Direct Drive Generator for Renewable Power Conversion from Water Currents

ERIK SEGERGREN
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Abstract

In this thesis permanent magnet direct drive generator for power conversion from water currents is studied. Water currents as a power source involves a number of constraints as well as possibilities, especially when direct drive and permanent magnets are considered. The high power fluxes and low current velocities of a water current, in combination with its natural variations, will affect the way the generator is operated and, consequently, the appearance of the generator. The work in this thesis can, thus, be categorized into two general topics, generator technology and optimization. Under the first topic, fundamental generator technology is used to increase the efficiency of a water current generator. Under the latter topic, water current generators are optimized to a specific environment. The conclusion drawn from this work is that it is possible to design very low speed direct drive generators with good electromagnetic properties and wide efficiency peak.

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C E. Segergren and Mats Leijon, Relation Between Generator Geometry and Resistance in Armature Winding, Accepted for publication in Applied Energy


Assembly comprising a Water Turbine and a Generator, the Rotor of which is Direct-Connected to each one of the Blades the Turbine, PCT-application for Swedish patent SE 0400667-2, public 11 September 2005
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<tr>
<td>$S$</td>
<td>VA</td>
<td>Apparent Power</td>
</tr>
<tr>
<td>$C_T$</td>
<td>-</td>
<td>Turbine Efficiency</td>
</tr>
<tr>
<td>$\rho_{fluid}$</td>
<td>kg/m³</td>
<td>Density of a fluid</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Velocity</td>
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<tr>
<td>$V_T$</td>
<td>V</td>
<td>Terminal voltage</td>
</tr>
<tr>
<td>$I_a$</td>
<td>A</td>
<td>Armature Current</td>
</tr>
<tr>
<td>$f$</td>
<td>Hz</td>
<td>Frequency</td>
</tr>
<tr>
<td>$N_e$</td>
<td>-</td>
<td>Number of Effective Turns</td>
</tr>
<tr>
<td>$B_d$</td>
<td>T</td>
<td>Magnetic Flux in the Air Gap</td>
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<td>-</td>
<td>Number of Poles</td>
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<td>Number of Slot per Pole and Phase</td>
</tr>
<tr>
<td>$n_s$</td>
<td>-</td>
<td>Number of Cables per Slot</td>
</tr>
<tr>
<td>$c$</td>
<td>-</td>
<td>Number of Parallel Paths</td>
</tr>
<tr>
<td>$P$</td>
<td>Pa = N/m²</td>
<td>Pressure</td>
</tr>
<tr>
<td>$g$</td>
<td>m/s²</td>
<td>Acceleration of Gravity</td>
</tr>
<tr>
<td>$z$</td>
<td>m</td>
<td>Depth Below Surface</td>
</tr>
<tr>
<td>$A$</td>
<td>Tm</td>
<td>Magnetic Vector Potential</td>
</tr>
<tr>
<td>$D$</td>
<td>C/m²</td>
<td>Electric Displacement Field</td>
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<tr>
<td>$t$</td>
<td>s</td>
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<td>Vs/Am</td>
<td>Magnetic Permeability</td>
</tr>
<tr>
<td>$h_{hp}$</td>
<td>m</td>
<td>Height of permanent magnet</td>
</tr>
<tr>
<td>$A_z$</td>
<td>Tm</td>
<td>$z$-component of the Vector Potential</td>
</tr>
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<td>$\sigma$</td>
<td>A/Vm</td>
<td>Conductivity</td>
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<td>$\partial V/\partial z$</td>
<td>V/m</td>
<td>Applied Potential</td>
</tr>
<tr>
<td>$\rho_f$</td>
<td>W/m²</td>
<td>Iron Loss</td>
</tr>
<tr>
<td>$k_f$</td>
<td>-</td>
<td>Stacking Factor</td>
</tr>
<tr>
<td>$k_h$</td>
<td>-</td>
<td>Coefficient of Hysteresis</td>
</tr>
<tr>
<td>$k_e$</td>
<td>-</td>
<td>Coefficient of Excess Loss</td>
</tr>
<tr>
<td>$k_{eddy}$</td>
<td>-</td>
<td>Coefficient of Eddy Current Loss</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>T = V/s/m²</td>
<td>Magnetic Flux Density</td>
</tr>
<tr>
<td>$d$</td>
<td>m</td>
<td>Stator Steel Thickness</td>
</tr>
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</table>
Preface

In September 2000 Mats Leijon PhD, took up a newly defined professorship in Electricity (a combination of the professorship in Plasma Physics and the professorship in Lightning Research) at Uppsala University. Until then, he had been Head of High Voltage Electromagnetic Systems at ABB Corporate Research and recipient of a large number of scientific distinctions for inventing the first high voltage generator (the Powerformer™).

The department was funded through a large donation in the 1930-ies and had been focusing entirely on lightning and electric discharges. For a long period, it was an independent institute and not a part of the university. The installation of the new professor would change the path of the department, at least partially. Besides the traditional lightning and discharge researchers, there is today a new research group, which studies renewable power generation and power storage.

Since electricity is a subject that has historically been closely associated with universities, it is rather surprising to notice that this new professorship is the only one of its kind in Sweden. Although universities have continuously conducted research on electromagnetism, the gap between the academic world and the industry has led to very few inventions with infrastructural impact as well as to an inability to challenge limits. Consequently, no new means of power conversion from renewable power has been presented, despite a continuously growing power demand. Existing systems for energy conversion from renewable power sources, with the exception of hydropower, struggle with low utilization and would not be economically viable without subsidies. The ideal would of course be the opposite.

