the left and linear scale to the right (from Paper VI).

To see more clearly which range of water current velocities would be suitable for such generator-turbine combinations, the generator efficiency as a
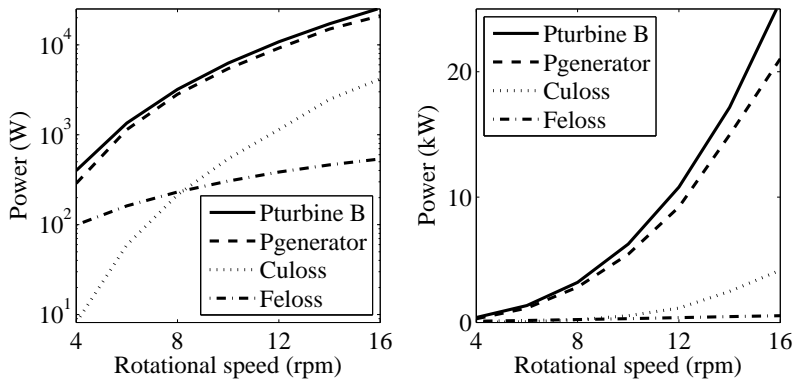
Figure 5.8: Generator performance with turbine B presented in logarithmic scale to the left and linear scale to the right (from Paper VI).

function of current velocity is shown in Fig. 5.9 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 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 m/s. Below 1 m/s the efficiency decreases for both generator-turbine combinations, however turbine B can still be operated with reasonable efficiency down to 0.5 m/s. For other water current velocities, a different combination of generator and turbine may be more suitable.
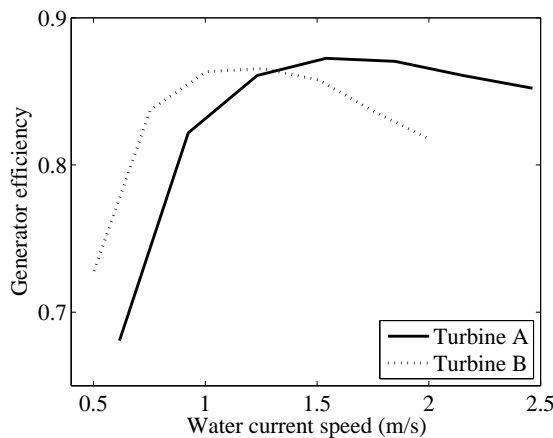

Figure 5.9: The generator efficiency as a function of rotational speed while under fixed tip speed ratio operation with turbines A and B (from Paper VI).

6. Conclusions

The geographic and oceanographic conditions for tidal current energy conversion seem favourable in Norway. Based on available data in pilot books more than 100 sites have been identified as interesting with an 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. Furthermore, a literature review reveals that the theoretical resource is likely to be a poor indicator of how much energy that can be extracted at a site. The review also reveals that further work, most likely both measurements and simulations, is required to reach a more reliable estimate of the extractable resource.

A variable speed directly driven PM generator designed for the low velocities inherent to the tidal resource has been constructed based on previous finite element simulations. 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 accommodate fixed tip speed ratio operation with different fixed pitch vertical axis turbines in current velocities in the range 0.5–2.5 m/s.

7. Future work

The work leading up to this thesis has mainly been focused on finalizing the first prototype generator and performing the measurements needed to compare the performance of the machine with the results obtained from finite element based simulations. Keeping in mind the system perspective and a holistic view of the design process, it would be of interest to include power electronics, generator, turbine, and tidal current characteristics in the analysis to simulate and evaluate the whole system.

The experimental setup for the prototype generator is rather versatile and several interesting experiments could be carried out. One would be to include strain gauges on the generator shaft to measure the torque and thereby evaluate the generator efficiency over the whole range of operation. Another would be to do experiments with a diode rectifier load corresponding to the expected scheme of operation. Furthermore, thermal measurements and simulations at overload conditions would be of interest as the temperature in the winding insulation is expected to set the upper limit of operation.

For the project as a whole, the next major step is to test the whole system in an offshore environment.

