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Grid Connection of Permanent Magnet Generator Based Renewable Energy Systems

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Abstract

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Renewable energy is harnessed from continuously replenishing natural processes. Some commonly known are sunlight, water, wind, tides, geothermal heat and various forms of biomass. The focus on renewable energy has over the past few decades intensified greatly. This thesis contributes to the research on developing renewable energy technologies, within the wind power, wave power and marine current power projects at the division of Electricity, Uppsala University. In this thesis grid connection of permanent magnet generator based renewable energy sources is evaluated.

A tap transformer based grid connection system has been constructed and experimentally evaluated for a vertical axis wind turbine. Full range variable speed operation of the turbine is enabled by using the different step-up ratios of a tap transformer. This removes the need for a DC/DC step or an active rectifier on the generator side of the full frequency converter and thereby reduces system complexity. Experiments and simulations of the system for variable speed operation are done and efficiency and harmonic content are evaluated.

The work presented in the thesis has also contributed to the design, construction and evaluation of a full-scale offshore marine substation for wave power intended to grid connect a farm of wave energy converters. The function of the marine substation has been experimentally tested and the substation is ready for deployment. Results from the system verification are presented. Special focus is on the transformer losses and transformer in-rush currents.

A control and grid connection system for a vertical axis marine current energy converter has been designed and constructed. The grid connection is done with a back-to-back 2L-3L system with a three level cascaded H-bridge converter grid side. The system has been tested in the laboratory and is ready to be installed at the experimental site. Results from the laboratory testing of the system are presented.

Keywords: VAWT, H-rotor, Tap Transformer, Cascaded H-bridge Multi-Level, Renewable Energy, Wind power, Wave power, Marine Current Power

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To my family

List of papers

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

I **S. Apelfröjd**, and S. Eriksson, "System Efficiency of a Tap Transformer Based Grid Connection Topology Applied on a Direct Driven Generator for Wind Power," *The Scientific World Journal*, vol. 2014, Article ID 784295, 7 pages, 2014. doi: 10.1155/2014/784295.

II **S. Apelfröjd**, and S. Eriksson, "Evaluation of Harmonic Content from a Tap Transformer Based Grid Connection System for Wind Power," *Journal of Renewable Energy*, vol. 2013, Article ID 190573, 8 pages, 2013. doi: 10.1155/2013/190573

III **S. Apelfröjd**, S. Eriksson, and H. Bernhoff, "A Review of Research on Large Scale Modern Vertical Axis Wind Turbines at Uppsala University," *Energies*, vol. 9, no. 7, p. 570, Jul. 2016. doi: 10.3390/en9070570

IV R. Ekström, **S. Apelfröjd**, and M. Leijon, "Transformer Magnetization Losses Using a Non-filtered Voltage-Source Inverter," *Advances in Power Electronics*, vol. 2013, Article ID 261959, 7 pages, 2013. doi: 10.1155/2013/261959

V R. Ekström, **S. Apelfröjd**, and M. Leijon, "Transformer Magnetizing Inrush Currents Using a Directly Coupled Voltage-source Inverter," *ISRN Electronics*, vol. 2013, Article ID 361643, 8 pages, 2013. doi: 10.1155/2013/361643

VI R. Ekström, **S. Apelfröjd**, and M. Leijon, "Experimental Verifications of Offshore Marine Substation for Grid-connection of Wave Energy Farm," *Electric Power and Energy Conversion Systems (EPECS), 2013 3rd International Conference on*, Istanbul, 2013, pp. 1-6. doi: 10.1109/EPECS.2013.6712994

VII K. Yuen, **S. Apelfröjd**, and M. Leijon, "Implementation of Control System for Hydrokinetic Energy Converter," *Journal of Control Science and Engineering*, vol. 2013, Article ID 342949, 10 pages, 2013. doi: 10.1155/2013/342949

VIII **S. Apelfröjd**, R. Ekström, K. Thomas, and M. Leijon, "A Back-to-Back 2L-3L Grid Integration of a Marine Current Energy Converter," *Energies*, vol. 8, no. 2, pp. 808-820, Jan. 2015. doi: 10.3390/en8020808

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X M. Rossander, E. Dyachuk, **S. Apelfröjd**, K. Trolin, A. Goude, H. Bernhoff, and S. Eriksson. "Evaluation of a Blade Force Measurement System for a Vertical Axis Wind Turbine Using Load Cells," *Energies*, vol. 8, no. 6, pp. 5973-5996, Jun. 2015 doi:10.3390/en8065973

XI M. Grabbe, K. Yuen, **S. Apelfröjd**, and M. Leijon, "Efficiency of a Directly Driven Generator for Hydrokinetic Energy Conversion," *Advances in Mechanical Engineering* Jan.-Dec. 2013 5: 978140, Oct. 10, 2013 doi:10.1155/2013/978140

XII S. Lundin, J. Forslund, N. Carpman, M. Grabbe, K. Yuen, **S. Apelfröjd**, A. Goude, and M. Leijon, "The Söderfors Project: Experimental Hydrokinetic Power Station Deployment and First Results," *In Proceedings of the 10th European Wave and Tidal Conference (EWTEC)*, Aalborg, Denmark, 2013.

XIII **S. Apelfröjd**, F. Bülow, J. Kjellin and S. Eriksson, "Laboratory Verification of System for Grid Connection of a 12 kW Variable Speed Wind Turbine With a Permanent Magnet Synchronous Generator," *In proceedings of EWEA 2012 Annual Event*, Copenhagen, Denmark, April, 2012.

XIV **S. Apelfröjd**, R. Ekström, B. Ekergård, K. Thomas and M. Leijon, "Evaluation of Damping Strategies for Maximum Power Extraction From a Wave Energy Converter with a Linear Generator," *Grand Renewable Energy Conference on Energy Network and Power Electronics*, Tokyo, Japan. 2014.

XV R. Ekström, **S. Apelfröjd**, B. Ekergård, K. Thomas and M. Leijon, "Inverter Topology with Integrated On-Load Tap Change for Grid-Connection of Renewable Electric Energy Sources," *Grand Renewable Energy Conference on Energy Network and Power Electronics*, Tokyo, Japan. 2014.

XVI V. Castellucci, M. Eriksson, R. Waters, **S. Ferhatovic***, M. Leijon, "Wireless System for Tidal Effect Compensation in the Lysekil Research Site," *Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering*, vol. 7, pp. 293-298. July 1-6, 2012.

XVII J. de Santiago, H. Bernhoff, B. Ekergård, S. Eriksson, **S. Ferhatovic***, R. Waters and M. Leijon, "Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review,," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 2, pp. 475-484, Feb. 2012. doi: 10.1109/TVT.2011.2177873

XVIII M. Leijon, B. Ekergård, **S. Apelfröjd**, J. de Santiago, H. Bernhoff, R. Waters and S. Eriksson, "On a Two Pole Motor for Electric Propulsion System", International *Journal of Engineering Science and Innovative Technology (IJESIT)*, vol. 2, no. 1, pp. 99-111, Jan. 2013.

*The author changed his surname from Ferhatovic to Apelfröjd in April 2012.

Contents

Nomenclature

Symbol	Unit	Description
A	m^2	Area swept by the turbine
$A_{0,1}$	-	Shape constant
c	-	Scale factor
C_f	F	Filter capacitor
C_p	-	Power coefficient
f_s	Hz	Switching frequency
I_c	A	Collector current
I_h	A	Amplitude of the h:th current harmonic
I_{mag}	A	Magnetizing current
I_{sc}	A	Maximum short-circuit current at PCC
k	-	Form factor
λ	-	Tip speed ratio
m_a	-	Modulation index
η	%	System efficiency
ω_t	rad/s	Rotational speed of turbine
Φ_{core}	Wb	Core flux
P_t	W	Power extracted from turbine
R	m	Turbine radius
R_g	Ω	IGBT gate resistor
ρ	kg/m^3	Air density
t_f	s	Fall time
T_j	°C	Junction temperature
t_{off}	s	Turn-off time
t_{on}	s	Turn-on time
t_r	s	Rise time
v	m/s	Wind speed
V_{ce}	V	Collector-emitter voltage
V_{dc}	V	DC-bus voltage
V_l	V	RMS line to line voltage

Abbreviations

Abbreviation	Word/Phrase
2L-VSC	Two-Level Voltage Source Converter
3L-CHBVSC	Three-Level Cascaded H-Bridge Voltage Source Converter
AC	Alternating Current
ADCP	Acoustic Doppler Current Profiler
cRIO	CompactRIO
DC	Direct Current
FPGA	Field-Programmable Gate Array
HAWT	Horizontal Axis Wind Turbine
IGBT	Insulated-Gate Bipolar Transistor
NI	National Instruments
PCB	Printer Circuit Board
PCC	Point of Common Coupling
PLL	Phase Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse-Width Modulation
RMS	Root Mean Square
SG	Synchronous Generator
SPWM	Sinusoidal Pulse-Width Modulation
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine
VSC	Voltage Source Converter

1. Introduction

Renewable energy is harnessed from continuously replenishing natural processes. Some commonly known are sunlight, water, wind, tides, geothermal heat and various forms of biomass. The focus on renewable energy has over the past few decades intensified greatly. Some of the driving factors for this strong development have been diminishing supplies of fossil fuels [1], pollution, growth, global warming [2] and a steadily increasing demand for energy. Today there are several mature technologies to harness renewable energy on the commercial market but there is still a great demand for innovation and development. At present there are numerous ongoing research project in all the areas of renewable energy trying to reduce the cost of energy as much as possible. This thesis contributes to the research on developing renewable energy technologies. Here, applied power electronics and grid connection topologies are in focus, within the research projects in the wind power, wave power and marine current power at the division of Electricity, Uppsala University. The renewable energy projects at the division of Electricity, Uppsala University, are presented in Chapter 2.

At the division of Electricity we utilize a direct driven generator approach in all our renewable energy projects. This can have several advantages such as removing the gearbox, reducing the number of moving parts, reducing the system complexity and increasing overall system efficiency. However, there are some challenges associated with a direct driven approach. One of them is that the voltage from a direct driven generator varies in both frequency and amplitude, which makes direct grid connection of the generator not viable. This is also true for the three renewable energy projects discussed in this thesis. It is most apparent for the unaided eye in the wave power project. The output voltage from a deployed wave energy converter during a typical sea-state is shown in Figure 1.1. Here we can clearly see that the voltages are not harmonic free, symmetrical and sinusoidal 50 Hz voltages. Thus, there is a need for a full frequency conversion system for the grid connection of the generator. There are several commercial technologies that address this issue. What drives the research is to try to do it better, with higher efficiency, at lower cost and with less need for maintenance. The goal is to, through innovative solutions, reduce the cost of energy. There are several parameters that can be modified and tuned to try to achieve this goal, such as reducing complexity to reduce the maintenance cost, removing components from the chain to increase efficiency, improving the controllers or even increasing the complexity to increase the system efficiency.

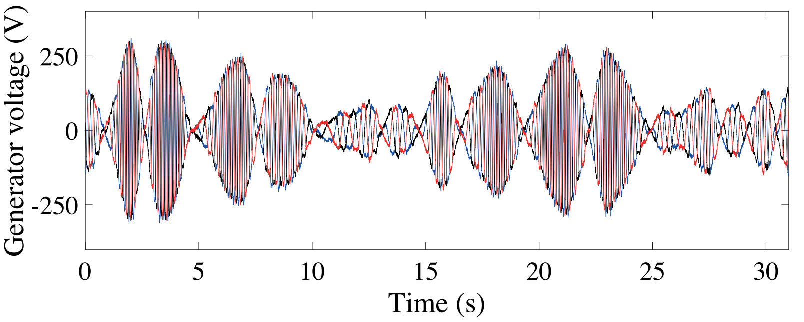


Figure 1.1. Three-phase voltage output from the wave energy converter L9 during typical sea operation.

Working in engineering science differs in various ways from natural science. Natural science focuses on trying to understand and explain natural phenomena, whereas engineering science is the art of making things work, or more precisely the art of turning things into means of an end and creating new systems, objects and solutions. The work is done based on knowledge gained from the essential understanding of how natural phenomena work, i.e. natural science. Engineering science is an iterative process that generates solutions, ideas and designs. These are then tested, usually through simulations and experiments, to gather new knowledge about how the constructed systems work in a complex setting. The knowledge gained is then used to further develop the ideas. Some obstacles can be greater in engineering science than in natural science. For example, going forward and innovating are not always easy tasks, as success can depend on several human factors such as politics, economics, public acceptance and regulations.

1.1 Aim and Layout of the Thesis

The work presented in this thesis evaluates, through simulations and experiments, grid connection topologies for renewable energy sources with the main focus on wind power, wave power and marine current power. The aim has been to evaluate a tap-transformer topology for wind power and wave power and to develop a grid connection system for marine current power. The work has contributed with 18 published papers covering different aspects of this area. The main contributions from the author have been in the area of applied power electronics. The greatest contributions to the field by the author comes from Papers I-IX and they are the main focus of this thesis.

The work has strongly focused on experiments and laboratory testing of different systems. In Chapter 2 an introduction is given to the different renewable energy projects at Uppsala University. Some of the basic components and terminology used in a full frequency converter are covered in Chapter 3. Chapters

4-6 focus, respectively, on grid connection systems for each of the renewable energy sources; wind power, wave power and marine current power. In these chapters the research methods and some of the main results from the papers are presented and discussed. The work is summed up with some of the main conclusions from all the papers presented in Chapter 7 and recommendations for future work are given in Chapter 8.

2. Background

In this chapter the three main renewable energy projects at the division of Electricity, Uppsala University, are presented. The three research projects are ongoing and investigate wind power, wave power and marine current power.

2.1 Wind power

In the last century wind power has emerged as a new large scale renewable energy technology. The drivers of the new technology have been a combination of political ambition, technical development and technical innovation. The ongoing discussions on global climate change and the desire to reduce carbon dioxide emissions [3] has been one of the main political incentives. In this respect, wind power represents an environmental friendly energy source without fuel cost and with small gas emissions. Present technology is dominated by the MW-scale Horizontal Axis Wind Turbines (HAWT) and has demonstrated the viability of large scale systems capable of supplying a substantial part of the electric energy supply on national and even continental level [4].

Vertical Axis Wind Turbines (VAWT) have been pursued and developed in a number of different projects, but none has yet reached significant commercial take off. The Eole is one of the more famous projects in this area, a joint venture project between Hydro-Quebec and the National Resource Council of Canada to develop a large-scale Darrieus VAWT in the early 1980s. The Eole, a 96 m high Darrieus turbine constructed in 1986, was built with a rated maximum power of 3.8 MW and a swept area of 4000 m^2 [5]. During the 5 years that the Eole was in operation is delivered close to 13 GWh of electric energy. Due to failure of the bottom bearing the machine was shut down in 1993. The company FloWind is another example that in the 1980s built several wind farms with Darrieus turbines [6]. The machines had problems with fatigue of the blades, which were designed to flex [7].

Several new VAWT projects have started in the resent years with a strong focus on offshore. One example of a ongoing project is the DeepWind project where a floating offshore VAWT with a Darrieus type rotor is proposed [8, 9]. One of the major advantages for VAWT offshore is the possibility to place several of the large and heavy components, such as transformer and generator at the bottom of the tower, which is not the case for HAWTs. This is especially beneficial in floating constructions. The aim of the DeepWind VAWT project is to investigate the possibility of building a 5 MW offshore wind turbine.

The VAWT project at Uppsala University aims at developing a robust large-scale VAWT technology based on electrical control with a direct driven energy converter and has been ongoing for more than a decade. A review of the work done at Uppsala University is the main focus of Paper III, which covers the ongoing work as well as adds some deeper insight in the development of the 200 kW VAWT at the Falkenberg experimental site discussed later. The direct driven approach allows for a simplification where most or all of the control can be managed by the electrical system, reducing investment cost and the need for maintenance. The main idea behind the concept is to reduce the number of moving parts and achieve a cost-efficient and robust design.