By studying the characteristics of different power sources, renewable motions can be found in nature. With the right technology, these motions could be used for electricity production with high utilization. One such motion, among others, is water current.

Power extraction from water in motion has been studied for many years and has repeatedly been deemed uninteresting. An opinion based rather on the shortcomings of the presented technology than on the power source itself. By adopting entirely new, as well as some very, very old ideas, power conversion from water currents can become feasible. Electromagnetic power conversion is yesterday’s limitation and tomorrow’s possibility.
Acknowledgments

I would like to express my gratitude to my supervisor professor Mats Leijon and assistant supervisor Dr. Niklas Dahlbäck for their guidance and help in my work.

Dr. Karl Erik Karlsson and Dr. Arne Wolfbrandt, are hereby gratefully acknowledged for the development of the design tool for electric generator, as well as their will to share their great knowledge.

The Swedish Energy Agency (STEM) and Graninge AB are also gratefully recognized for their financial support of this research project.

Last, but not least, I would like to express sincere gratitude to my lunch-box-pals and all my friends and colleagues at the Ångström Laboratory.
Introduction

Ocean currents and tidal currents have long been appreciated as a possible power source. A study, which identified over 106 European underwater power sites, claims that marine current power has potential to cover a significant part of Europe’s future energy need [1]. Despite this, water currents remains almost unexploited. The first steps towards power extraction from moving water masses in the oceans were made during the mid-1970 oil crisis. Since then, a number of projects have been started at various locations all over the world. Patents have been applied for; sites have been suggested for exploitation, surveys have been carried out etc. Recent advances in offshore and in wind power technology have made marine current energy much more probable today than it was 30 years ago.

The technology studied at the division for Electricity and Lightning Research consists of a vertical axis turbine and a direct drive permanent magnetized generator. The idea is to have the device placed on the seabed, with the generator and the turbine on the same axis. This concept has a small number of moving parts, in order to keep the construction as simple as possible. A simple construction will reduce the need for maintenance, which is likely to be difficult once the device is placed under water.

The Resource

Water in motion can be categorized into:
1. Tidal currents: currents caused by interaction between the Earth’s oceans and the gravitational fields of the moon and the sun
2. Watercourses: where water is forced to move due to difference in potential energy
3. Currents in straits: generally caused by differences in salinity and temperature
4. Ocean currents: caused by the coriolis effect due to the rotation of the Earth [2]

These water motions are usually rather slow but seabed topography, particularly between islands and the mainland, around ends of headlands and in estuaries, can magnify the motion and give rise to much higher velocities.
Water current energy extraction resembles wind power conversion. The huge difference in density between air and water, however, makes a quite moderate tidal current of 4 m/s correspond to a power density that only occurs in a full hurricane, see Figure 1. Another appealing property of ocean currents is that they are completely predictable, especially tidal currents but also ocean currents such as the Gulf Stream.

Peak velocities of 4 m/s up to 10 m/s in a moving body of water, with a surface area of hundreds of square kilometres, are not uncommon [3-9]. Some locations in Europe in particular, have extremely intense currents, such as the Pentland Firth (between Scotland and Orkney), the Alderney Race (between the Channel Islands and France) or the Big Russell (off Guernsey). Other locations with swift currents are the Severn Estuary (on UK’s north Devon coast), the straits between Ratline Island and Northern Ireland, the straits of Messina between Italy and Sicily and various channels between the Greek islands in the Aegean. It is also possible to find marine current energy resources in regions such as south East Asia, on both the east coast and the west coast of Canada [9] and in the Florida Current of the Gulf Stream [10].

The peak current velocity is a key factor in the design of the marine current turbine, as it dictates both the maximum output of the unit as well as the maximum force on rotor components and submarine structures [11].

Tidal currents

Two different factors control the tides. The primary factor controlling the temporal rhythm and height of tides is the moon. The gravitational attraction of the moon produces two tidal bulges on the surface of the Earth. One tidal bulge is located at the point on Earth closest to the moon. Seawater is drawn towards the moon where the strength of the gravitational attraction is strong-
est. On the direct opposite side of the Earth, another tidal bulge is produced away from the moon as this point experiences the weakest force of the moon's gravity. Thus, any given point on the Earth's surface experiences two tidal crests and two tidal troughs during each tidal period. If the moon were stationary in space, the tidal cycle would be 24 hours long. However, the moon is revolving around the Earth with a speed of 27 days per revolution, which adds about 50 minutes to the tidal cycle. As a result, the tidal period is 24 hours and 50 minutes in length. The second factor controlling tides on the surface of Earth is the gravity of the sun. About one third of the height of the tide can be traced to the gravity of the sun. At certain times, when the directions of the gravitational attraction of the moon and the sun are aligned, the highest and lowest tides of the year are produced. These tides are called spring tides and occur at every full and new moon. When the gravitational attractions of the moon and sun are at right angles to each other, the daily tidal variations are at their least. These events are called neap tides and occur during the first and last quarter of the moon.

In reality, there is a rather complex ratio between incoming and outgoing peak currents [12,13]. There are also other non-tidal or residual components, which are relatively random. Examples of such, non-tidal variations, are:

- Seabed topography
- Global oceanic marine conditions
- Wind fetch
- Density differences
- Waves

Constant currents

Currents generated by other phenomena than tides can, at some sites, be swift enough to be of interest. Although these currents are constant compared to tidal currents, they vary over the year. In the Mediterranean, where the currents in the Strait of the Dardanelles and in the sites of Samos, Kafirea, Kea and Kithnos are due to density differences caused by variations in salinity and temperature [1], it is easy to see that there must be seasonal variations. The debacle in springtime, with its increased flux of fresh water in the rivers, has a large impact on the salinity in the seas. It is also a well-known fact that the water temperature varies a lot from winter to summer. Even major marine current systems (see Figure 2) are affected by seasonal variations. Detailed measurements of the Gulf Stream show that the current in summer is 2.13 m/s, whereas in winter it is 1.62 m/s [10].
Power Conversion

To date, almost all applied research carried out on water current energy systems, has involved a turbine (in order to convert the linear movement of the current to a rotational movement) and an electric generator (in order to convert the rotational movement to electric power). Differences are restricted to concern about whether the turbine should be horizontal (cross flow, e.g. of Savonius or Darrieus type) or axial, as well as about whether the construction should be moored on the surface or seabed mounted.