8. Summary of Papers

The work presented in this thesis is mainly based on the following papers. Paper I is a review of the tidal current energy resource in Norway. The paper is the result of a still on-going effort to follow the latest developments in the field with the aim to reach a better understanding of the nature of the resource and its response to energy extraction. Based on the present knowledge of the characteristics of tidal currents as a renewable energy resource, a direct driven PM generator has been designed to suit the slow mowing tidal currents. Papers II–IV deal with the design and construction of a prototype PM generator for tidal current energy conversion. In Paper V, the generator is tested with a diode rectifier, and in Paper VI, the generator performance is evaluated in combination with different turbines. The author's contribution to each paper is specified in the following paragraphs.

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. *Submitted to Renewable and Sustainable Energy Reviews, October 2008.*

Paper II

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

This paper is a project update and a summary of the construction work of the 5 kW, 10 rpm prototype generator. The complete experimental setup is presented and all the stages in the assembly process are discussed.

The author has taken part in the design and construction of the experimental setup and made minor contributions to the writing process. *Reviewed conference paper, published in Proc. of OMAE 2007. Presented orally by Katarina Yuen, 12th June 2007, San Diego, USA.*

Paper III

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

Laboratory experiments with the prototype generator were carried out with the aid of a motor drive system and a resistive three-phase load. Results are presented for no-load and nominal load tests on the generator at the nominal speed of 10 rpm. The generator is shown to be well balanced, and there is good agreement between measurements and simulations.

The author has been actively involved in finalizing the prototype generator and also taken part in the writing process. *Reviewed conference paper, published in Proc. of EWTEC 2007. Presented orally by Katarina Yuen, 13th September 2007, Porto, Portugal.*

Paper IV

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 in 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.*

Paper V

Laboratory testing of a marine substation for wave power

The aim of this paper is to validate the feasibility of interconnecting several energy converters on a common DC-bus. The substation is intended for the electrical interconnection of wave energy converters offshore. For practical reasons, the substation was tested in the laboratory before offshore deployment with the aid of the prototype generator discussed in this thesis and a wind energy generator instead of wave energy converters. Simulations and measurements show how the generators intermittently deliver power to the common DC-bus and how, after rectification and filtering of the voltage, power is continuously delivered to a resistive load.

The author has taken part in the design and construction of one of the generators used in the experiments with the substation. The author has also made minor contributions to the writing process. *Submitted to IEEE Transactions on Power Delivery, November 2008.*

Paper VI

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

The aim with 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 performed the generator simulations used in Fig. 10–14 and contributed to the writing process. *Accepted for publication in IEEE Journal of Oceanic Engineering, November 2008.*

9. Svensk sammanfattning

Denna licentiatavhandling inom teknikvetenskap rör både resursen och tekniken för energiomvandling ur fritt strömmande vatten. Fritt strömmande vatten, så som 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.

Under Professor Mats Leijons ledning har forskning inom området kinetisk energiomvandling från fritt strömmande vatten bedrivits vid avdelningen för Elektricitetslära (Uppsala Universitet) sedan år 2000. Från och med 2004 har forskningen drivits vidare inom ramen för Centrum för Förnybar Elenergiomvandling (CFE). Målet var redan från början att se till helheten och söka finna ett tekniskt och ekonomiskt hållbart sätt att generera elektricitet 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 undviks 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. Detta arbete har lett fram till flertalet publikationer och två doktorsexamina inom området, nämligen Tekn. dr Erik Segergren och Tekn. dr Karin Thomas. Vid starten av detta licentiatarbete fanns därmed en färdig elektromagnetisk design av generatorn och det var dags att ta steget från simuleringar till en första prototyp. Därför har denna licentiatavhandling inom teknikvetenskap omfattande inslag av praktiskt arbete 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 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 generatorn 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. Slutsatsen kan dras att simuleringsverktyget kan användas för mycket långsamgående generatorer (2–16 Hz) anpassade för energiomvandling från strömmande vatten.

Parallellt med konstruktionen av prototypgeneratorn har även litteraturstudier utförts för att belysa rådande förståelse för denna energikälla och dess potential. Undersökningen visar att potentialen för förnybar energi från strömmande vatten ej är väl kartlagd i dagsläget. De data om strömmande vatten som finns tillhanda 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 har en mer ingående potentialbedömning utförts för Norge. Utifrån data om tidvattenströmmar i *Den Norske Los* [52] har över 100 intressanta platser längs den norska kusten funnits. 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.

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