The concept features an H-rotor that is omnidirectional in regards to wind direction, meaning that it can extract energy from all wind directions without the need for a yaw system. A direct driven permanent magnet synchronous generator (PMSG) is specifically developed to match the turbine speed and torque giving numerous advantages. A direct driven generator does not need a gearbox and is therefore spared from losses, maintenance and costs associated with a gearbox [10]. By removing the gearbox, the overall efficiency of the system is also expected to be higher. The gearbox is also a complex part with several moving components, by removing it the system becomes simpler. Further, a direct driven system has the ability to react more rapidly to changes in the wind and the load [11].

In [12] an investigation of failure statistics from four different sources comprising of a large number of wind turbines is done. Two sources are from Sweden, one from Finland and one from Germany. The study further strengthens the arguments for not having a gearbox in the system, since the gearbox is identified as one of the major reasons for downtime, as downtime per failure is higher for the gearbox than for other components. Several failures were also linked to the electric system, as well as sensors and blades/pitch components. As the VAWT system at Uppsala University does not need yaw or pitch system the faults and downtime associated to these subsystems can also be discarded. Further, the use of a tap transformer based grid connection system, with only one active component, is expected to be more robust and reliable. With this stated, it is believed that downtime and number of failures can be decreased significantly for vertical axis wind turbines. One of the major incentives for pursuing the vertical axis technology is to reach a higher degree of reliability. The benefits with this approach, having a direct driven generator and a vertical axis turbine, apply both to the wind power system discussed here and also to the marine current power system discussed later in this chapter.

2.1.1 History of VAWT

Vertical axis wind turbines have been used and developed during a very long time [4]. It has been argued that the reason for HAWTs being more common commercially is due to investment priorities rather than technical advantages [13]. Following are some main benefits of using VAWTs rather than HAWTs [14], beginning with that a VAWT most commonly does not need a yaw mechanism, since it is omnidirectional. The generator can be placed at the bottom of the structure, which can make maintenance and installation simpler and more cost effective. Furthermore, a VAWT is expected to produce less acoustic noise than a HAWT [15]. The most commonly known VAWT is the so called Darrieus wind turbine patended by Darrieus in 1931 [16] with troposkein blades. Commercial wind farms with Darrieus turbines have been built and tested [17, 18]. A known disadvantage with the Darrieus turbine is that the blades can be difficult to manufacture [18] and that the turbine is usually situated very close to the ground where the wind speed is lower and wind shear may cause structural problems. The turbine type used at Uppsala University is the straight-bladed vertical axis wind turbine and is commonly called H-rotor, straight-bladed Darrieus rotor or Giromill. The main difference is that the Darrieus turbine has curved blades fixated to the top and bottom of the tower while the H-rotor has straight blades usually fixated to the tower via one or several struts. The H-rotor has a simpler construction due to the straight blades, which can make it cheaper and easier to manufacture. Another advantage is that the H-rotor can be placed on a high tower and is then normally not as close to the ground as a Darrieus turbine would be. The H-rotor can also be designed to have better aerodynamic performance than the Darrieus rotor [13].

2.1.2 Experimental Site: Marsta

A scaled prototype vertical axis wind turbine was constructed during 2006 at the Marsta meteorological observatory located roughly five kilometers outside of Uppsala, Sweden. The site has been used by the meteorological group at Uppsala University for several decades [19] and is well characterized [20]. The Weibull fit of the wind speed data gathered at the site gives a form factor of 1.94 and a scale factor of 5.24 m/s. The site and the wind climate is further discussed in [21]. The average wind speed at the site is not very high but is still sufficient for research purposes [22].

The prototype turbine has a three-bladed H-rotor with NACA0021 wind sections and is rated to 12 kW at a wind speed of 12 m/s. The three blades are connected to the hub via struts and the hub is connected to the generator via a steel shaft enclosed by the turbine tower. The turbine can be seen in Figure 2.1. The power coefficient of the turbine has been experimentally derived in [23]. The paper presents the measured power coefficient for the turbine as a function of the tip speed ratio with a peak power coefficient of 0.29 at a tip speed ratio of 3.3.

Recently two papers presenting measurements of the tangential and normal forces on the 12 kW turbine have been presented, Paper X and [24]. In

Figure 2.1. 12 kW vertical axis wind turbine designed and constructed at Uppsala University.

Paper X, the forces acting on one of the blades on the turbine are measured using four single-axis load cells. The load cells were installed in-between the hub and the struts. The paper presents the experimental set-up, measurement system and necessary control system. Measured forces for the load cells are presented as well as the derived tangential and nominal forces. The measurements are compared to simulations and the results show a good agreement between the simulated normal forces and the measured values. Unexpected mechanical oscillations are present in the tangential forces, introduced by the turbine dynamics. The study adds valuable information and shows some of the difficulties associated with open site experiments.

2.1.3 Experimental Site: Falkenberg

The major topic in Paper III is the 200 kW turbine at the Falkenberg research site, as stated earlier in the text. The 200 kW VAWT was constructed and installed by Vertical Wind AB in 2010 in collaboration with Uppsala University, E.ON, Falkenberg Energi AB and The Swedish Energy Agency. The machine was seen as an important step to gain valuable experience and data for future construction of multi-megawatt VAWTs. The 200 kW VAWT can be seen in Figure 2.2. In March 2012, after a series of tests, the turbine had around 1000 h of operation and had delivered roughly 22.5 MWh to the grid. In the period since March 2012 the turbine has been operated for another 500 h. The design of the turbine follows the earlier discussed train of thought and is a direct driven machine without yaw or pitch system. To further simplify and to add to the robustness of the system the generator output voltages are passively rectified and then connected to the grid using a standard 2-Level Voltage Source Converter (2L-VSC).

Figure 2.2. The three bladed 200 kW vertical axis wind turbine in Falkenberg, Sweden.

The on-site estimated yearly average wind speed is 6.5 m/s at hub height. An anemometer (Thies Clima 4.3351.00.161) is placed in a measurement tower 100 m from the turbine at the hub height of 42 m, as required by the standard IEC 61400-12-1. The 200 kW system has been design rated as an IEC class II turbine, surviving extreme wind gust of 60 m/s. Parking strategies during high wind speeds for an H-rotor are the focus of the work presented in [25]. In the paper the authors propose that during storm conditions the generator can provide sufficient dampening by being short-circuited once the turbine has been stopped. This method has several advantages and is expected to reduce the loads on the machine.

A 225 kW permanent magnet synchronous cable wound generator was designed for the system. The generator design has been compared to simulations and verified in the laboratory [26, 27]. The laboratory testing presents measurements of the induced voltage as well as measurements of the magnetic flux density in the airgap of the generator. The generator efficiency, according to simulations, is above 96% at all wind speeds higher than 6.6 m/s. On-site a concrete foundation is used to support the stator of the generator. This approach is expected to substantially reduce cost for large multi-MW generators [28].

The generator is direct connected to the turbine via a long shaft enclosed by the tower. An innovative wood-fiberglass composite tower design has been used in the 200 kW turbine. Some of the great advantages of using a wooden tower is that it is environmental friendly and has a fairly low cost. Another reason for the use of a wooden tower is that it gives a thicker tower wall than a steel tower, removing buckling issues. A soft tower made out of steel would be more difficult to design cost effectively as it would give problems with buckling. A soft tower has a fundamental natural frequency lower than the blade passing frequency. A study focusing on the eigen frequencies of the tower is presented in [29].

A control method for the fixed-pitch 200 kW turbine has been implemented and evaluated in [30]. The measured power and rotational speed of the generator, together with a look-up table for the aerodynamic efficiency, are used to estimate the wind speed at the turbine. Experimental results where the estimated wind speed is compared to wind speed measurements from the anemometer for eight hours are also shown in [30]. The estimated wind speed follows the variations in measured wind speed closely. However, the estimated wind speed is roughly 7% lower than the wind speed measured by the anemometer. In the work presented in [31], successful stall regulation of the 200 kW turbine is presented. Results are shown for about 24 minutes of operation in gusty wind conditions. The aim of the study was to demonstrate stall control by keeping the rotational speed at a fixed value during gusty winds.

2.2 Wave Power

Wave energy is an unexploited renewable energy source with great potential that could significantly contribute to the electricity production across the globe. To attempt to utilize this potential, several wave energy converter concepts have been developed over the last decades. At Uppsala University a point-absorber based concept has been developed and tested in real sea conditions for a long period of time [32–42]. The design is based on a directly driven permanent magnet linear generator placed on the seabed. The moving part of the linear generator, the translator, is connected to the point-absorber via a wire. The main advantages of the concept are the gearbox free operation, robustness and simple mechanical design. One of the early models designed, constructed and deployed by Uppsala Univerity can be seen in Figure 2.3.

Figure 2.3. Wave energy converter, L9, before deployment at the Lysekil research site.

2.2.1 Experimental Site: Lysekil

The Lysekil wave power project has been ongoing for a long period of time with the project starting in 2001. The first full-scale wave energy converter was deployed in 2006 [34]. The experimental site is located a few kilometres south of the town Lysekil, on the Swedish west coast.

Several wave enery converters have been deployed at the site along with a first marine substation [43]. The wave energy converters are connected to the marine substation where the voltages are rectified and then converted to a fitting grid voltage and transferred to land via a sea cable. A second version of the substation, able to handle more power, has been the topic of [44]. Testing of the second substation for the Lysekil experimental site is the topic of Papers IV-VI. The second substation was deployed in 2015.

2.3 Marine Current Power

Unregulated rivers, tides and other ocean currents are renewable energy sources with great potential across the globe. One of the major benefits being the high predictability of tidal currents, to within a 98% accuracy [45]. There are several projects in this area with several academic and corporate groups around the world investigating and testing different concepts to convert the energy from free flowing water. Numerous large marine turbines with output power above 0.5 MW are presented in [46–51].

At Uppsala University we are working on converting the power in free flowing water using a vertical axis turbine with a direct driven permanent magnet generator [52–54]. The concept investigated at Uppsala University uses an omnidirectional, fixed pitch vertical axis turbine direct connected to a non-salient permanent magnet generator. The benefits of this approach are discussed earlier in Section 2.1. The generator is placed below the turbine, outside of the water flow passing through the turbine.

2.3.1 Experimental Site: Söderfors

A first full prototype unit was deployed in 2013 in the river Dalälven in the town of Söderfors by the research group at Uppsala University. The prototype, before deployment, is shown in Figure 2.4. Paper XII presents the deployment and the first results from the marine current energy converter. During the first testing the generator was connected to a resistive load and power output as well as the upstream and downstream water speed were measured. The first tests show that the system works and delivers power. The first control system for the test turbine is the focus of Paper VII and the testing of the generator before deployment is presented in Paper XI. A grid connection system for the turbine with a multi-level converter is presented in Paper VIII and Paper IX. Results from these papers are presented in Chapter 6.

Figure 2.4. Prototype marine current energy converter before deployment in the river Dalälven, Sweden.

The Söderfors project aims to construct and evaluate a complete system for converting hydro kinetic energy to electricity and to deliver it to the local electric grid in a realistic environment for an long period of time. The machine is placed downstream of a bridge at a water depth of roughly 7 m, about 1 km downstream of a hydropower plant that regulates the water speed at the site. The typical water speed is in the interval of 0.5-1.5 m/s. Low water speeds, under 2 m/s, are of special interest to the research group, since being able to effectively extract power at such sites would increase the number of possible locations for hydro-kinetic energy conversion across the globe. To measure the water velocity three acoustic Doppler current profilers (ADCP) are installed at the test site. Two are placed upstream of the turbine to measure the incoming flow and one is placed downstream of the turbine. A study of the wake of the marine current turbine using the ADCPs is presented in [55]. The marine current turbine is connected to an on-land control station roughly 150 m from the turbine. All the control and logging equipment is placed in the on-land control station. The turbine diameter is 6 m with a height of 3.5 m. The blade profiles are NACA0021. The maximum simulated power coefficient for the turbine, at the rated water velocity of 1.3 m/s and a tip speed ratio of 3.5, is 0.36 [52, 56].

3. Full Frequency Converter

A large portion of the work in this thesis has revolved around the Insulated-Gate Bipolar Transistor (IGBT) based voltage source converter. A voltage source converter, be it a rectifier or inverter, is present in almost all papers in this thesis. In this chapter some of the issues, concepts and terminology regarding voltage source converter are discussed to give a brief overview of the area. A full frequency converter has three main parts:

- A rectifier, AC-to-DC conversion step
- An energy storage, typically capacitors
- An inverter, DC-to-AC conversion step

Depending on the application, filtering can be placed before and/or after the converter. The type of filter used is determined by the application and the relevant regulations and requirements. There are many alternatives for how to design the three different parts, resulting in a large quantity of different full conversion systems. A one-line diagram of a typical full frequency converter system is presented in Figure 3.1. From the left, the PMSG phases are connected to the rectifier via a filter. The voltages is then rectified and charges the capacitors on the DC-bus. The DC voltage is then converted to an AC voltage with the help of the inverter. The inverter output is filtered before the system is grid connected via a transformer.

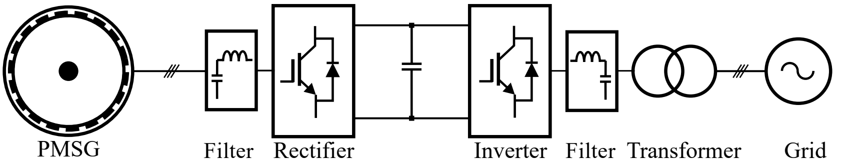


Figure 3.1. One-line diagram of a full frequency converter connecting a PMSG to the Grid via a transformer.

In wind power, the most commonly used converter system is the two level voltage source converter in back-to-back configuration [57]. In wind power there are two strong arguments for the use of full power electronic conversion systems. First, the ability to control the rotational speed of the generator almost freely giving the benefit of optimal energy absorption, reduced loads, gearbox-free turbines and reduced noise at low wind speeds. Second, the power electronics give the wind turbine the ability to be an active component in the power system [58]. This allows for control of active and reactive power flow and the ability to strengthen weak grids, giving the wind turbine a more positive influence on the network [59,60]. An evaluation of today's most commonly used power conversion topologies for wind power can be found in [61,62]. Similar benefits as those for wind power can be expected for wave power and marine current power.

3.1 IGBT - Principle of Operation

The IGBT is a three terminal power semiconductor primarily used in power switching applications. The three terminal of the IGBT are the Gate, Collector and Emitter. The circuit equivalent for an IGBT is shown in Figure 3.2.

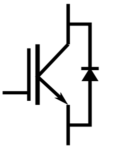


Figure 3.2. Circuit equivalent of an IGBT. The IGBT has three terminal: Gate, Collector and Emitter.

When the IGBT gate is supplied with a sufficient and fixed voltage the device is turned on and starts conducting. Then the collector-emitter voltage (V_{ce}) changes as a function of the collector current (I_c) and the junction temperature (T_j). The V_{ce} is used to calculate the power dissipation of the IGBT; the smaller the value the lower the power dissipation. The recommendation for most IGBT devices is to keep the current at the rated I_c or lower but most new modules can handle much larger currents for very short periods of time to withstand faults. Most high power IGBTs also have a built in current limiting feature that limits the current to roughly ten times that of I_c for a short period of time. Usually when the self limiting feature of the IGBT is activated this indicates a fault across the device.

The IGBT is most frequently used in switching operation so it is also important to understand the characteristics during the turn-on and turn-off of the device to be able to determine and understand the switching loss. The four most important times to keep track of are the rise time (t_r), the on-time (t_{on}), the fall time (t_f) and the off-time (t_{off}). The switching times are functions of the I_c and T_j. With increasing current or temperature, the switching times increase, resulting in higher losses. The gate resistor R_g also effects the switching times and can be tuned to adjust the switching times as desired.