Marine and tidal currents are especially attractive as a source of energy because [13]:

- It is a method for large-scale production of electricity with low environmental impact (no pollution, no noise, no land use and hardly any visual impact).
- Tidal currents are, in most cases, closely predictable in time so that planned base load power contributions are possible.
- At the better sites in Europe the energy intensity, although diffuse, is more intense and concentrated than most other forms of renewable energy.
The most prominent advantage is, however, the grade of utilization. Due to the varying nature of the tides, tidal current power is unlikely to have a utilization grade exceeding 50%, i.e. 4000 hours/year. Currents of more constant nature, such as unregulated watercourses or marine currents, can on the other hand, reach a utilization grade of up to 8000 hours/years. A high grade of utilization is crucial for the viability of the system (see Figure 3).

When designing a water current power conversion system, one has to take into account a number of different issues. The generator has to be highly efficient and produce a voltage of good quality. Low electromagnetic losses mean smaller forces and less heat development, resulting in less wear and higher reliability. Higher reliability means less maintenance. Maintenance as well as installation is assumed difficult when the power station is placed under the surface of fast flowing water. Some of these issues will affect the general design of the generator.

So far, only a limited numbers of projects have been carried out in this field. Important contributions of implemented applied research are summarized below:

**The Coriolis Program, 1973**

Between 1973 and 1978 Mr. Walter Hajduk privately supported the Coriolis Program through a corporation called Hydro-Energy Associates. The aim of the program was to develop an energy system to generate electrical power through an array of large ducted turbines (see Figure 4) moored about 30 km east of Miami in the Florida Current of the Gulf Stream [10].
ITDG/IT Power: River Nile, Sudan, 1976-83
The project consisted of the development of a range of river current turbines with a 3 m diameter rotor, intended for pumping irrigation water from the River Nile (Figure 5) [14].

Underwater Electric Kite (UEK), USA, 1981 -
The design features a self-contained moderately buoyant turbine-generator suspended like a kite in the tidal stream. A 40 ft wide twin-turbine is intended for deployment in the Gulf Stream off Florida. A 120 kW prototype suitable for tidal basins and rivers has been tested1.

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NRC (National Research Council)/Nova Energy Ltd: St. Lawrence River, Canada, 1982
A 25 kW unit with a 3-blade Darrieus/Davis rotor (1.8 m in diameter and 1.8 m high) was mounted between pontoons in the St. Lawrence River (Figure 6). The unit generated power for over 2200 hours during two summers [15].

NRC/Nova Energy Ltd: Sheet River, Canada, 1983
A 10 kW unit with a 3-blade Darrieus/Davis rotor (1.8 m diameter and 1.8 m high) was mounted in the sluice gate of an existing low dam (1.5 head). The unit failed after a few hours of operation but was rebuilt in 1985. The unit delivered power to the local Nova Scotia Power grid [15].

Nihon University: Kurushima Straits, Japan, 1983-88
Three projects deploying a 3-bladed Darrieus turbine (3.5 kW), shown in Figure 7, on the seabed in the Kurushima Straits were executed. The unit ran for approximately twelve months and was considered a major step forward [14].

A 4 kW unit (1.2 m diameter and 1.2 m high) was towed from a 300 ft research vessel at a depth of 200 ft. The vessel was then moored in 1000 ft deep water at mid Gulf Stream. This was the first ever project to produce electrical energy from the Gulf Stream[14].

Russian Joint Stock Co of Energy & Electrification
Development of an axial flow generator of 1.8 m diameter in ducts mounted in a twin-hulled pontoon, intended for use in rivers [14].

Scottish Nuclear, IT Power, NEL: Loch Linnhe, Scotland, 1994
Development of a “proof of concept” experimental tidal current system, consisting of an axial-flow 3.5 m rotor suspended below a floating catamaran pontoon. The unit successfully produced some 15 kW in a current of 2.25 m/s at Loch Linnhe [14].
Northern Territory University: Apsley Straits, Australia, 1994
Experiment using axial-flow rotors deployed from a moored pontoon buoy in the Apsley Straits north of Darwin [14] (see Figure 8).

The EU JOULE CENEX project, 1994-95
Under the EU JOULE-II energy research program, DGXII of the European Union supported a technical and resource assessment of marine current energy in Europe. The study found that the cost of electricity is especially sensitive to the size of the machines, economic parameters (lifetime, discount rate), operational and mainte-
nance costs and the load factor obtainable from the velocity-duration for that particular site [14].

_Tide mill feasibility study for Orkney and Shetland, 1994-95_  
A feasibility study was conducted for supplying Orkney and Shetland with electricity from tidal steam turbines. The study was partly funded by the EU [14].

_Marine Current Turbines Ltd, Lynmouth, Devon, UK, 1999-2003_  
An industrial consortium of UK and German companies (supported by the UK Department of Trade and Industry, the Joule Programme of the European Commission, and the German Government) launched a 300 kW experimental set-up with an 11m turbine in the tidal currents approximately 3 km NE of Lynmouth in north Devon, UK. This project came about as the culmination of the ‘Seaflow’ project and comprises the first phase in a three-phase programme. Phase 2 and 3 of the programme should result in the installation of a small tidal current power farm by 2005².

_Hammerfest Strøm AS, Kvalsundet, Norway, 2002_  
The project encompasses a 350 kW, windmill resembling, tidal current power plant, installed in an average current of 1.8 m/s in the strait of Kvalsundet outside the city of Hammerfest, northern Norway. It is the first plant to deliver tidal current power to the national power grid³.

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² http://www.marineturbines.com/home.htm (30 June 2005)  
Exim/Seapower, Sweden/Scotland, 2002 -
This design features a Savonius turbine mounted under a floating buoy. A prototype turbine has been tested in Shetland. The final evaluation of locations with suitable streams is currently being performed [16].

Hydro Venturi Ltd, UK, 2002 -
The Rochester Venturi is a pressure amplifier governed by Bernoulli’s principle. It uses shapers placed into a primary flow to accelerate the flow and generate a reduction in pressure at the point where that flow is most constricted. The reduction in pressure can then be used to pull water or air from another location into the primary flow. This secondary flow is used to drive a turbine. The technology has been tested in the North of England since June 20024.

TidEl Generator, UK, 2003 -
This is a mid-depth moored concept generator, which can be installed in deep water. In zero current (slack water), the turbines will float in a vertical position and when there is a current the turbines will automatically align themselves to the direction of the flow. The generator runs with variable speed. The NaREC test centre5 completed testing on a 1:10 scale model in 2004. A full sized system of approximately 1 MW, based on the findings from the trials, is planned to be developed and installed shortly.

Lunar system, UK, 2003 -
This system features a ducted turbine, fixed to the seabed through a gravity foundation. The blades are bi-directional and there is no yaw mechanism as the Venturi-effect of the ducting helps to maximize the energy from the water flow even when the flow is not parallel to the turbine axis. A 1:20 scale model was tested in April 2004. A 1 MW prototype is expected in 2005 and a commercial launch in 20066.

The Engineering Business Ltd, Stingray Tidal Stream Generator, 2005
Instead of the conventional turbine/generator concept, the Stingray converts energy from high-pressure oil in hydraulic cylinders that are

4 http://www.hydroventuri.com/ (2005-06-01)
5 The New and Renewable Energy Centre (NaREC) is an organization set up to bring substantial benefits to the UK’s new and renewable energy industry. NaREC is a Centre of Excellence, fast-tracking concept evaluation, feasibility studies and prototype evaluation and testing through to early commercialization. http://www.narec.co.uk, (2005-08-01)
6 http://www.lunarenergy.co.uk/ (2005-06-01)
forced to extend and retract by a hydroplane. Unfortunately, the owner of the project, The Engineering Business, had to put its plans to install a 5 MW Stingray farm off Shetland on hold in February 2005, due to economic difficulties7.

Clean Current, Race Rocks Ecological Reserve, Canada, 2005 -

Canada’s first free-stream tidal power project is planned at the Race Rocks Ecological Reserve for early 2006. A bi-directional ducted horizontal axis tidal turbine attached to a direct drive variable speed permanent magnet generator is said to have higher than 50 % water-to-wire efficiency8.

The drawback with water currents as a source of energy is the low speed [3-9,16]. A phenomenon similar to boiling, called cavitation further complicates the problem. Cavitation occurs when an object moves fast through water and causes the partial pressure to fall below the vapour pressure of water. This has to be avoided as it causes fast abrasion on the turbine blades. The easiest way to achieve this is by limiting the rotational speed of the turbine [17]. This is probably the reason why so few water current power plants have been constructed. By increasing the number of generator poles, the gearbox can be excluded with less maintenance and lower losses as a consequence, though the induction is preserved [18,19,20]. More poles require a larger generator diameter. A large generator diameter will interfere with the turbine, especially if a conventional windmill type of power plant is considered. On the other hand, if a cross-flow turbine is used these problems can be excluded. Vertical axis or cross-flow turbines, for example Darrieus turbines [21,22], are frequently considered in solutions for waterpower conversion systems.

The use of permanent magnets in the rotor, instead of electromagnets, [23-26] has several advantages. Complicated electrical connections to the rotating rotor can be avoided. Although permanent magnets make a more reliable and efficient generator, there are drawbacks. An electromagnetic has variable magnetization that can be used to instantly adjust the generator’s level of excitation, and thereby the voltage at different loads. A permanent magnetized generator is more difficult to integrate with the grid. One reason why the generator voltage should be rectified and digitally reconverted into alternating voltage [27] is that water currents, although predictable in time, vary in velocity. Variations in flow velocity will cause variations in the power and frequency generated by the direct drive generator. It is therefore impossible to connect to the grid without digital adjustment. Another reason is that both the power plant and the grid connection

are located under water. When an insulated high voltage cable is placed under water, it forms a capacitor together with the surrounding water. Alternating current does suffer from capacitive losses, as opposed to direct current.

In order to keep down the costs and to maintain good environmental qualities, both in the sea and on land, the size of the power plant has to be considered. A small generator has lower installation costs since small units are easier to transport and major parts of the work can be conducted in the workshop. A large generator has limited placing possibilities whereas a small unit can be placed in many different locations. Furthermore, a small generator has less impact on the marine environment. If a higher power output is required, several small units can be combined into a park, which could, for example, be connected directly to a nearby power consumer.