3.1.1 IGBT Drivers

During the work in this thesis several IGBT drivers have been designed built and implemented to fit the various needs of projects at hand. One of the finished drivers can be seen in Figure 3.3. The IGBT drivers can be designed in several ways depending on the application but there are some key features that are implemented in most designs. The IGBT driver is the interface between the controller and the IGBT and connects the low voltage logics with the operating voltage of the system, allowing the system to control the IGBTs efficiently. To be able to preform this task the IGBT driver galvanically isolates the incoming low voltage control signals from the rest of the system. This adds protection from the high power circuit but also enables the driver to supply the IGBT gate with a sufficient voltage. The galvanic isolation can be achieved in several ways but the most common are optocouplers and pulse transformer solutions. The driver also has the ability to supply a high pulse current to quickly turn on the IGBT gate. In the set-ups presented in this thesis, the peak currents from the IGBT drivers have been around 8 A.

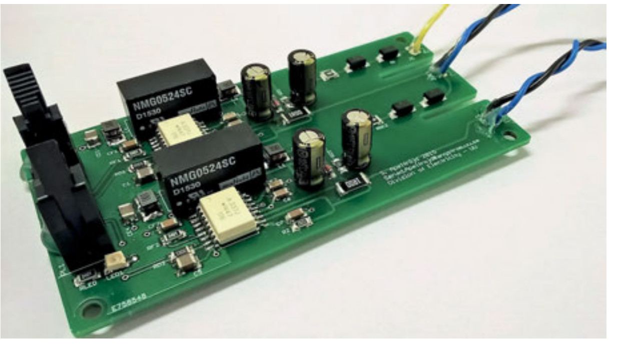


Figure 3.3. An IGBT driver designed during the work in this thesis able to supply a peak current of 8 A.

The IGBT driver most commonly also protects the IGBT from short-circuit currents. This is done by sensing the voltage across the IGBT after it has been turned on. If the voltage is above a pre-set threshold the driver turns off the IGBT preventing damage to the device. This type of protection is implemented on the IGBT driver as the short-circuit faults need to be cleared very quickly, several times faster then the rest of the control system operates. The current measurements done by the control system are used to protect the device from over-current, that is currents that change slowly in respect to short-circuit currents and can be more easily detected.

3.2 LCL-Filter

To be able to connect the system to the grid the voltages need to be sufficantly harmonic free. There are various standards that state the limits for different harmonics. The standard that has been used the most in this work is the IEEE 519-1992 [63], some of the limits are presented in Paper II. To achieve this a filter is most commonly placed between the VSC and the grid. The LCL-filter reduces the switching harmonics from the voltage source converter and has grown in popularity due to its better filtering capacity and smaller size in comparison to an L-filter and LC-filter for the same application [64–67]. The LCL-filter, in some form, has been used in most of the set-ups here. The design of the LCL-filter is an important part of the grid connection as it determines several parameters. The filter effects the total harmonic content of the output voltage as stated above but also other factors. One of them is the ripple current from the inverter, dominantly set by the inductor closest to the inverter. The filter also effects the reactive power flow from the grid. If a large filter capacitor is used the system will draw unnecessary amounts of reactive power. The filter also adds a resonance peak to the system that needs to be handled. The resonance peak is usually set in the region between the fundamental frequency supplied to the grid and switching frequency used in the VSC. The entire system also needs to be examined as the addition of the filter can add new, or move, existing system resonances.

3.3 Control and Measurement Systems

To be able to grid connect the system a control and monitoring unit it required. There are several tasks that need to be executed to reliably deliver power to the grid and this is where the control hardware comes in. In most of the projects in this thesis the base of the control system has been the CompactRIO (cRIO) platform from National Instruments (NI). The main control loops, PID controllers, measurements, pulse with modulation (PWM), grid synchronization and tracking have been implemented on the Field-Programmable Gate Array (FPGA) part of the cRIO. The FPGA ensures that everything is executed at the correct time. The more computational heavy tasks, as well as data logging, have been implemented on the real-time processor part of the cRIO. The real-time part of the cRIO is much like a normal PC and allows for several similar features like FTP services, login options, network access and user interface. Figure 3.4 shows a cRIO filled with different types of modules selected to add needed functionality to the hardware such as digital output and inputs, analog inputs and output and so on.

A great deal of measurements are also done in the different projects, both for control purposes as well as for monitoring and evaluation of the systems. To measure the current a current transducer of the type HAIS-50P or equivalent is used in most cases. Changes are made depending on the range of the incoming currents and the distance between the cRIO and the sensor. Voltages have usually been measured with LV-25-P sensors or equivalent sensors. Both sensor types have good accuracy over their entire range and a good bandwidth. Additional hardware has been added to the sensors to condition and filter the signals before everything is logged with a NI9205 module at a rate of 1-10 kHz

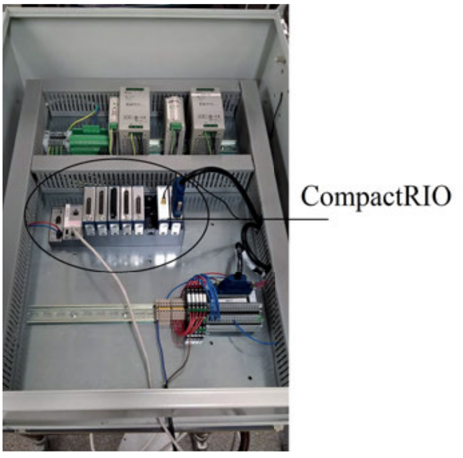


Figure 3.4. Typical cabinet with CompactRIO used in the work presented here, filled with interface modules.

per channel depending on application. A typical isolated voltage-measurement sensor, designed by the author, mounted on a printed circuit board is shown in Figure 3.5. To ensure the quality of the measurements the systems are always calibrated using high precision calibrated instruments available at the laboratory. In some applications the above sensors and log system does not have a sufficient bandwidth, for example when examining the high frequency harmonic content. Then an external factory calibrated probe such as a SI-9002 differential voltage probe has been used together with an oscilloscope.

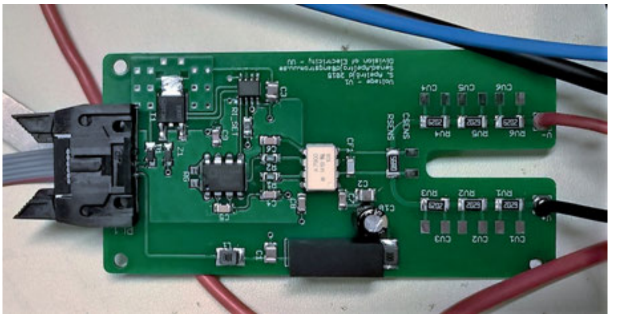


Figure 3.5. Typical voltage-measurement sensor mounted on a printed circuit board used in the work in this thesis.

3.4 Tap Transformer

A tap transformer is used in several of the projects presented here. A tap transformer is very similar to a regular transformer. The main difference is that the tap transformer has more than one step-up ratio, a tap transformer usually has several different step-up ratios. This is achieved by splitting up the transformer windings and can be done on both the low and high voltage side of the transformer. The ability to change the step-up ratio of the transformer during operation adds to the flexibility of the system. The variable step-up ratios can be used to remove the need for a DC/DC converter or a boost rectifier after the generator to handle the variation in the generator voltage. The use of a DC/DC or a boost rectifier is a common way to handle the variation in voltage [68]. When the voltages are low a high step-up ratio of the tap transformer is used and when the voltages are higher the step-up ratio is lowered. This has the advantage of being able to keep the currents in the system low and thereby increasing efficiency. A schematic drawing of a tap transformer circuit with four taps is shown in Figure 3.6.

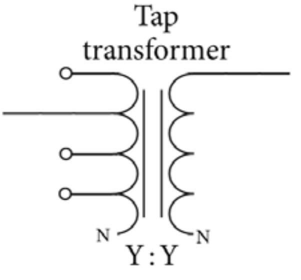


Figure 3.6. A schematic drawing of a tap transformer circuit with four taps on the left side of the transformer.

4. Tap-Transformer Topology for Wind Power

In the following text some of the basic concepts of the system topology considered in Paper I-II and XIII are described and the theory behind them is presented.

The amount of power, P_t, that can be extracted from a wind power turbine in given by Eq. 4.1,

$$P_t = \frac{1}{2}\rho A Cp(\lambda) v^3 \tag{4.1}$$

where ρ is the air density, A the area swept by the turbine, Cp the power coefficient and v the wind speed. The power coefficient is a function of tip speed ratio (TSR) and represents the aerodynamic efficiency of the turbine. The tip speed ratio is defined in Eq. 4.2,

$$\lambda = \frac{\omega_t R}{v} \tag{4.2}$$

where ω_t is the rotational speed of the turbine and R is the turbine radius. The $Cp - \lambda$ curve for the 12 kW turbine can be found in [22]. Eq. 4.1 and Eq. 4.2 also apply for the submerged turbine in the marine current power project, the difference being that ρ is replaced with the density of water.

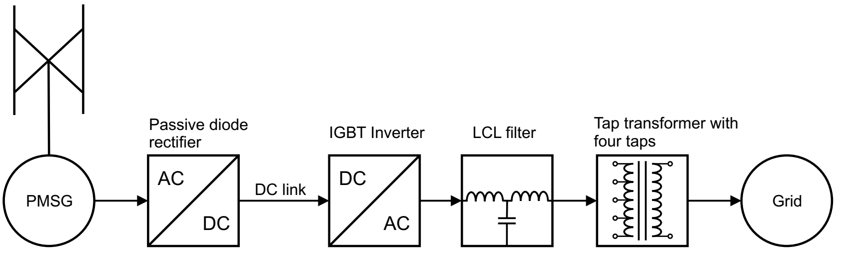


Figure 4.1. Block diagram of the system topology considered in Paper I-II and XIII.

A block diagram of the system topology considered in Paper I-II and XIII is shown in Figure 4.1. The generator voltage is rectified using a diode rectifier without the generator neutral connected. An insulated gate bi-polar transistor based two level voltage source converter, controlled with pulse-width modulation, is used to convert the DC voltage to the desired three phase 50 Hz AC voltages.

The control and measurements for the operation of the inverter are all done in LabVIEW and implemented on a cRIO platform utilizing both the FPGA and realtime part of the system. The inverter outputs are filtered through an LCL-filter before the tap transformer and grid connection. The tap transformer has three different step-up ratios. If tap one is selected the step-up ratio of the tap transformer is 7, tap two has a step-up ratio of 4 and the third tap has the lowest step-up ratio with a ratio of 3.

In Paper II and XIII the harmonic content in the output currents is examined. The total harmonic content in the current, THD_I, is calculated using Eq. 4.3 in accordance with the guidelines presented in IEEE 519-1992 [63].

$$THD_I = \left[\frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \right] 100\% \tag{4.3}$$

where I_h is the amplitude of the h:th harmonic and I_1 the amplitude of the fundamental. The amplitudes of the current harmonics are derived with the use of the fast fourier transform with a flat top window. The total demand distortion of the current waveform, TDD_I, is given in Eq. 4.4

$$TDD_I = \left[\frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_L} \right] 100\% \tag{4.4}$$

where I_L is the fundamental maximum demand load current. The total demand distortion can often be difficult to find as it can be difficult to determine the location of the point of common coupling (PCC). For the study in Paper II we assume the maximum demand current to be the nominal current of the system at rated load. This gives a worst case scenario in respect to TDD.

4.1 Load and Site Characteristics

The Weibull parameters for the wind speed data at the Marsta site are a scale factor of 5.24 m/s and a form factor of 1.94. The Weibull probability density function is given in Eq. 4.5

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{4.5}$$

where k is the form factor and c the scale factor. The designed control strategy for the turbine is described in [22]. The turbine is started at a wind speed of 4 m/s and runs at optimal tip speed ratio from the wind speed 4 m/s to 10 m/s. Between 10 m/s and 12 m/s the turbine is run at a fixed speed of 127 rpm. The rotational speed will still vary slightly due to voltage drops in the generator as the current is increased and due to controller limitations. The variation will be small so it can still be seen as fixed rotational speed operation. According to the designed control strategy the turbine would have been kept at fixed rotational speed until cut out. In paper I-II we choose to deviate from that control scheme and instead run the turbine at nominal power of 12 kW from 12 m/s until the cut out speed of 20 m/s.

4.2 Simulations

The author did the simulations in Papers I-II and XIII, the details can be found in the papers. Here follows a short summary. Before laboratory testing the full system, see Figure 4.1, was simulated using MATLAB/Simulink mostly using the built in blocks of the simulation tool. In Paper I the system efficiency is in focus and in Paper II and XIII a closer look at the system harmonics is presented.

The inverter is operated at a switching frequency of 6 kHz and the SPWM is generated using a PLL and dq-controller. In the papers a resistive load is used instead of the grid, therefore a 50Hz sinusoidal reference is internally generated for the PLL. Each tap of the tap transformer was modelled as a linear star-delta transformer. A transformer core saturation model is not used in Papers I and XIII; all the magnetizing and eddy current losses are represented by the magnetizing impedance, R_m and L_m. The transformer in Paper II was modelled in two different ways. The first case, Case I, is the same as in Paper I and XIII, using the magnetizing impedance. The second case, Case II, uses a simple saturation model for the transformer core without hysteresis [69,70]. The saturation effects are described by an arctan function with the saturation limits at 120% of the nominal voltage and nominal magnetizing current, derived from the magnetizing impedance. The core flux, Φ_{core}, as a function of magnetizing current, I_{mag}, used in this model is shown in Eq. 4.6 where A_0 and A_1 are shape constants. The function is used for positive currents and then mirrored symmetrically to the negative quadrant.

$$\Phi_{core}(I_{mag}) = A_0 \arctan(A_1 I_{mag}) \tag{4.6}$$

4.3 Experimental Set-up

In the following text the experimental set-up used in Papers I,II and XIII is presented and briefly described. More details and component ratings can be found in the papers. In the following text each block in the system overview in Figure 4.1 as it is implemented in the experimental set-up, from left to right, will be described.

The generator, seen in Figure 4.2, is identical to the direct driven generator installed in the 12 kW VAWT prototype and has a rated voltage of 161 V. The generator has a round rotor and is star-connected with the neutral not

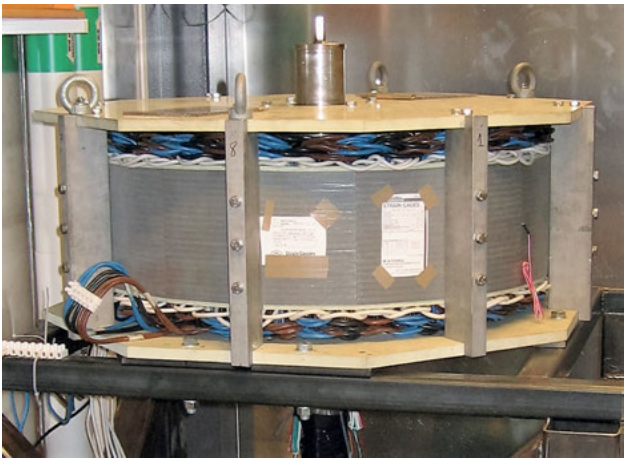


Figure 4.2. Permanent magnet synchronous generators used in the experimental set-up.

connected. Previous work on this generator can be found in [71]. In the experiment the generator is driven by an induction motor.

The AC/DC conversion in Figure 4.3 consists of a diode rectifier and a capacitor bank. The generator phase currents are rectified using diodes (Semikron SKKD 100/12) rated at 1.2 kV and 100 A. The IGBT modules (SEMIX252GB126HDs with Skyper 32R drivers) used in the inverter can be seen in Figure 4.4.