The papers in this thesis primarily cover the electrical and magnetic properties of the generator. However, the other aspects, such as weight and material usage, are kept in mind. The most important design parameter has been the electromagnetic losses. All the electromagnetic simulations have been performed using design tool software for rotating electric generators (developed by Arne Wolfbrandt PhD and Karl Erik Karlsson PhD). The program uses full physics simulations based on finite element method (FEM) calculations of the electromagnetic field.

Design and simulation of electric machines

The development of numerical methods for calculating the magnetic field on electrical machines, which emerged together with the availability of powerful computers, is extensively covered in [28]. The first successful attempts to apply the finite element method (FEM) to the magnetic field analysis of electrical machines were reported in the early 1970-ies [28]. In the mid 1970-ies and the early 1980-ies [28,29], attempts to combine external circuits connections with the magnetic field solution proved successful. In 1983, the voltage equation of windings made of thin separate conductors was included [30]. Computations in the time domain and methods for transient behaviour were first reported when the operation of an induction motor was computed in 1985 [31]. In late 1988, methods for eddy current problems were proposed [28].

Today, computer based design and calculation programs can be used for completely parameterised, full physics, simulations of conventional generators as well as for electro-magnetized, permanent-magnetized, turbo generators and linear generators, based on modern high voltage generator technology [32,33]. When a model of a very low speed generator for use in, e.g., energy conversion from marine currents is studied, special attention is paid to electromagnetic losses and geometric dimensions so it is possible to compare it with systems that involve off-the-shelf generators with a gearbox.
Method

Although other concepts exist, conversion of power from a flowing fluid is usually done using a turbine. The active power, $P$, harnessed by the turbine is determined by the area of the cross-section, $A_c$, according to

$$P = \frac{1}{2} C_p A_c \rho_{\text{fluid}} \nu^3,$$  \hspace{1cm} \textit{Equation 1}

where $C_p$ is the turbine efficiency related to the turbine design, $\rho_{\text{fluid}}$ is the density of the water and $\nu$ is the flow velocity. The efficiency factor, $C_p$, usually referred to as the Betz factor [34], varies from turbine to turbine [35-37] but is assumed to have a theoretical maximum at approximately 0.59.

The active power, harnessed by the turbine, is converted into electrical power by the generator. The electrical power is determined by

$$P = V_i I_a \cos \theta,$$  \hspace{1cm} \textit{Equation 2}

where $V_i$ is the terminal voltage, $I_a$ is the armature current and $\theta$ is the phase current. The relation between the terminal voltage and the armature current is determined by Ohm’s law. The internal line voltage of the generator can be derived from Faraday’s law of induction resulting in:

$$E_i = \sqrt{\frac{3}{2}} f_r \frac{2pqn_s}{c} B_0 L \nu,$$  \hspace{1cm} \textit{Equation 3}

where $f_r$ is the winding factor, $p$ is the number of poles, $q$ the number of slots per pole and phase, $n_s$ the number of cables per slot, $c$ the number of parallel paths, $B_0$ is the amplitude of the magnetic flux density in the air gap, $L$ is the axial length and $\nu$ is the peripheral speed of the rotor.

Although this theory is rather rudimentary, it is obvious that a generator can be adjusted to suit any power source, by varying fundamental generator parameters such as geometry, number of poles, frequency etc.

The rotor speed of a direct drive water current generator is limited by cavitation. Cavitation, which causes fast abrasion of the turbine blade, occurs when the partial pressure locally falls below the vapour pressure of water,
i.e. when the velocity exceeds evaporation velocity, \( v_{vap} \). Evaporation velocity is a function of pressure, density and depth according to:

\[
v_{vap} \approx \sqrt{\frac{2(P_{atm} - P_{vap})}{\rho_{fluid}} - 2gz}
\]

Equation 4

where \( P_{atm} \) and \( P_{vap} \) is the atmospheric pressure and evaporation pressure, respectively, \( \rho_{fluid} \) is the density of water, \( g \) is the acceleration of gravity and \( z \) is the depth below surface. One meter below the surface, in a 2.5 m/s stream, the evaporation speed is approximately 14 m/s. On the surface of a moving object, such as a turbine blade, the fluid will reach up to twice the speed of the moving object [37], which is why the maximum periphery speed of a turbine under water usually is set to 7 m/s [38,39].

In a direct drive system the varying nature of the power source will affect the design of the generator. The generator must have high efficiency at part load and overload as well as at nominal load, i.e. low no-load losses. Moreover, it has to have a low load current at nominal load. Low current is needed because the efficiency of a generator increases with increasing load. The primary limiting factor in an overload situation is following the temperature of the armature winding, thus the current density. When the current is low at nominal load it can be allowed to increase before it reaches unacceptable levels. In contrast to a system with a gearbox, the direct drive generator will experience a varying speed, thus deliver a voltage that varies in amplitude and frequency. A generator that delivers a varying power cannot supply a national power grid. An intermediate DC stage in combination with a DC to AC inverter and a variable transformer has to be used. In order to achieve an efficient rectification, it is important to have power factor (\( \cos\phi \)) equal to 1 at nominal load and close to unity at part load and overload.

**Mathematical model of a generator**

**Geometry**

Before the computer simulation of the model generator is carried out, a picture of the geometry, i.e. a two dimensional cross-section of the generator (similar to Figure 9), is generated entirely from straight lines and circular arcs. This generates geometric domains corresponding to different parts of the generator. Symmetries in both geometry and in electromagnetic field mean that the generator can be represented by a two dimensional unit cell. This covers a full cycle of the armature winding, as determined by the num-
number of slots per pole and phase. The machine ratings are input-parameters to the program.