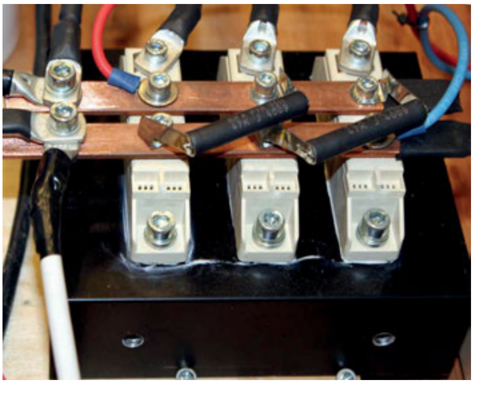


Figure 4.3. Passive diode rectifier consisting of three Semikron SKKD 100/12 rectifier modules.

The tap transformer, seen in Figure 4.5, is delta-star connected with the delta side connected to the resistive load. The tap-transformer has three different step-up ratios, tap 1 with a step-up ratio of 7, tap 2 with a ratio of 4 and tap 3 with a ratio of 3.

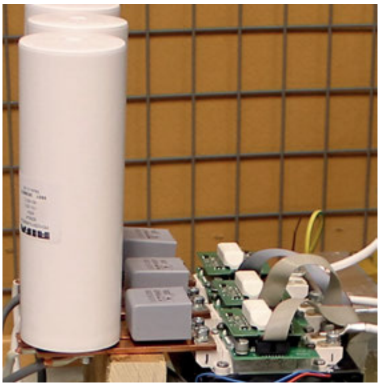


Figure 4.4. IGBT based voltage source converter used in the experimental set-up and the DC-link capacitors.

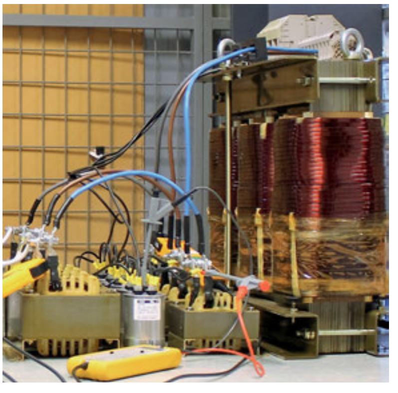


Figure 4.5. LCL filter to the left and tap transformer, with three different step-up ratios, to the right.

The resistive load consists of several modified electric heaters with a maximum power rating of 2 kW each. The resistors were connected differently to produce eight different loads within the operating range of the system, resulting in up to six different loads per tap as not all loads are applicable on all taps for the given turbine operation.

In the experiments in Paper XIII, the system was connected to a resistive load of 3 kW at 230 V, which is one fourth of the nominal power output for the system. In this first study the modulation was fixed and the generator and taps were run in such a way that the wanted 3 kW was produced. In paper I and II, the simulation model presented earlier was used to collect data about modulation index and generator rotational speed for each resistance. This operational data was then used for the same fixed resistance in the experiments. Measurements to obtain the DC and AC power were performed and an efficiency was calculated. The same inverter control scheme, with an internally generated PLL reference, was used in the experimental set-up as in the simulations.

A limiting factor for the experiments on the tap with highest step-up ratio was the current. The experimental system has a current limit of 80 A per phase. This limits the power per phase on transformer tap 1 to roughly 2.6 kVA, whereas the other taps were limited by their inability to produce a sufficiently high voltage at low DC levels. A limitation for all taps were the discrete resistance values that only allowed for a few points in the operational range. The control of the inverter was implemented on the built-in FPGA of the NI-cRIO9074 unit and executed with a NI9401 digital output module.

In the rest of this chapter the most important results from the papers are presented and discussed.

4.4 Wind System Efficiency

The results from the simulations in Paper I are shown in Figure 4.6 where the full operating range for each tap is presented. The efficiency is lowest at low wind speeds and increases with increasing wind speeds. It levels out when the fixed power region of operation is reached. This is expected, as all major losses are constant and we only have a slight increase in current as the DC link voltage decreases. Furthermore, we see in Figure 4.6 that the efficiency at nominal power is increased by roughly 6% by going from transformer tap 1 to tap 2 and by approximately 8% by changing from tap 1 to tap 3 which is a significant increase.

The results from the experiments in Paper I are shown in Figure 4.7. Here we see the same trends in efficiency as in the simulated results but with a deviation of roughly 2%, see Figure 4.7. The deviation can be caused by a number of different things such as measurement errors, the low order frequency model for the transformer or a need for adjusting the magnetization impedance of the transformer when using PWM. However, we still see a clear increase in efficiency as we change tap.

4.4.1 Case Study

In the case study in paper I we examined different tap selections and evaluated how this effects the turbine operation with different scale factors for the Weibull distribution, see Eq. 4.5. For each case, the Weibull site parameters are combined with the simulated efficiency and discussed control strategy for the turbine to calculate the average power output. To get a proper understanding of the average power output from the system four cases are chosen as described below:

Case I

Here we assume a standard transformer that can deliver power to the grid at

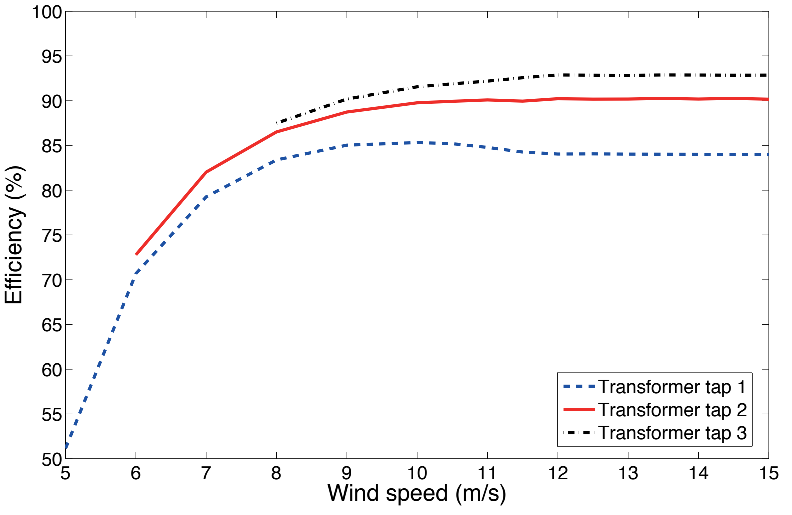


Figure 4.6. Simulated system efficiency as a function of wind speed for three different taps on the tap transformer.

all wind speeds. This is represented by running the system only using tap 1 on the tap transformer for the full operational range of the turbine.

Case II

The system is run using all available taps and the tap change is done as soon as a tap with a higher efficiency is available, with some hysteresis implemented. In winds from 4 m/s until 7 m/s tap 1 is used, at 7 m/s until 9 m/s tap 2 is used and for the rest of the wind speeds tap 3 is used.

Case III

The low wind speeds are ignored and only tap 2 and 3 are used. In this mode of operation the wind turbine does not start to deliver power to the grid until a wind speed of 6 m/s is reached and the tap change from tap 2 to tap 3 is done at 9 m/s.

Case IV

In this scenario tap 2 is excluded and the turbine is run with tap 1 and tap 3. In winds from 4 m/s until 9 m/s tap 1 is used and for the rest of the wind speeds tap 3 is used.

The difference in power output for the four cases relative to the base case, Case I, is presented in Table 4.1. The results from the case study show an increase in overall power by roughly 5% for Case II, and slightly above 3% for Case IV compared to the base case for the Marsta site. This is a significant increase in production. However, these results are very site specific and for a wind site with higher mean wind speed a higher utilization of the high taps is

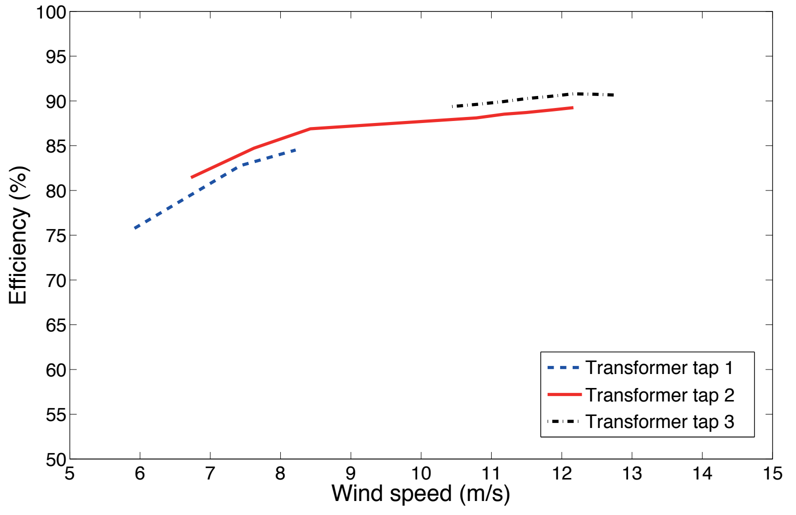


Figure 4.7. Experimental system efficiency as a function of wind speed for three different taps on the tap transformer.

achieved, giving an even more significant impact on the overall power production as seen in Table 4.1. Case III only becomes an option at sites with high mean wind speeds.

Table 4.1. *Power output for the different cases relative to the base case, Case I, for different scale factors.*

Case	I	II	III	IV
c=4 - Power output (%)	100	102.65	47.20	100.94
c=5.24 - Power output (%)	100	104.52	76.32	103.26
c=6 - Power output (%)	100	105.69	86.58	104.62
c=7 - Power output (%)	100	106.86	94.68	106.03
c=8 - Power output (%)	100	107.66	99.33	107.03
Taps used	1	1, 2, 3	2, 3	1, 3

4.5 Total Harmonic and Demand Distortion

In Paper II we took a close look at the harmonic content in the output currents from the tap-transformer based grid connection system. The experimental results from Paper II are shown in Figure 4.8. The two vertical lines, in both the sub figures, correspond to one third and two thirds of the nominal power reached at 12 m/s. The system THD as a function of wind speed is presented in Figure 4.8a. The system THD is highest at low wind speeds and decreases with increasing wind speed. We can see a significant drop in the total harmonic distortion when we make a tap change to a lower step-up ratio. The effect is greater when we have a larger change in the step-up ratio. The change from tap 1 to tap 2 has a greater reduction than the step from tap 2 to tap 3, see Figure 4.8a. This effect was expected as we utilize a larger part of the inverter side transformer winding at low step-up ratios. The system TDD as a function of wind speed is presented in Figure 4.8b. The TDD is lowest at low wind speed and increases with higher wind speeds. As we move up in wind speed the TDD goes up mostly due to the increase in output current from the system. Here we also see the same trends during tap change as with the THD, which is a reduction when operating on a lower step-up ratio. Notice that the system has its best TDD at the same time as the THD is at its highest value. The THD and TDD is assumed to be roughly constant for the wind speeds from 12 m/s until 15 m/s. This is due to that the turbine operates at a fixed power within this region. There will still be small DC voltage variations due to the speed reduction during stall but this is believed to have a very small effect on the THD and TDD. This study shows that the system TDD is well within the limits set in IEEE 519-1992 for the full operating range.

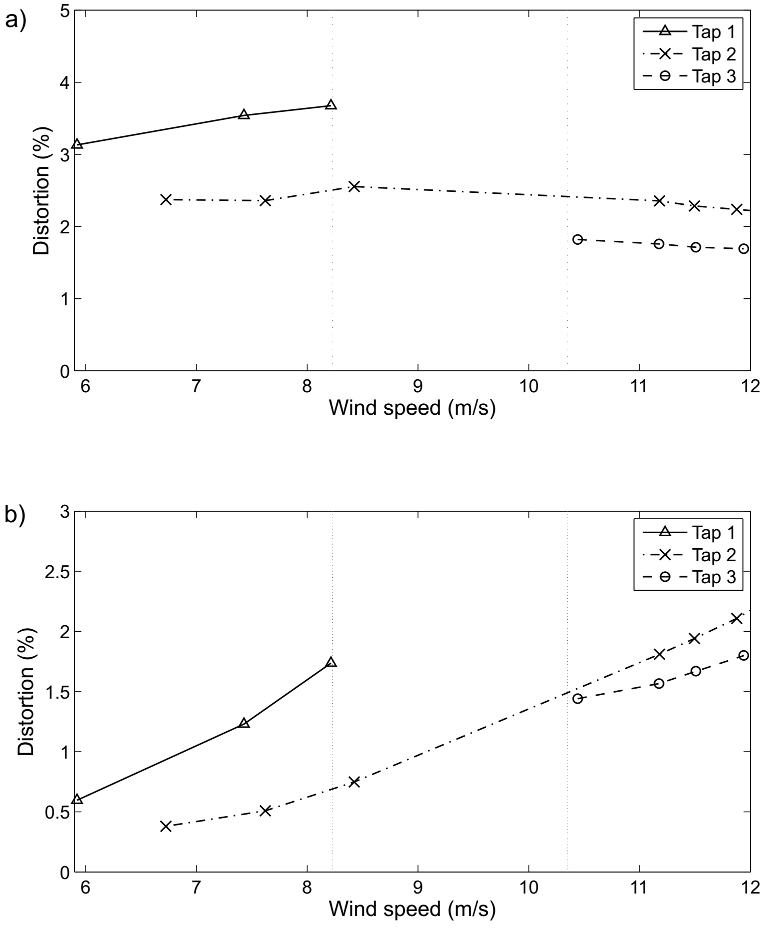


Figure 4.8. Results from the experiments for all three taps on the tap transformer a) THD b) TDD. The vertical lines in the two figures correspond to one third and two thirds of the nominal effect from the turbine reached at 12 m/s. We can see an improvement in THD as we go up in power and an improvement in both THD and TDD as we go up in tap.

5. Marine Substation for Wave Power

The work in this thesis contributes to the construction and development of the second marine substation deployed at the Lysekil test site. The marine substation is discussed in great detail in [44]. The main contributions to the marine substation are from Papers IV-VI, XIV and XV. In Papers IV and Paper V the substation tap transformer is in focus and in-rush currents as well as magnetization losses are examined. Paper VI presents the laboratory full-system tests before deployment. Paper XIV looks briefly at how to maximize the power output from a wave energy converter and Paper XV takes a closer look at the on-load tap change for a tap-transformer topology.

5.1 Laboratory Evaluation

The marine substation has a very important role in the wave energy farm. It is used to gather the power from the farm and transmit it to the closest grid connection point. By having the substation at the same location as the wave energy farm only one cable is needed to connect the farm to the grid and the transmission efficiency can be greatly improved. The substation houses all the needed components to grid connect and monitor the wave energy converters. By adding an energy buffer in the substation the power output can be smoothed, further improving the utilization of the sea cable. The substation, as it is being assembled in the laboratory, can be seen in Figure 5.1.

The one-line diagram of the substation is very similar to the tap transformer topology discussed in Papers I, II and XIII. The substation uses a passive rectifier to first rectify the incoming wave energy converter voltages and the DC-voltage is smoothed using a large capacitor bank. The system is then grid connected via a tap transformer and LCL-filter. The main difference is that in the marine substation the LCL-filter is placed after the tap transformer and the inverter is directly connected to the tap transformer. This has the benefit of having a smaller filer but the drawback of increasing the strain on the transformer.

In Paper VI the full marine substation is tested, generator to grid, before deployment at the research site in Lysekil. To test the substation the PMSG presented in Chapter 4 and shown in Figure 4.2 was used. The drive train for the generator was programmed to behave in a similar way to the wave energy converters. That is the speed of the machine was varied to produce a voltage output similar to that of a wave energy converter assuming a sinusoidal wave.

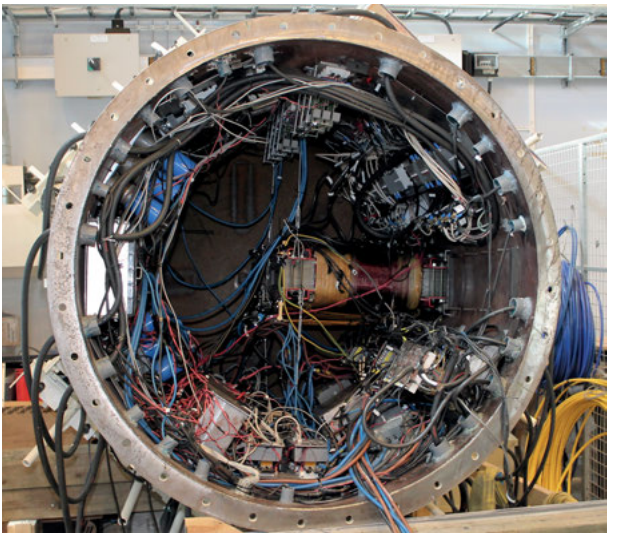


Figure 5.1. Marine substation being assembled in the laboratory, seen from the bottom of the structure.

All complex bouy-generator dynamics and wire issues are not accounted for as the test focuses on the main circuit of the marine substation. For the testing a wave time period of 6 s and 12 s was used. More details on the control system, main circuit and measurement system in the substation can be found in Paper VI.

Some of the results from the evaluation of the system are presented here. In Figure 5.2 the phase to neutral voltage and the phase current from the PMSG are displayed. In the figure we can see that the generator is only delivering power once per wave cycle. The DC-voltage was set to a high value in relation to the generator output voltages in this specific test and power is only delivered when the wave lifts the buoy. When the substation is deployed the DC-voltage will be continuously adjusted by the control system to maximize the power output from the wave power farm.

In Figure 5.3 the output power to the grid is presented for a few waves. We can observe that the system successfully delivers power to the grid every time the generator output voltage reaches the DC-link voltage. The output power therefore also fluctuates in a similar wave to the incoming wave. This is a type of worst case scenario looking at the power fluctuations as only one unit is connected to the substation and the DC voltage is rather low, not utilizing the full capacitor bank. Once the substation is deployed several units will be connected to it and the power input and output will be smoothened out more [43].

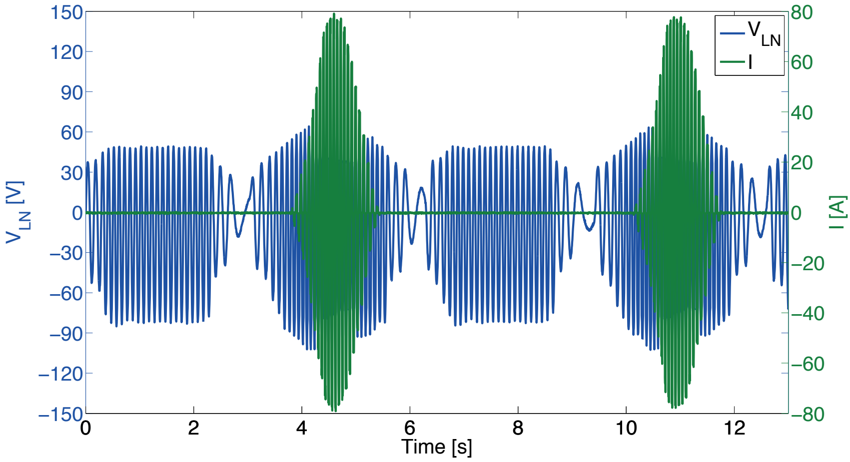


Figure 5.2. Output voltage and current from the test generator used to test the marine substation.

5.2 Transformer Testing

To further understand and evaluate the marine substation and effects of having the inverter directly connected to the tap transformer, the transformer magnetization losses were evaluated in Paper V. In-rush currents to the transformer during magnetization are the topic of Paper IV. A single-line diagram of the experimental set-up used for the experiments in both papers is shown in Figure 5.4. The rectified grid voltage is used as a DC-source in the experiment. The DC-capacitor bank is rated at 19 mF. The three-phase inverter consists of six 400GB126D IGBTs with 2SC0108T2Ax-17 Concept driver boards, as shown in Figure 5.5a. The switching frequency for the inverter, is set to 6 kHz. The inverter is connected to the low side of the YY 345/1kV 80kVA three-phase transformer shown in Figure 5.5b. The transformer characteristics are found in Paper V. The three phase voltages on the terminals of the transformer are measured by high-frequency differential voltage probes SI-9002. The three phase currents are measured with current clamps Fluke i310s. All measurements are sampled at 400 kHz.

5.2.1 Magnetization losses

In the experiments to evaluate the transformer magnetization losses, in Paper IV, the DC-voltage is set to three different levels, and the total power loss is measured while the amplitude modulation of the inverter is varied. The simulations are done in Matlab/Simulink. A saturation curve for the transformer was measured and then used in the simulations. In the results presented i Fig-

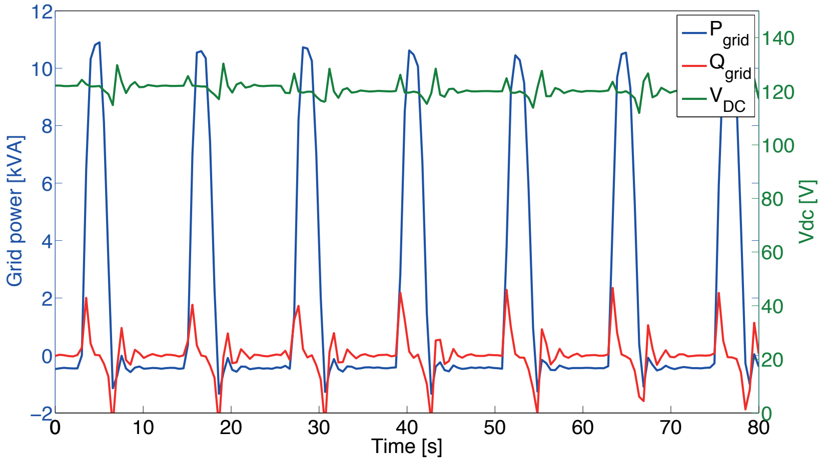


Figure 5.3. Power delivered to the grid during the testing of the marine substation.

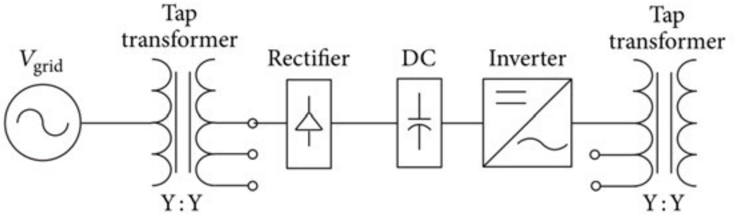


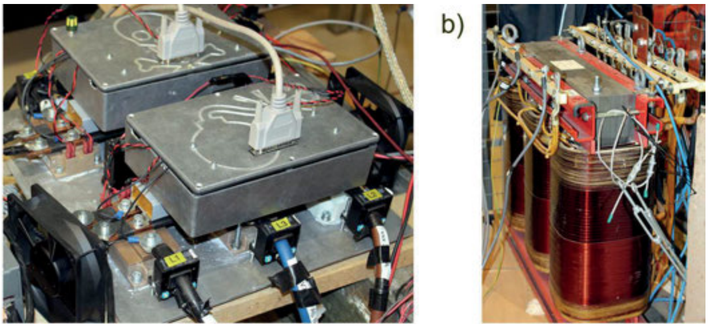
Figure 5.4. Single-line diagram of the experimental set-up. The tests are done on one tap of the tap-transformer to the right.

ure 5.6a, the DC-level is set to 145 V, in Figure 5.6b 335 V and in Figure 5.6c 550 V respectively.

There is good agreement between simulations and experiments in Paper V. For the lower DC-voltages, the power loss is approximately proportional to m_a, whereas it starts to increase with the square of m_a for the highest voltage. This is reasonable, since the losses increase with the square of the rms voltage. Also, the magnetic core will be in its linear region for lower voltages and magnetic fluxes, whereas it will go into partial saturation as the induced voltage is increased. When the transformer is SPWM-magnetized at its rated voltage by the inverter, ($V_{DC} = 550$V;$m_a = 1$), the magnetization losses are ten times higher than the 50 Hz magnetization at rated voltage.

5.2.2 In-rush Currents

In the system seen in Figure 5.4 the transformer is directly magnetized by the inverter. This way the magnetization of the transformer can be done smoothly



a) b)

Figure 5.5. The inverter and transformer used in the transformer magnetization loss study a) three-phase inverter consisting of six IGBTs b) three-phase transformer

without the need for any external magnetization circuits. In Paper V, three different magnetization strategies are evaluated. The first is a step response with remanent flux, the second is a step response without remanent flux and the third and final case is a ramped up voltage with remanent flux. In the first case the inverter is started abruptly at full voltage, giving full magnetization of the transformer. This is the case most similar to an immediate grid connection of the transformer. The resulting in-rush currents will be high and be strongly dependent on the difference between the firing angle and the stop angle, i.e. where in the sine wave the transformer was disconnected and where it now is connected to the grid. A magnetization using strategy one, can be seen in Figure 5.7. Here we can see the in-rush currents quickly build up and being cut off by the over-current protection implemented in the inverter. When the remnant flux is removed, in the second case, the in-rush currents are somewhat lower and less dependent on the firing angle. This is expected as the starting point is always the same but the currents are still high.

The full advantage of having the inverter is utilized in the third case where it is possible to slowly build up the voltage and soft-magnetize the transformer. This cannot be done directly from the grid as the grid voltages are fixed. The ramp-time, the time between zero voltage and nominal transformer voltage, can be varied with the inverter. Different ramp-times are presented in Paper V. In Figure 5.8 we can see the transformer magnetized from zero to nominal over three 50 Hz cycles, 60 ms. This largely removes all problems with in-rush currents to the transformer and the currents are within operating range for all components. Further details on how the peak currents vary with different ramp-times are presented in greater detail in Paper V.

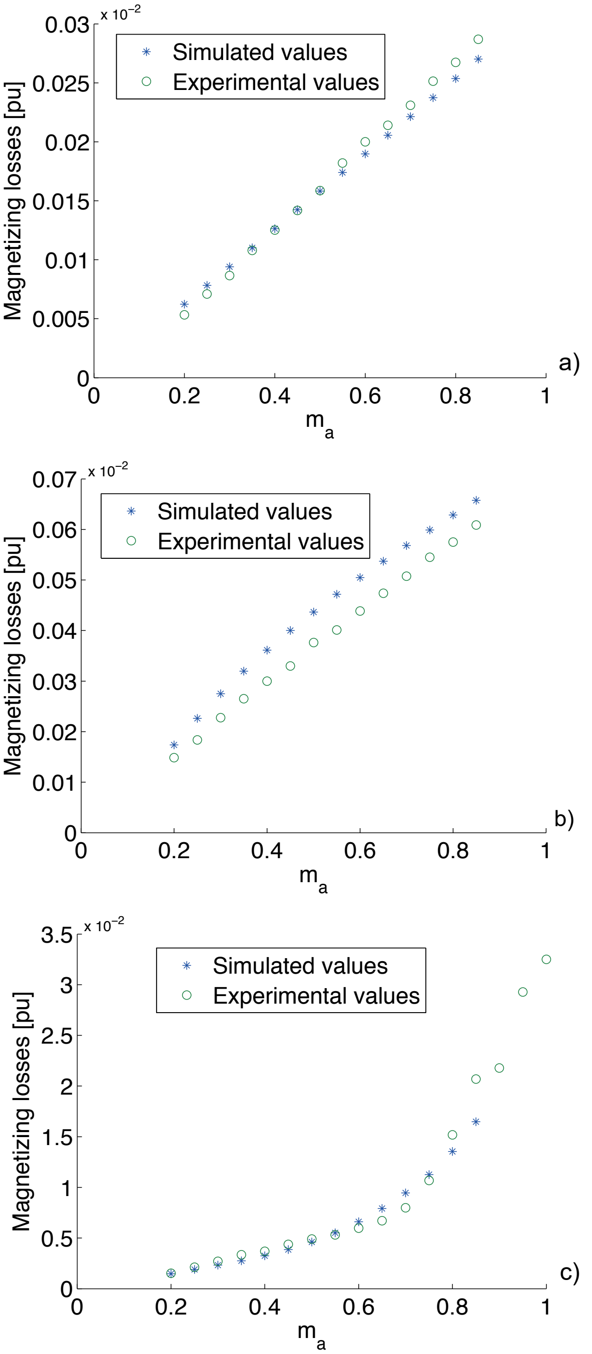


Figure 5.6. Comparison of magnetization losses between simulations and experiments, at different values of V_{DC}. The DC-level is set to a) 145 V, b) 335 V and c) 550 V.

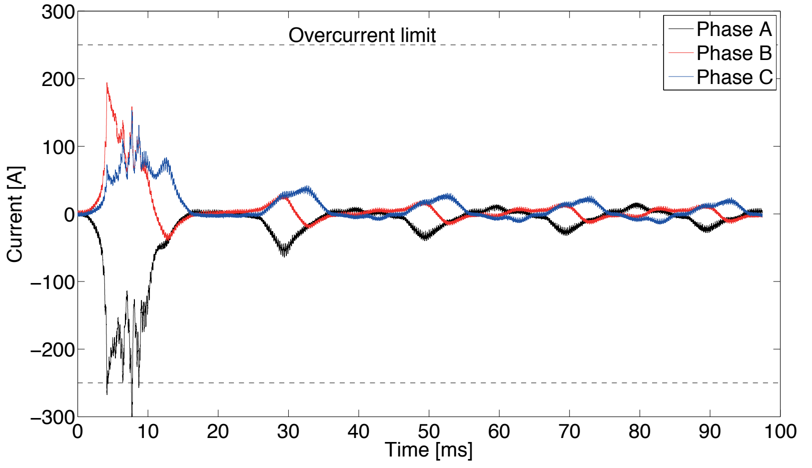


Figure 5.7. Transformer in-rush currents when the inverter is started at nominal voltage for the transformer. Peak currents are cut-off by the inverters over-current protection.

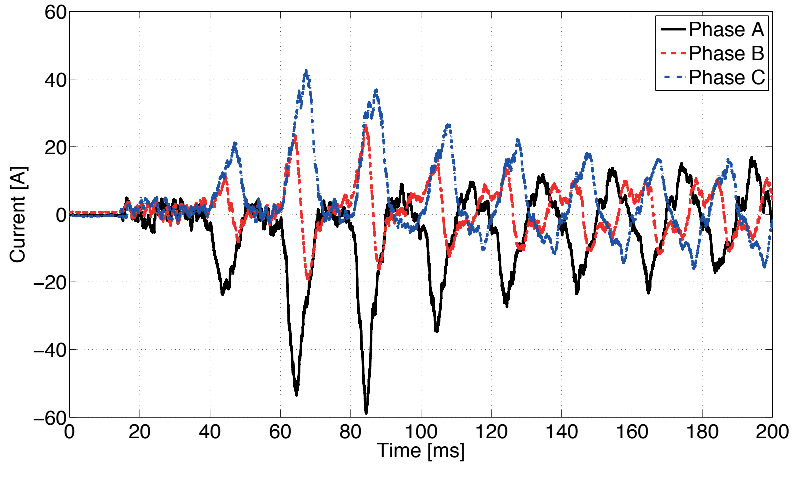


Figure 5.8. Transformer magnetization done over 60 ms to reduce the in-rush currents.