From the apparent power, power factor and terminal voltage, it is possible to determine the armature current. Usually current densities around 2A/mm² are desired in the armature winding. The thickness of the insulator and the semiconductor layers around the cable are related to the terminal voltage. The program includes a variety of standard cables and initially the most suitable cable is chosen automatically. The cable diameter, in combination with information about slot configuration, bolt hole and cooling duct location, makes it possible to generate a complete picture of the stator. A large number of different cable slot configurations, such as single row, double row, double row with tubes etc., are prepared for in the program. Of course, it is possible to use cables and cable slots designed uniquely for each application.

From the frequency, rotor speed and pole configuration, it is possible to generate a complete picture of the rotor. Similar to slot configurations, a number of different pole configurations, such as electromagnets, permanent magnets with pole shoe, surface mounted permanent magnets etc., are included in the program.

In addition to the stator and rotor geometry, information about the stator yoke, air gap and the iron rim in the rotor is needed to complete the geometry.

Figure 9. This Two-dimensional generator cross-section, generated by the design tool, can be used to represent the whole generator using adequate boundary conditions.
**Boundary**

There are four boundaries in the geometry in need of extra attention (see Figure 10). Usually the vector potential, $A$, is set to zero at the inner perimeter of the rotor and the outer perimeter of the stator. The boundary condition on the left- and right hand side of the geometry is either periodic or anti-periodic, depending on whether the geometry covers a full or half AC-cycle. Symmetric boundary condition means that the vector potential on the left hand side of the geometry, $A_L$, is equal to the vector potential on the right hand side of the geometry, $A_R$. Anti-symmetric boundary condition means that $A_L$ equals $-A_R$.

**Material**

Each geometric domain is assigned material properties. The material properties of every material used in a real generator, from stator steel to cross-linked polyethylene and ferrite magnets, are defined in the simulation program. In addition to fundamental material properties (such as permeability, resistivity, thermal conductivity, density, remanence and thickness), which apply for every material, the BH-curve is defined for materials with non-linear magnetic characteristics (e.g. stator steel).

**Source**

Sources are currents and thermal sources. They can be represented by constants or, in more complicated cases, by circuit equations. As the geometry is defined, there are two electromagnetic sources, the armature winding and the rotor magnet.

The armature current is handled differently in different applications of the design and simulation program. In the application that handles rotating machines, in contrast to the application that handles the linear generator, the armature current is determined by the apparent power, the terminal voltage and the frequency. The current in each cable can be directed inwards or outwards, depending on the winding pattern.

![Figure 10 Generator unit cell with boundary conditions](image)
Mathematically the magnets are treated almost identically whether they are permanent magnets or electromagnets. For a permanent magnet, an infinitesimally thin (solenoid) coil is used to simulate the behaviour of the magnet. The magnetizing current in the coil, \( I_p \), is determined by the geometry of the magnet and the material properties of the magnetic material according to:

\[
I_p = \frac{B_r h_{sp}}{\mu_0 \mu_r},
\]

Equation 5

where \( B_r \) and \( \mu_0 \mu_r \) is the remanence and permeability of the magnetic material respectively, and \( h_{sp} \) is the height of the magnet. Figure 11 shows how the simulation of the magnetizing coil in a permanent magnet is handled in the two-dimensional simulations program. The behaviour of the electromagnet, on the other hand, is determined by a coil with real dimensions. In this case, coil parameters such as the number of turns and the geometric dimensions of the coil, are input-parameters to the program.

Analysis

The calculations are based on a two-dimensional finite element method (FEM). When \( \frac{\partial \mathbf{D}}{\partial t} \) is neglected, Maxwell’s equations and the relations describing the behaviour of materials can be combined into the equation that is actually solved by the design and simulation program:

\[
\sigma \frac{\partial A_z}{\partial t} = \nabla \left( \frac{1}{\mu_0 \mu_r} \nabla A_z \right) - \sigma \frac{\partial V}{\partial z}
\]

Equation 6

where \( A_z \) is the z-component of the vector potential, \( \mu_0 \mu_r \) is the magnetic permeability, and \( \sigma \) is the resistivity. The term \( \frac{\partial V}{\partial z} \), traditionally called the applied potential, is a current density in the z-direction corresponding to the sources in the geometry. It should be noted that, in the transient regime, the equation is solved with separate coordinate system for the rotor and stator. The two different solutions are coupled to each other as boundary condition in the air gap. The final solution is determined from a number of different, discrete, rotor positions. This simplifies the calculation procedure since only the boundary conditions are varying (instead of including the velocity in the equation). The distance between these positions is decided by the speed.
The magnetic field from a permanent magnet is generated with an infinitesimally thin coil with magnetizing current \( I_f \).

The time derivative, \( \partial A / \partial t \), in the equation corresponds to the diffuse penetration of a magnetic field in a material, i.e. the skin effect. The skin depth, \( \delta_{\text{skin}} \), is dependent on the resistivity of the material

\[
\delta_{\text{skin}} \approx \frac{1}{\sqrt{\mu_0 \mu_i \sigma f}}
\]

where \( f \) is the frequency of the generator, i.e. the rotational frequency of the rotor times the number of poles.

**Mesh**

The calculation and simulation program uses an automatically generated mesh with a variable number of grids. In order to provide a better solution in the essential parts of the generator and to speed up the calculation, areas of less importance, such as the yoke and the rotor rim, have a coarser mesh while the mesh is more detailed in the air-gap and in the stator teeth.

**Solver**

The accuracy of the calculations can be linear, quadratic or cubic with three, six or ten nodes per mesh grid respectively. Newton-Raphson iteration is used to solve the equation by finding the correct length of the machine. The correct machine length is the length that provides the magnetic flux needed to achieve the voltage (input-parameter).