6. Grid Connection for Marine Current Power

A part of this thesis has focused on the control and grid connection of the marine current power converter in Söderfors. The vertical axis turbine used here is very similar to the one used in wind power. The same equations for extracted power and the tip speed ratio from Chapter 4, Eq. 4.1 and 4.2, also apply here with the difference being that water density is used instead of air density.

6.1 First Control System

The topology for the first control system designed for Söderfors, presented in Paper VII, is shown in Figure 6.1. The generator can be connected to four different parts of the control system via breakers. To start the machine the grid voltages are rectified via a transformer and diode rectifier. A 2L-VSC is used to spin up the machine using signals from Hall-sensors mounted inside of the generator. The load control is built up of a rectifier, a capacitor bank, a resistive load, and an IGBT to control the amount of power dissipated in the resistive load. The IGBT is switched to regulate the duty cycle on the load thus controlling the power drawn from the generator and the speed of the turbine. The system also has an emergency brake, connecting the machine to a star-connected resistive load.

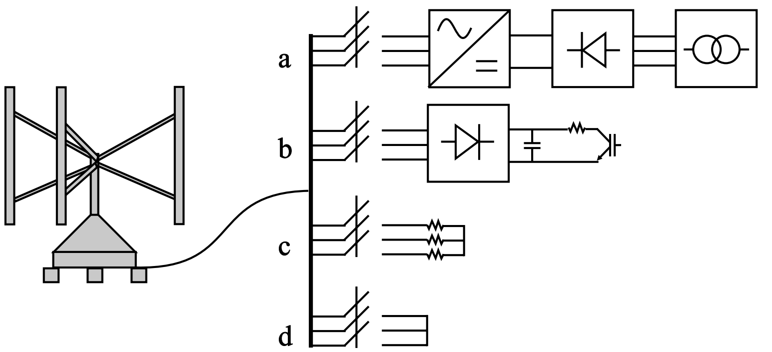


Figure 6.1. Schematic illustration of the control system. The three phases of the generator can be connected to different parts of the control system. (a) start-up system, (b) load, (c) emergency brake, and (d) parking brake.

The main focus of Paper VII, was the design and testing of the control system. Most of the control system is placed in the enclosure shown in Figure 6.2.

The layout of the enclosure is as follows: (a) the power cable from the generator is connected. (b) Contactors and fuses connect and disconnect the different branches of the control system. (c) A diode rectifier. (d) Capacitors are mounted in a separate enclosure. (e) Two IGBT's are used for load control. (f) The inverter used for start-up is mounted on a heat sink. (g) The short-circuit that serves as a parking brake is manually operated. (h) Voltage and current measurements are collected by three printed circuit boards mounted in shielded boxes. (i) The CompactRIO.

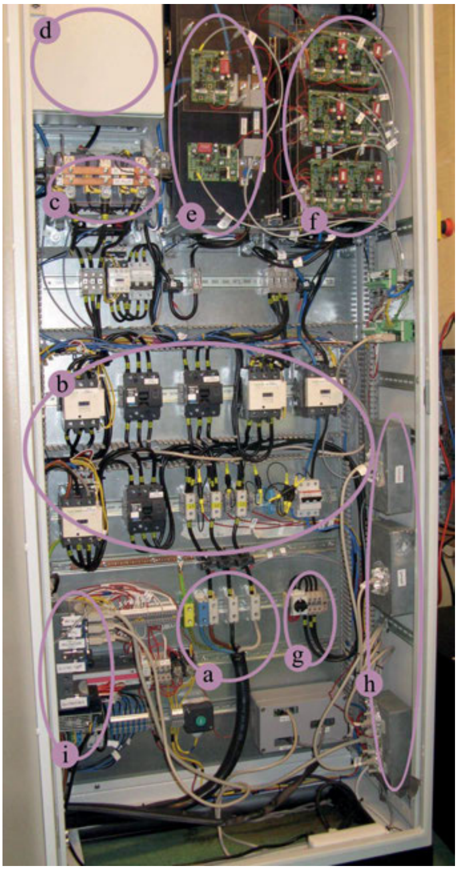


Figure 6.2. The enclosure for the control system of the marine current energy converter. (a) Generator power cable , (b) breakers and fuses , (c) diode rectifier , (d) enclosed capacitors , (e) load control IGBT's, (f) start-up inverter , (g) manually operated parking brake , (h) voltage and current measurements and (i) CompactRIO.

The Hall-sensors mounted on the stator of the generator are latch type sensors, A1210, from Allegro. Three sensors are mounted on a printed circuit board (PCB) containing supplemental electronic components according to the manufacturer's application notes. The PCB is designed to separate the sensors by 120 electrical degrees in the stator, and is attached onto a plastic mount placed on the stator.

In the laboratory testing of the system in Paper VII the test generator was connected to a motor drive that could be torque-controlled. In this set-up, it was possible to test if the load control system could keep a specified rotational speed and a specified load voltage. Between about 4 and 15 rpm the control system was able to hold a fairly constant rotational speed when the torque was varied. Start-up of the generator for Söderfors was tested using laboratory voltage supplies. The start system was able to rotate the generator smoothly up to 13 rpm and was deemed to function satisfactory. The system performed satisfactory in the laboratory and was later installed at the Söderfors research site. After some minor modifications to the start-up system the control system was able to start-up and control the machine and the first results of the generator are presented in Paper XII. The first results show that the turbine is operating as intended and presents voltages and currents across a fixed resistive load.

6.2 Multi-level Grid Connection System

In Papers VIII and IX a grid connection system for the Söderfors marine current energy converter is proposed, designed, constructed and verified in the laboratory. The two papers are a continuation of the work done in Paper VII. The work presented in the two papers is a step towards grid connection of the prototype. One of the main considerations when choosing this grid connection topology was the ability to scale it up for much larger marine current energy converters. A bidirectional topology is chosen as the turbine is not self-starting and needs to be accelerated from standstill in order to absorb power from the water. This eliminates the need for a separate start-up circuit as the one used in Paper VII. The work in Paper VIII presents a start-up of the turbine, active power injection to the grid, at rated water velocity, and dynamic performance during a step in water velocity using simulations. In Paper IX the system is tested in the laboratory and the system is used to inject power to the grid and subjected to a step in power to evaluate the dynamic performance.

The electrical system for the grid connection of the marine current energy converter is presented in Figure 6.3. The generator-side converter is an IGBT based, two-level voltage source converter operating in rectifying mode when the system is injecting active power into the grid and in inverting mode during the turbine start-up. The grid side converter is an IGBT based, three-level cascaded H-bridge voltage source converter (3L-CHBVSC) operating in inverting mode when power is injected into the grid and used as an active rectifier during the turbine start-up. This topology is viewed as a good option for connecting one unit and can easily be adapted to a cluster of turbines all connected to the same DC-link. A general structure for cascaded power converters is presented in [72] and a survey of different cascaded H-bridge topologies, control strate-

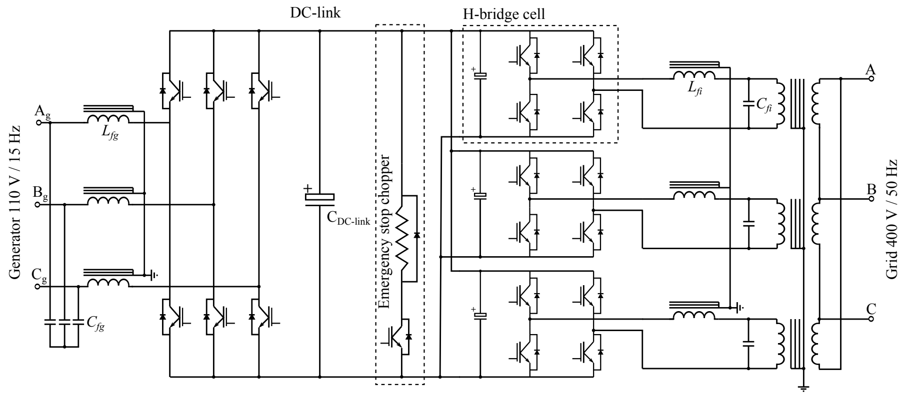


Figure 6.3. The electrical system for the grid connection of the marine current energy converter. An IGBT based two-level converter generator-side with an IGBT based cascaded three-level converter grid-side.

gies and modulation schemes is presented in [73]. The use of multilevel converters brings several advantages such as smaller grid filters, higher efficiency and more sinusoidal voltages and currents among other advantages [74].

Cascaded operation from a single DC-link is achieved with the use of a Star/Delta transformer with the Star side connected to the inverter without a neutral connection as shown in Figure 6.3. This effectively isolates the H-bridges allowing them to operate from the same DC-link. A better utilization of the DC-link is also achieved as the inverter produces phase voltages from the DC-link instead of the usual line-to-line voltage.

There is a harmonics filter of the *LC*-topology after each converter as shown in Figure 6.3. The filters together with the generator winding and transformer winding, respectively, form an LCL-filter and are intended to remove unwanted harmonics and reduce stress on the components as well as reduce the harmonic losses in the generator's windings and core.

An emergency stop chopper is placed on the DC-link to stop the turbine in case of DC-link over-voltage due to grid faults, grid loss and other faults.

Some of the results from the simulations of the systems, presented in Paper VIII, can be seen in Figure 6.4. In Figure 6.4 the system in steady state operation during rated conditions is shown. The results from the other two cases can be found in the Paper VIII. The grid-side and generator-side currents are presented in Figure 6.4a and Figure 6.4b, respectively. There is very little ripple in both sets of currents. The DC-link voltage, Figure 6.4c, is kept steady at the reference level of 400 V with some minor ripple. Figure 6.4d displays the active power injected into the grid. The results are promising for the case shown here and for the two others simulated in the paper and the results are in-line with expectations for the system.

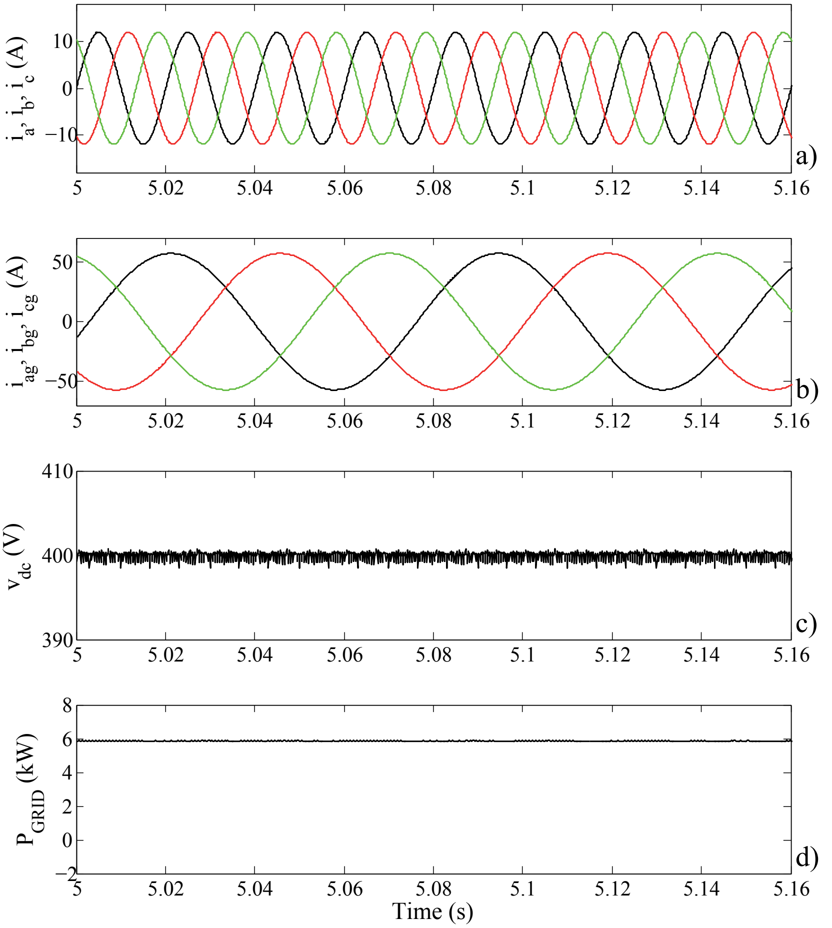


Figure 6.4. Results from the simulations of the grid connection system. a) Grid currents b) Generator currents c) DC voltage d) Active power injected into the grid

6.2.1 Experiments

For the laboratory testing of the system an early prototype of the on-site generator was used. This is the same generator that was used in some of the test in Paper VII. The generators are very similar to each other and information about the design and testing of the first machine can be found in [75,76]. The control system is described in detail in Paper VIII for both the grid side control and the generator side control. The control and measurement system for the grid connection system was implemented on a cRIO platform. The main control loops, measurements, pulse width modulation and grid synchronization are implemented on the FPGA part of the cRIO. This assures that all time-critical implementations are executed correctly. The more computational heavy tasks, as well as data logging, are implemented on the real-time processor part of the cRIO. Voltages and currents before and after the grid connection system are measured, as well as the DC-link voltage. The currents are measured using HAIS-50P current transducers and the voltages are measured using LV 25-P sensors. Everything is logged with a NI9205 module at a rate of 8 kHz per channel.

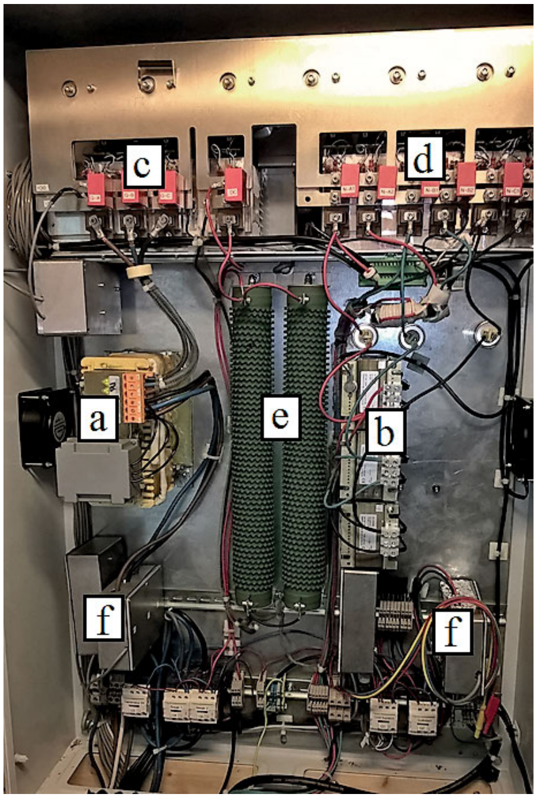


Figure 6.5. The grid connection system for the marine energy converter. a) Generator side filter b) Grid side filter c) Generator side inverter d) Grid side inverter e) Chopper resistors f) Measurements. The control system is in a separate enclosure.

The grid connection system was assembled in the laboratory and is seen in Figure 6.5. The IGBT modules used in both the grid and generator side voltage source converters are of the type 2MBI100TA-060-50 driven by A2SC0108T drivers. The grid side voltage source converter runs at a PWM frequency of 6 kHz and the generator side converter is running at a PWM frequency of 4 kHz.

In Paper IX two cases were tested. We were unable to test the start-up of the turbine as the laboratory generator is connected to a drive train not intended to be driven in reverse. The system was operated at nominal power for several hours to evaluate if the system works properly and a power-step from rated power to no power injected to the grid was done to test the robustness of the system. In Figure 6.6 the system in steady state operation during rated conductions for the prototype generator is shown. The generator currents are presented in Figure 6.6a and the generator voltage with respect to the generator neutral are presented in Figure 6.6b. Both the voltage and current of the generator look satisfactory and behave as expected. The DC-link voltage is shown in Figure 6.6c, the system keeps a steady 400 V during the testing. In Figure 6.6d power to the grid is presented and we can see that the power has a small oscillation. This can be due to several things such as a high level of harmonics in the grid voltage at the connection point or the need for further tuning of the grid side regulators. These issues need to be examined further when the system is moved to the site for final tuning. At this point the system has all needed functionality.