**Interpretation**

The solution can be presented in various ways. The most common and perhaps the most descriptive is the field plot, which displays the magnetic flux density in the geometry.

Losses are categorized as copper losses or iron losses depending on where in the generator they occur. Copper losses, i.e. ordinary resistive losses, are situated in the copper cables while the iron losses occur in the stator steel. The iron losses, \( P_{Fe} \), are defined as:
where $k_f$ is the stacking factor, $k_h$ the coefficient of the hysteresis loss and $k_e$ the coefficient of the excess loss. The right hand terms represent the hysteresis loss, eddy current losses, and excess loss respectively. The coefficient, $k_{edd}$, of eddy current loss for thin sheets is:

\[ k_{edd} = \pi^2 \frac{\alpha d^2}{6} \]

where $d$ is the stator steel sheet thickness.
Summary of Papers

All the papers have the design and simulation tool of direct drive power converters for use in water conditions in common. The papers focus on two general topics, i.e. fundamental generator technology and optimization of a generator to specific situations. They are presented in these two categories. Within each category, the papers are presented in order of time of publication.

Generator Technology


Generators with different rotors but identical stators were simulated. Two of the generators had rotors with permanent magnets, one with pole shoes and ferrite magnets and one with surface mounted neodymium-iron-boron magnets. The third generator had an electro-magnetized rotor. The simulations showed that it is possible to design generators with identical properties independently of the rotor.

Although an electro-magnetized rotor has a large number of benefits, permanent magnets might be preferable. A much less complicated, thus more reliable, machine can be achieved with permanent magnets. Reliability is very important, as maintenance and installation are believed to be difficult.

This paper was presented at a very early stage in my work. The design and simulation tool still lacked some of the functions it has today. Losses in the rotor, that would have been interesting, especially in this paper, were not included.

Paper B: E. Segergren, K. Nilsson and M. Leijon, Frequency Optimisation With Respect to Weight and Electric Efficiency for Direct Drive Underwater Power Generator

The power from a direct drive generator in a water current power plant will vary with the natural variations of the power source. A varying power source cannot supply a national power grid unless an intermediate DC-stage followed by a DC/AC-inverter and a variable transformer is used. An intermediate DC-stage means that the electric frequency of the generator can be used as an arbitrary design parameter. The aim of this article is to show that the efficiency of the generator varies with the frequency and/or the generator geometry while every other parameter is kept constant. Especially the resistive losses in the armature winding show an interesting geometry dependent minimum.

Accepted for publication 2004-11-04 in the IEEE Journal of Oceanic Engineering

Paper C: E. Segergren and Mats Leijon, Relation Between Generator Geometry and Resistance in Armature Winding

The length of the armature winding is related to the diameter and length of the generator. For certain relations between the generator diameter and generator length, the length of the armature winding is minimal. Theoretically, it can be shown that this relation occurs when the coil ends are about the same length as the core cable. In this paper, this theoretical assumption is verified with the design and simulation program for generators.

Accepted for publication 2005-08-14 in the Elsevier Journal of Applied Energy


A water current power plant with a gearbox allows the generator to operate at optimal speed all the time, while the wing tip speed ratio of the turbine is varying. In a direct drive system on the other hand, the turbine is operated at optimal speed all the time while the generator speed is varying. In order to gain efficiency, it is therefore important that the direct drive generator has a high and wide efficiency peak. The efficiency at part load is especially important since higher load means higher efficiency.
Optimization


The flow profiles and power flux changes from one watercourse to another. By adjusting the turbine individually to a certain watercourse, up to 90% of the total power flux can be covered by a turbine with small cross-section relative to the cross-section of the watercourse. Individually adjusted turbines need individually adjusted generators. This paper presents simulated results for several direct drive permanent magnet generators, with different rotation speeds, designed to meet the requirements of an unregulated watercourse. The simulations are based on data for an existing watercourse.

Presented orally by PhD-student Karin Nilsson at the Fifth European Wave Energy Conference, September 2003, Cork, Ireland


Although written after paper B, this paper was published earlier. The main principles and results from Paper B are used in order to optimize permanent magnetized direct drive generators and vertical axis turbines for conversion of the kinetic energy in Swedish unregulated or partly regulated watercourses.


This paper is the result of collaboration between the division of Electricity and Lightning Research and Professor Domenico P. Coiro of the Department of Aeronautical Engineering, University of Naples. The ENERMAR system is a floating support structure supplied with a three bladed, vertical axis, Kobold turbine in order to demonstrate the convenience of using the energy in marine currents. The first pilot plant, which is moored outside the Sicilian coast, experiences an expected current of 2m/s. At the time of writing this paper, the turbine was connected to a gearbox and an off-the-shelf generator.
The objective of the paper was to show that the efficiency could be increased with a specially designed directly coupled generator.

Presented orally by Professor Coiro at the conference EnergyOcean 2004, September 2004, Palm Beach, Florida


Hydropower is the largest renewable energy source in the world today. In Sweden alone, approximately 70TWh/year is produced by hydropower plants, built mainly during 1940-1960. In this paper, five high voltage generators of different sizes have been calculated and simulated. Losses and overall efficiency of the high voltage generators have been compared with five existing hydropower generators in Sweden. The outcome shows that the losses can be lowered, especially if the new generators are adapted to the existing grid.

Published in Journal on Hydropower and Dams, Volume eleven, Issue 3, May 2004, pp104-108


This paper is an update on the applied research conducted at the department. In order to verify theoretical results, a low speed, permanent magnet generator is constructed. The construction work was, however, still in its infancy at the time of writing the paper.