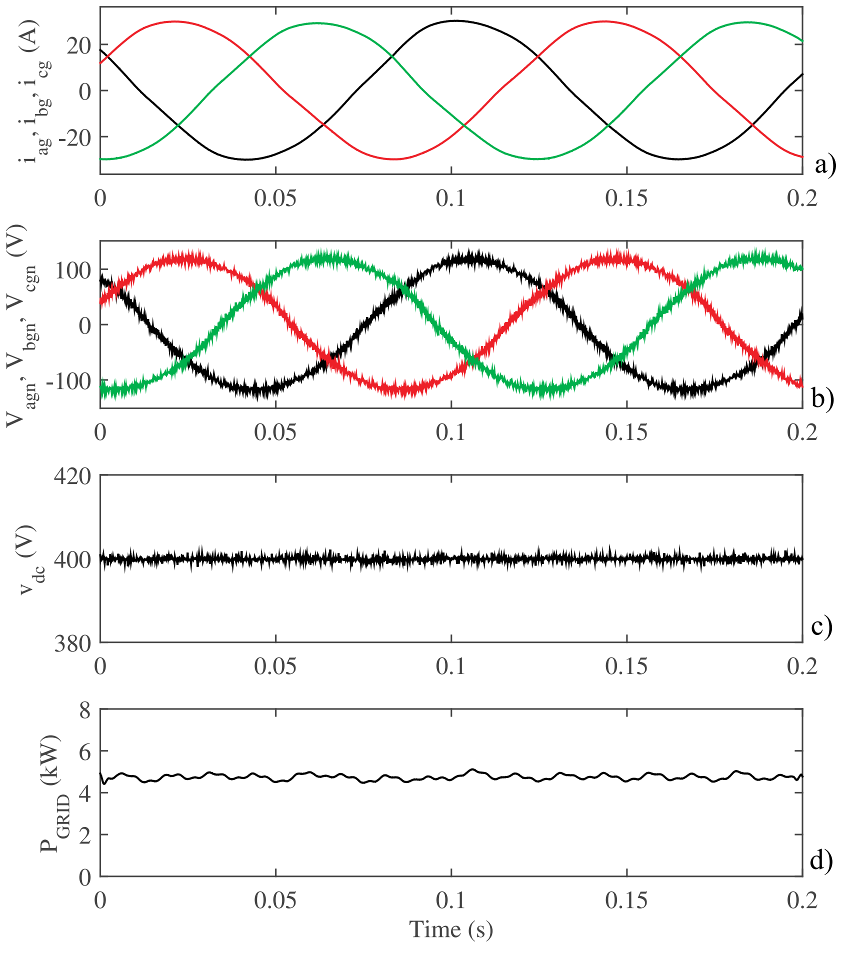


Figure 6.6. Results from the laboratory verifications. (a) Generator side current (b) Generator side voltage with respect to the generator neutral (c) DC-link voltage (d) Active power delivered to the grid.

7. Conclusions

This thesis is based on 18 published papers and the main conclusions from the work are presented here. The body of work can roughly be divided into three main areas by renewable energy source, that is wind power, wave power and marine current power. That grouping is done here for a more concise conclusion. However, it is not necessary to make that distinction as with minor modifications all different grid connection topologies presented can be adapted to each of the renewable energy sources.

Vertical axis wind turbines and their grid connection system is the focus of Papers I - III and XIII, where an innovative solution using a tap transformer based grid connection is discussed and examined. The tap transformer topology has the advantage that no boost converter is needed. This simplifies the system greatly as the only needed active component in the system is the DC/AC converter, potentially increasing efficiency, reducing the maintenance need and failure rate of the system. In the papers, the system is tested in several ways and we can conclude that the system is a viable solution for grid connection. The system harmonics are evaluated and meet the requirements set-up in IEEE 519-1992. The system efficiency is tested and we see that the system has advantages against normal single step-up ratio transformers running from a fluctuating DC voltage.

In papers IV - VI, XIV and XV a grid connection system for wave power is presented. Here the work aids in the development and construction of a unique marine substation for wave power intended to connect a wave energy park to the local grid. The topology of the grid connection system is very similar to that used in the wind power project, that is a tap transformer topology is used with the difference that the LCL-filter is moved to the grid side of the tap transformer. This is done to reduce the size of the filter as the size of the system is an important factor in the submerged substation. In the work the tap transformer is tested and the transformer inrush currents as well as the transformer losses with a direct driven inverter approach are evaluated. The conclusions are that the direct driven approach can almost remove the in-rush current problem by slowly ramping up the voltage. However, the no-load losses of the transformer increase significantly. Thus the transformer might need to be adjusted or a small inductor placed before it to reduce the losses. This can be done without effecting the slow ramp-up of voltage the removes the in-rush current problems. The functionally of the marine substation is also tested and it is concluded that it is ready for deployment at the research site with all systems working as expected and after successful grid operation in the laboratory.

In papers VII-IX, XI and XII the marine current energy converter system is in focus. The deployment of the machine is covered as well as the first tests from the research site. A first control system is built and was shown that it successfully can control the turbine from start-up to power deliver as well as to monitor the outputs. In papers VIII and IX a grid connection system for the marine current energy converter is presented and evaluated using simulations and experiments. The system is differs from the tap transformer topology and instead increases the complexity by introducing a multi-level converter to improve the system efficiency and reduce its size. Here a three-level cascaded voltage source converter is used grid side to connect the system to the grid. The full system including control and measurement systems are designed, developed, implemented and verified. The system has a better utilization of the DC voltage than a regular two-level grid connection topology and by having a fixed DC-voltage the system also utilizes the DC-link capacitors more efficiently. The better utilization of the DC voltage also implies a lower output current from the system as a direct consequence of the higher output AC voltages at the same power rating. This further reduces the size of the system. The work concludes that this is a viable system for the grid connection of the marine energy converter and it is ready for installation at the research site.

Overall the thesis looks at grid connection of different renewable energy sources and shows that there is still room for innovation and improvements on the existing commercial systems.

8. Future Work

An interesting topic would be to do a reliability, availability and maintenance study for the different power electronic topologies presented in this thesis. The study would start off with designing and dimensioning each topology for the same energy converter, for example a 1 MW VAWT or a 1 MW farm of wave energy converters. Looking at how the volume and size of each topology scales with increasing power rating would also be an interesting study.

In the marine current power project, a likely next step is to connect the marine current energy convert to the grid using the 2L-3L grid connection system and to collect long-term data on the operation of the full system. Before this is done the system needs to be integrated with the on-site systems.

In the case of the marine substation for wave power the next step is to grid connect a wave power farm and start gathering and evaluating data from the different parts of the farm.

9. Svensk Sammanfattning

Förnybar energi är energi som kommer från källor som naturligt förnyas i en snabb takt. Några allmänt kända källor är solljus, vatten, vind, tidvatten, jordvärme och olika former av biomassa. Satsningen på förnybar energi har under de senaste decennierna intensifierats kraftigt. Några av de drivande faktorerna för den starka utvecklingen har varit den minskande tillgången på fossila bränslen, föroreningar, global uppvärmning och en stadigt ökande efterfrågan på energi. Denna avhandling bidrar till forskningen inom förnyelsebara energikällor genom att bidra till teknikutvecklingen inom området med fokus på kraftelektronik. Arbetet är gjort inom den forskning som görs i vindkraft, vågkraft och marin strömkraft vid avdelningen för elektricitetslära, Uppsala Universitet.

En gemensam utmaning för användandet av dessa energikällor är att spänningen från systemet varierar i både frekvens och amplitud. Denna typ av spänning kan inte anslutas direkt till elnätet utan behöver omvandlas med hjälp av ett elektriskt konverteringssteg. Denna avhandling jobbar med att utveckla och förbättra detta konverteringssteg som gör det möjligt att ansluta förnyelsebara energikällor så som vindkraft, vågkraft och marin strömkraft till elnätet. Bidraget har gjorts genom 18 publikationer som tittar på olika aspekter i konverteringssteget och utvärderar lösningar genom simuleringar och experiment.

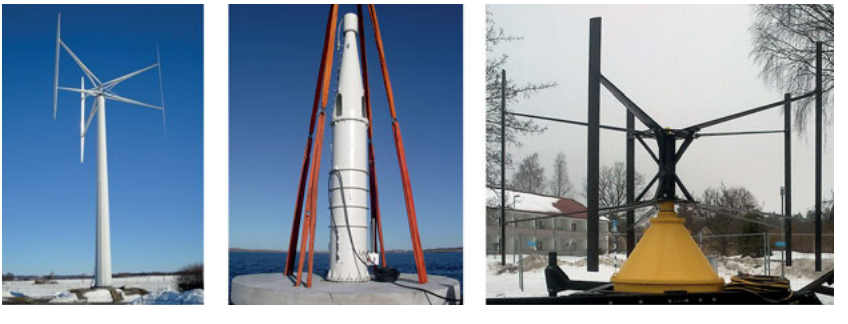


Figure 9.1. Tre olika kraftverk som har utvecklats vid avdelningen för elektricitetslära vid Uppsala Universitet. Från vänster, vertikalaxlat vindkraftverk i Falkenberg, vågkraftverk i Lysekil, vertikalaxlat marint strömkraftverk i Söderfors.

Inom vindkraft jobbar vi på Uppsala Universitet med att utveckla en robust storskalig teknik med en vertikalaxlad vindturbin i fokus. Den största skillnaden mot konventionella vindkraftverk är att vindkraftverkets blad roterar kring en vertikal axel istället för de konventionella vindkraftverken där bladen roterar horisontellt. Detta koncept medför flera fördelar bland annat kan generatorn placeras på marken vilket potentiellt gör det enklare och billigare att bygga och underhålla generatorn. Andra fördelar med en vertikalaxlad turbin är att den kan absorbera vind från alla riktningar och inte behöver vridas in i vinden som de konventionella vindkraftverken. Systemet är även direktdrivet vilket innebär att man tar bort växellådan som i vanliga fall ansluter turbinen till generatorn. Detta gör att man inte behöver underhålla växellådan och kan därmed undvika de förluster som förknippas med den. I Figure 9.1 kan man se de olika kraftverken som har utvecklats vid avdelningen för elektricitetslära. Det vänstra kraftverket i bilden är ett vertikalaxlat vindkraftverk på 200 kW som är installerat i Falkenberg.

I mitten på Figure 9.1 kan man se ett vågkraftverk som har utvecklats inom vårt vågkraftsprojekt. Vågkraft är en förnyelsebar energikälla med enorm potential och många utmaningar. Vågkraft kan på sikt komma att stå för en stor andel av den globala energikonsumtionen och det finns idag många pågående projekt världen över som försöker utveckla en fungerande teknik för att omvandla energin. Vid Uppsala Universitet har vi forskat inom området under en lång tid och vi är en utav de ledande forskningsgrupperna inom området. Huvudspåret har varit att utveckla en robust teknik som är mekaniskt enkel med få rörliga delar. Det koncept man använder sig av består av en boj vid havsytan och en linjärgenerator som placeras på havsbotten. Bojen är kopplad till generatorn via en lina och rör sig med vågorna. Denna rörelse flyttar då translatorn i generatorn och gör det möjligt att omvandla energin i vågorna till elektricitet.

Det sista kraftverket i Figure 9.1 är ett marint strömkraftverk och syns till höger i bilden. Marina strömmar, d.v.s strömmar i älvar och hav, utgör en stor energiresurs och kan komma att bidra till den globala energiproduktionen. Vid avdelningen för elektricitetslära har vi under en längre tid arbetet med ett koncept för att utvinna energi från strömmande vatten som bygger på en vertikalaxlad turbin som är direktkopplad till en generator, likt vårt vindkraftsprojekt i uppbygganden men placerat under vattenytan. Under de senaste åren har en första prototyp av ett kraftverk installerats i Dalälven vid staden Söderfors norr om Uppsala. Söderforsanläggningen har som mål att testa en hel anläggning från strömmande vatten till elnätet, i en realistisk miljö.

Inom vindkraften och vågkraften har arbetet fokuserat på en tapptransformatorbaserad nätanslutning, där de olika tapparna på transformatorn tillsammans med en omriktare används för att hantera variationerna i spänning. Genom att använda en tapptransformator behöver man inte använda sig utav en DC/DC-omvandlare eller annat konverteringsssteg som höjer DC-spänningen. Detta gör att systemet blir enklare och behöver färre aktiva komponenter. I Artiklar I-III och X, XIII är vindkraftsprojektet i fokus.

I vågkraften har arbetet i avhandlingen bidragit till utvecklingen av ett marint ställverk som ska användas för att ansluta en vågkraftspark i Lysekil till det lokala elnätet. Här har hela systemet från generator till elnät testats och utvärderats i labbet. Resultaten är lovande och systemet är redo för att sjösättas. Artiklarna IV-VI, XIV-XVI presenterar olika delar inom vågkraftsprojektet.

Inom marin strömkraft har arbetet bidragit till utvecklingen av ett första kontroll och styrsystem för kraftverket. Detta system användes för att göra de första testerna efter installation av turbinen i Dalälven. I avhandlingen presenteras även ett nätanslutningssystem för det marina strömkraftverket som bygger på en flernivåomriktare. Systemet är konstruerat och testat i labbet och klart för installation i Söderfors. Artiklar VII-IX, XI, XII fokuserar på det marina strömkraftverket.

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With Best Regards
Senad Apelfröjd

11. Summary of Papers

In the following text the papers presented in this thesis are summarized and the authors contribution is presented. A common contribution from the author to all articles is the discussion and the involvement in the planning stage of each paper.

Paper I

System Efficiency of a Tap Transformer Based Grid Connection Topology Applied on a Direct Driven Generator for Wind Power

Results from experiments on a tap transformer based grid connection system for a variable speed vertical axis wind turbine are presented. Simulations using MATLAB/Simulink have been performed in order to study the behaviour of the system. A full experimental set-up of the system has been used in the laboratory, where a clone of the on-site generator was driven by an induction motor with the system connected to a resistive load to better evaluate the performance. Furthermore, the system is run and evaluated at variable speed operation and realistic wind speeds. The results show high system efficiency at nominal power and an increase in overall power output for full tap operation in comparison with the base case; a standard transformer. In addition, the loss distribution at different wind speeds is shown, which highlights the dominant losses at low and high wind speeds. Finally, means for further increasing the overall system efficiency are proposed.

This paper is published in *The Scientific World Journal*, vol. 2014, Article ID 784295, 7 pages, 2014. doi: 10.1155/2014/784295.

The author did the majority of the work.

Paper II

Evaluation of Harmonic Content from a Tap Transformer Based Grid Connection System for Wind Power

The total harmonic distortion (THD) and total demand distortion (TDD) of a tap transformer based grid connection system for a vertical axis wind turbine (VAWT) with a permanent magnet synchronous generator (PMSG) is evaluated and discussed for variable speed operation. The full variable speed operation is enabled by the use of the different step-up ratios of the tap transformer. In the laboratory study a full experimental set-up of the system was used, a clone of the on-site PMSG driven by a motor was used and the grid was replaced with a resistive load. With a resistive load, grid harmonics and possible unbalances are removed. The results show a TDD and THD below 5% for the full operating range and harmonic values within the limitations set up by IEEE-519. Furthermore, a change in tap, going to a lower step-up ratio, results in a reduction in both THD and TDD for the same output power.

The paper is published in the *Journal of Renewable Energy*, vol. 2013, Article ID 190573, 8 pages, 2013. doi: 10.1155/2013/190573.

The author did the majority of the work.