Presented orally by PhD-student Karin Nilsson at the 24th International Conference on Offshore Mechanics and Arctic Engineering, June 2005, Halkidiki, Greece

Paper J: Assembly comprising a Water Turbine and a Generator, the Rotor of which is Direct-Connected to each one of the Blades the Turbine

This patent relates to an assembly which is primarily, but not solely, intended for production of electrical energy from water currents and shows that the research field is newsworthy. The claim of the patent comprises the special feature that each turbine blade is individually connected to the gen-
erator rotor. The need for a particular load-carrying structure for the turbine blades is, thereby, eliminated when since the rotor is a solid and robust body. The result is a less complicated structure consisting of components that any-way is present for other reasons, as well as more a more well-defined and stable turbine.

The PCT-application for Swedish patent SE 0400667-2 is included in this thesis. The patent is public from 11 September 2005.
Summary of Results and Discussion

Generator Technology

At steady state operation, there are no significant differences between a permanent magnetized generator and a generator with electromagnets (Paper A). Differences might occur when the generators are manufactured and when the generator is taken in or out of production. However, permanent magnets provide much simpler technical solutions and are consequently a more appealing alternative in situations where repair and maintenance are difficult, such as under water.

From an electromagnetic point of view, the most efficient generator is achieved at the highest generator speed. For a direct drive system, the generator speed is equal to the turbine speed. The speed of the turbine varies with the current velocity and, as a result, so does the terminal voltage and the frequency of the generator. Hence, the output from the generator has to be rectified and reconverted into a stable AC before it is connected to a power grid. The rectification means that the electric frequency of the generator is arbitrary and can be used as a free design parameter. Higher electric frequency means higher electromagnetic efficiency (Figure 12), until frequency-dependent iron losses become significant. Higher electric frequency also means a wider, shorter machine and possibly a lighter machine (Paper B and Paper F). Some losses do however vary with the geometry. Resistive losses in the armature winding, especially, vary with geometry of the generator, since both the length of the coil end and the length of core conductor are closely connected to the diameter and the length of the machine. It can be shown that there is an optimal geometry with respect to resistive losses. This optimum occurs when the coil end is about the same length as the core cable (see Figure 13 and Paper C).
Figure 12 The Electromagnetic loss varies with frequency. A higher frequency generally means higher efficiency.

An appealing effect of a direct drive system is that the turbine always rotates at optimal speed. This means that the generator operates in overload when the current is strong and at part load in weak currents. This denotes an increase in system efficiency only if the generator has a higher and wider efficiency peak than the turbine. The generator must therefore be able to manage overloads and maintain a high efficiency at part loads. Consequently, the generator should be designed to have a low armature current at nominal load (Paper D).

Figure 13 The conductor lengths as a function of the generator geometry clearly shows a minimum
Optimization

A first, and often correct, step to take when power should be converted from a previously unexploited power source is to convert its motion into a rotation. If electricity is desired, this is handled by an off-the-shelf generator. Since it is not always possible to find a generator with suitable rated speed, a gearbox must be used. This is a rather vulnerable solution though, due to the high number of moving parts and because overloads are handled mechanically. When dealing with a new power source, consumers may initially accept disturbances in supply. Soon however, their expectations will rise. The power source and the power conversion system must therefore be efficient, reliable and, in the end, economically viable.

In order to reach optimal reliability and efficiency, the whole system must be considered all over again. A good example of this is hydropower with its extremely high utilization and efficiency. In a hydropower plant, the turbine is optimized to the flux and the head of the watercourse. The generator is optimized to the turbine and the grid connection is optimized to the generator. New technology can be used to improve existing hydropower. Although these improvements only make up a small fraction of the total rated power of the power plant it might be worth the while due to the high utilization (Paper H).

Power conversion from water currents, as well as from other power sources, can apply the same basic principles as hydropower to increase the utilization and efficiency.

Two basic types of turbines can be used in a free flow water current: vertical axis (cross flow) or horizontal axis (propeller) turbines. An appealing property of the cross flow turbine is that the height and diameter of the turbine can be adjusted to the depth and width of the water current (Figure 14). A correctly adjusted turbine, in the main stream, can cover up to 90% of the energy in the water current, even though the area of the turbine is much smaller than the cross section of the watercourse (Paper E). The turbine speed is limited by cavitation, thus limiting the diameter of the turbine. A power conversion system with a turbine adjusted for top efficiency at one unique site must be provided with a generator designed uniquely for that site (Paper F and Paper G).

![Figure 14 A vertical axis (left) and a horizontal axis turbine (right) with the same cross section](image-url)
Conclusions

- It is important that the generator has a higher and wider efficiency peak than the turbine, i.e. that the generator maintains a high efficiency at part load and withstands overload. This is achieved by designing a machine with low armature current at nominal load.
- A generator can have an optimal geometry with respect to resistive losses. This optimum occurs when the coil end is about the same length as the core cable.
- A correctly adjusted turbine, in the main stream, can cover up to 90% of the energy in the water current, even though the area of the turbine is much smaller than the cross section of the watercourse.
Suggestions for Future Work

The natural continuation of this project is to verify the results with an experimental set-up. Comparisons between finite element method based generator design programs and real generators show a good correlation, but these comparisons have been conducted mainly on hydropower generators.

At present, the construction of a 5 kW experimental set-up for laboratory work has been initiated. The rotor ring, with unusual milled grooves for the mounting of the permanent magnets, has been delivered. A motor and gearbox, together with a frequency converter, will be used to drive the generator in the laboratory. As an extension, parts of the experimental set-up could be used in a real direct drive power conversion system for tests in a laboratory system or in real water currents.

It is not clear when the work can be completed since external funding is currently not available.
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