Paper III

A Review of Research on Large Scale Modern Vertical Axis Wind Turbines at Uppsala University

This paper presents a review of over a decade of research on Vertical Axis Wind Turbines (VAWTs) conducted at Uppsala University. The paper presents, among others, an overview of the 200 kW VAWT located in Falkenberg, Sweden, as well as a description of the work done on the 12 kW prototype VAWT in Marsta, Sweden. Several key aspects have been tested and successfully demonstrated at our two experimental research sites. The effort of the VAWT research has been aimed at developing a robust large scale VAWT technology based on an electrical control system with a direct driven energy converter. This approach allows for a simplification where most or all of the control of the turbines can be managed by the electrical converter system, reducing investment cost and need for maintenance. The concept features an H-rotor that is omnidirectional in regards to wind direction, meaning that it can extract energy from all wind directions without the need for a yaw system. The turbine is connected to a direct driven permanent magnet synchronous generator (PMSG), located at ground level, that is specifically developed to control and extract power from the turbine. The research is ongoing and aims for a multi-megawatt VAWT in the near future.

The paper is published in *Energies*, vol. 9, no. 7, p. 570, Jul. 2016. doi: 10.3390/en9070570.

The author did the majority of the work.

Paper IV

Transformer Magnetization Losses Using a Non-filtered Voltage-Source Inverter

Results from the magnetization of an 80 kVA power transformer, using a directly coupled non-filtered three-phase voltage-source inverter VSI, are presented. The major benefits of this topology are reduction in switching filter size as well as filter losses. Drawbacks include higher stress on the transformer windings and higher transformer magnetization losses. In this article, the total magnetization losses are presented for different voltage levels. The transformer has been magnetized with rated frequency of 50 Hz at various voltage levels. The saturation characteristics as well as the magnetizing resistance are derived as functions of the voltage. These are used as inputs to the simulation model of the system. The magnetization losses have then been experimentally measured and simulated for three different DC-levels with variations in the amplitude modulation index. The results from the simulation model show good agreement with the experimental results. The pulsed voltage waveforms generates larger magnetization losses than the corresponding 50 Hz case. The losses are strongly dependent on the selected DC-level.

The paper is published in *Advances in Power Electronics*, vol. 2013, Article ID 261959, 7 pages, 2013. doi: 10.1155/2013/261959.

The author did the MATLAB/Simulink simulations and assisted with hardware implementation and inverter design.

Paper V

Transformer Magnetizing Inrush Currents Using a Directly Coupled Voltage-source Inverter

The connection of a power transformer to the grid is associated with magnetizing inrush currents that may result in power quality issues as well as faulty relay tripping. In distributed generation, the transformer may instead be premagnetized from the source to avoid this. In this paper, a VSI is directly coupled to a transformer. Three different strategies of premagnetization are implemented into the control system, and the inrush currents are measured for various values of the remanent flux in the core. The results show good reduction in the peak magnetizing inrush currents without using any external circuitry.

The paper is published in *ISRN Electronics*, vol. 2013, Article ID 361643, 8 pages, 2013. doi: 10.1155/2013/361643.

The author assisted in the experimental work, hardware implementation and inverter design.

Paper VI

Experimental Verifications of Offshore Marine Substation for Grid-connection of Wave Energy Farm

An offshore marine substation has been designed and constructed for grid-connection of a wave energy farm. The substation will be deployed 2 km off the Swedish West coast, on the seabed at a depth of 25 m. Before the deployment, the substation electrical circuit has been tested in the laboratory. The functionality and total substation efficiency have been evaluated at different voltage levels. A synchronous generator with variable speed control has been programmed to generate a similar voltage output as a single wave energy converter. The generator output has been connected to the substation and power transferred to the local grid at unity power factor. The impact on the total efficiency by adding a DC/DC boost converter is also discussed. The conducted experiments verify the functionality of the marine substation before deployment.

The paper was presented at the *Electric Power and Energy Conversion Systems (EPECS) by Ekström R., 2013 3rd International Conference on*, Istanbul, 2013, pp. 1-6. doi: 10.1109/EPECS.2013.6712994.

The author assisted in the experimental work, hardware implementation and inverter design.

Paper VII

Implementation of Control System for Hydrokinetic Energy Converter

A system for converting the power in freely flowing water using a vertical axis turbine directly connected to a permanent-magnet generator is investigated. An experimental setup comprising a turbine, a generator, and a control system has been constructed and will be deployed in the Dalälven river in the town of Söderfors in Sweden. The design, construction, simulations and laboratory tests of the control system are presented in this paper. The control system includes a start-up sequence for the turbine, and load control. These functions have performed satisfactorily in laboratory tests. Simulations of the system show that the power output is not maximized at the same tip-speed-ratio as that which maximizes the turbine power capture.

The paper is published in *Journal of Control Science and Engineering*, vol. 2013, Article ID 342949, 10 pages, 2013. doi: 10.1155/2013/342949.

The author had an integral roll in the overall system design as well as designed and constructed the power electronics and measurement hardware.

Paper VIII

A Back-to-Back 2L-3L Grid Integration of a Marine Current Energy Converter

The paper proposes a back-to-back 2L-3L grid connection topology for a marine current energy converter. A prototype marine current energy converter has been deployed by a research group at Uppsala University. The concept behind the prototype revolves around a fixed pitch vertical axis turbine directly connected to a permanent magnet synchronous generator (PMSG). The proposed grid connection system utilizes a well known and proven two level voltage source converter generator-side combined with a three-level cascaded H-bridge (CHB) multilevel converter grid-side. The multilevel converter brings benefits in terms of efficiency, power quality and DC-link utilization. The system is here presented for a single marine current energy converter but can easily be scaled up for clusters of marine current energy converters. Control schemes for both grid-side and generator-side voltage source converters are presented. The start-up, steady state and dynamic performance of the marine current energy converter are investigated and simulation results are presented in this paper.

The paper is published in *Energies*, vol. 8, no. 2, pp. 808-820, Jan. 2015. doi: 10.3390/en8020808.

The author did the majority of the work.

Paper IX

Experimental Verification of a Back-to-Back 2L-3L Grid Connection System for a Marine Current Energy Converter

Rivers, tides and other ocean currents are renewable energy sources with great potential across the globe. A research group at Uppsala University is working on converting the power in rivers and ocean tides using a vertical axis turbine with a directly driven permanent magnet generator. The concept in focus uses an omnidirectional, fixed pitch vertical axis turbine directly connected to a permanent magnet generator. Few moving parts and an overall low mechanical complexity is the main idea behind the concept. A first full prototype was deployed in 2013 in the river Dalälven in the town of Söderfors. The work presented here is a step towards grid connection of the marine current energy converter prototype. A back-to-back 2L-3L grid connection topology has been proposed. The system is adapted to the scaled prototype but is intended for larger turbines. The proposed grid connection system utilizes a three-level cascaded H-Bridge voltage source converter (3L-CHBVSC) on the grid side together with a well know two-level voltage source converter on the generator side. The use of a multilevel converter brings several advantages such as higher efficiency, more sinusoidal voltages and currents and smaller grid filters among other advantages. The proposed grid connection system has been constructed in the laboratory. The work presented here aims to evaluate the system in the laboratory. A synchronous generator with a very similar design to the on-site generator is used for the tests. The generator, driven by an induction motor, is connected to the system and power is successfully transferred to the grid. The conducted tests are used to verify the functionality of the system before installation at the research site.

The paper was presented by Apelfröjd S., oral presentation, at the *2nd International Conference on Offshore Renewable Energy (CORE2016)*, Glasgow, UK, Sep. 2016. In Proceedings of, pp. 294-299.

The author did the majority of the work.

Paper X

Evaluation of a Blade Force Measurement System for a Vertical Axis Wind Turbine Using Load Cells

Unique blade force measurements on an open site straight-bladed vertical axis wind turbine have been performed. This paper presents a method for measuring the tangential and normal forces on a 12-kW vertical axis wind turbine prototype with a three-bladed H-rotor. Four single-axis load cells were installed in-between the hub and the support arms on one of the blades. The experimental setup, the measurement principle, together with the necessary control and measurement system are described. The maximum errors of the forces and accompanying weather data that can be obtained with the system are carefully estimated. Measured forces from the four load cells are presented, as well as the normal and tangential forces derived from them and a comparison with theoretical data. The measured torque and bending moment are also provided. The influence of the load cells on the turbine dynamics has also been evaluated. For the aerodynamic normal force, the system provides periodic data in agreement with simulations. Unexpected mechanical oscillations are present in the tangential force, introduced by the turbine dynamics. The measurement errors are of an acceptable size and often depend on the measured variable. Equations are presented for the calculation of measurement errors.

The paper is published in *Energies*, vol. 8, no. 6, pp. 5973-5996, Jun. 2015 doi:10.3390/en8065973.

The author assisted in the planning and design of the load cell setup and measurement system.

Paper XI

Efficiency of a Directly Driven Generator for Hydrokinetic Energy Conversion

An experimental setup for hydrokinetic energy conversion comprising a vertical axis turbine, a directly driven permanent magnet generator, and a control system has been designed and constructed for deployment in the river Dalälven in Sweden. This paper is devoted to discussing the mechanical and electrical design of the generator used in the experimental setup. The generator housing is designed to be water tight, and it also acts as a support structure for the turbine shaft. The generator efficiency has been measured in the range of 5-16.7 rpm, showing that operation in the low velocity range up to 1.5 m/s is possible with a directly driven generator.

The paper is published in *Advances in Mechanical Engineering* Jan.-Dec. 2013 5: 978140, Oct. 10, 2013 doi:10.1155/2013/97814.

The author assisted in the experimental work.

Paper XII

The Söderfors Project: Experimental Hydrokinetic Power Station Deployment and First Results

The Division of Electricity at Uppsala University recently deployed an experimental hydrokinetic power station for in-stream experiments at a site in a river. This paper briefly describes the deployment process and reports some initial results from measurements made at the test site.

The paper was presented by Lundin S. at the *10th European Wave and Tidal Conference (EWTEC)*, Aalborg, Denmark, 2013.

The author assisted in the installation and development of the hardware.

Paper XIII

Laboratory Verification of System for Grid Connection of a 12 kW Variable Speed Wind Turbine With a Permanent Magnet Synchronous Generator

In this paper the first laboratory tests of the grid connection system, connected to a resistive load, for a vertical axis wind turbine with a permanent magnet generator are presented. The system is based on a tap-transformer topology with a voltage source inverter. The harmonic content of the current from the experiments and simulations done in Simulink using the LCL-filter and the different taps on the transformer is shown. The simulated currents, fed to the resistive load, had a total harmonic distortion, THD, of 0.5% to 0.9% for the different taps. The experimental set-up hade a current THD ranging from 1.8% to 2.7%. The difference is expected to be due to unbalances, delays and dead times in the experimental set-up as the major THD contribution is from harmonic orders below 11. The results show that a LCL filter can be designed to meet the demands on power quality for grid connection of the system with all the taps of the tap transformer in accordance with IEEE 519-1992.

The paper was presented by Apelfröjd S., poster presentation, at the *EWEA 2012 Annual Event*, Copenhagen, Denmark, April, 2012, In Proceedings of.

The author did the majority of the work.

Paper XIV

Evaluation of Damping Strategies for Maximum Power Extraction From a Wave Energy Converter with a Linear Generator

In this paper a point-absorber concept with a permanent magnet linear generator placed on the seabed is in focus. The study looks at different electrical damping strategies to maximize the power absorbed from the waves. The strategies are evaluated using simulations and measurements done on a deployed generator during sea trials. Passive rectification is compared to a resonance circuit topology and an active front end converter. The strategies are evaluated based on maximum average power output. System complexity and cost are also discussed. The results show that the active front end converter with a resistive modulation gives the highest output power but has the most complex implementation.

The paper was presented by Apelfröjd S., poster presentation, at the *Grand Renewable Energy Conference on Energy Network and Power Electronics*, Tokyo, Japan, 2014.

The author did the majority of the work.

Paper XV

Inverter Topology with Integrated On-Load Tap Change for Grid-Connection of Renewable Electric Energy Sources

The intermittent characteristics of many renewable energy sources results in that the grid-connected power electronics conversion system often will operate at partial rating, and thus lower efficiency. Also, maximum power extraction requires the system to run within a range of voltages, making it harder to optimize. In this paper, a topology with two voltage-source inverters and a tap transformer is suggested for grid-connection of intermittent energy sources. The modular design allows for the system to operate at higher efficiency for partial rating, and decreases the downtime in case of semiconductor failures. Fast on-load tap change is possible, without any external circuitry. The tap changing process is described for two taps, but can be extended to any number of taps. Initial results for the topology are presented in this paper.

The paper was presented by Ekström R. at the *Grand Renewable Energy Conference on Energy Network and Power Electronics*, Tokyo, Japan, 2014.

The author assisted in the experimental work, hardware implementation and inverter design.

Paper XVI

Wireless System for Tidal Effect Compensation in the Lysekil Research Site

This paper describes, firstly, the rope adjustment device for wave energy converters (WECs) to minimize the tidal effect on the electricity production and, secondly, a wireless communication network between point absorbing WECs in the Lysekil Research Site and a computer station at the Department of Engineering Sciences at Uppsala University. The device is driven by a motor that activates when the main water level deviates from the average. The adjustment is achieved through a screw that moves upwards during low tides and downwards during high tides. For the purpose of testing the device in the research site, a wireless connection between the buoy in the sea and a computer on land will be designed. A sensor located close to the research site monitors the sea water level and, every time a significant variation is registered, it sends wireless signals to the data logger that controls the power to the motor. The position of the screw is observed by a second sensor and the measurements are retrieved back to Uppsala via GSM connection. The full scale device is tested in the lab and it is demonstrated to work properly, requiring less than 750 W to lift and lower different loads. Moreover, the wireless communication network is designed and once it will be built, it will allow to recall and store data, send information from one node of the system to another, monitor the proper functioning of the device and modify the control as desired.

The paper was presented by Castellucci V. at the *31st International Conference on Ocean, Offshore and Arctic Engineering,* vol. 7, pp. 293-298. July 1-6, 2012.

The author assisted with the power electronics in the project.

Paper XVII

Electrical Motor Drivelines in Commercial All-Electric Vehicles: A Review

This paper presents a critical review of the drivelines in all-electric vehicles (EVs). The motor topologies that are the best candidates to be used in EVs are presented. The advantages and disadvantages of each electric motor type are discussed from a system perspective. A survey of the electric motors used in commercial EVs is presented. The survey shows that car manufacturers are very conservative when it comes to introducing new technologies. Most of the EVs on the market mount a single induction or permanent-magnet (PM) motor with a traditional mechanic driveline with a differential. This paper illustrates that comparisons between the different motors are difficult by the large number of parameters and the lack of a recommended test scheme. The authors propose that a standardized drive cycle be used to test and compare motors.

The paper is published in *IEEE Transactions on Vehicular Technology*, vol.

61, no. 2, pp. 475-484, Feb. 2012. doi: 10.1109/TVT.2011.2177873

The author assisted in the information gathering for the review paper.

Paper XVIII

On a Two Pole Motor for Electric Propulsion System

Recent development of "All Electric Vehicle" and "All Electric Propulsion System" has been devoted to four, six and eight pole electric machines. This has primarily been due to existing technology and existing trends. In the present paper we present results from a high speed permanent magnet two pole machine with variable frequency, which can have an impact of the whole electric propulsion system .The simulation results indicate an improvement on the working efficiency and facilitate on the mechanical design. The design can thereby offer a more sustainable and cost-effective electric motors in the range of 20 kW to 1 MW used in electric propulsion systems. The first prototype is constructed and initial experiments with the rotating motor and its control system has been performed.

The paper is published in the *International Journal of Engineering Science and Innovative Technology (IJESIT)*, vol. 2, no. 1, pp. 99-111, Jan. 2013.

The author assisted in the information gathering on the previous work done in the area.

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