Laboratory Experimental Verification of a Marine Substation

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Abstract

Wave energy is a renewable energy source with vast potential, which could make significant contribution to world electricity demand in the future. In this paper, a way to electrically interconnect wave energy converters into a farm is described. Measurements of voltage and current wave forms in the interconnection of two PM synchronous machines on the common DC-bus of a marine substation are compared with simulations in MATLAB Simulink. It is demonstrated how the generators intermittently deliver power to the common DC-busbar and how the power, after rectification and filtering of the voltage, is continuously extracted in a resistive load. A unique feature of the variable frequency substation at hand is that it will be located on the seabed.

At the Lysekil Research site, were the marine substation will be installed, the DC-bus voltage will be actively controlled by means of an inverter. This will change the damping and hence the absorption width of the linear generator-based WECs that are connected to the substation. The experiments carried out here demonstrate the principle of operation and verifies that the system works as expected.

Keywords: Marine substation, permanent magnet linear generator, experimental verification.

1 Introduction

Unexploited renewable energy sources, such as wave power, have for many years been known to have a vast potential. Estimates show an extractable potential for wave energy in the order of 10 000 TWh (or annual mean power of roughly 1 TW, 10^{12} W) along the coastlines of the world [1]. This could make significant contribution to world electricity demand in the future. The physical wave resource is an order of magnitude larger, 10 TW [1].

Many suggestions of solutions to the issue of power smoothing from wave energy converters (WEC) have been made during the years of active wave energy development. A number of solutions can be found in [2]. High-pressure gas accumulators in oil hydraulic systems are frequently suggested as energy storage mechanism in several different WEC concepts. Over-topping devices store energy as potential energy in its reservoir from which the water spills back into the ocean via axial- or cross-flow hydropower turbines. In an oscillating water column, partial power smoothing is sometimes achieved via a mechanical flywheel on the turbine shaft. The practical implementation of another way to achieve power smoothing is presented in this paper.

A. Scope of Paper

In this paper, voltage and current wave forms in the interconnection of two direct-driven, permanent magnet synchronous generators (PMSG) on a common DC-bus are simulated using MATLAB Simulink. To verify that the built system works according to expectations, measurements taken in a laboratory experimental set-up are compared with the simulation results. The functionality of the experimental set-up resembles, to reasonable extent, the rectification, interconnection and filtering of power from direct-driven offshore WECs interconnected to a marine substation. Here, the main circuit of the substation is tested. The functionality of the marine substation is explained in detail below in *Experimental Set-up*. The aim is to experimentally validate the feasibility of intermittently delivering power to the common DC-bus and subsequently smooth the DC-voltage before power is continuously extracted from the DC-bus by means of an inverter.

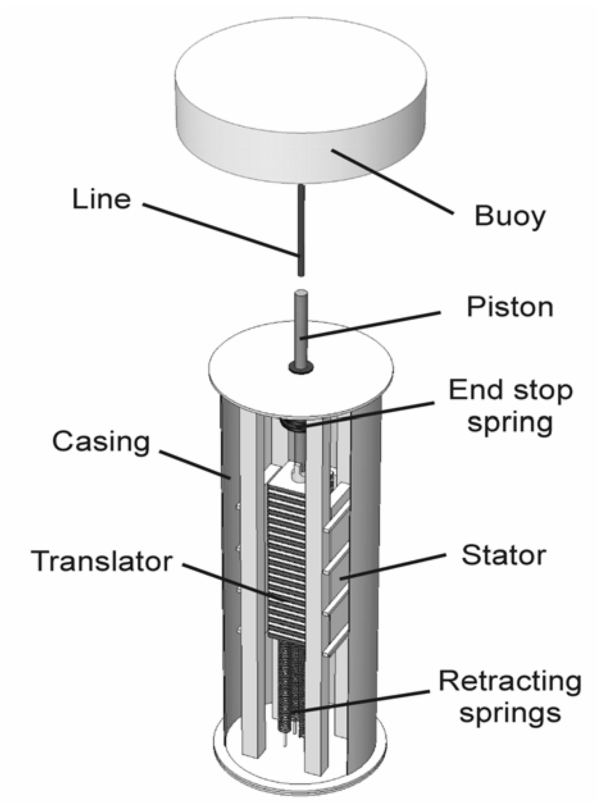

Figure 1. Illustration of WEC concept.

Figure 2. The location of the Lysekil research site.

A. Background

The WEC concept, for which the marine substation of the present study is designed, is based on a directly driven permanent magnet linear generator, located on the seabed, with a point absorbing buoy on the ocean surface. Fig 1 illustrates how the cylindrically shaped buoy is connected to the moving part of the linear generator, the translator, via a line and a piston. The piston leads through the casing and thus prevents seawater from interacting with the electromechanical parts of the linear generator. The buoy moves in a heaving motion as it pulls the translator upwards. In large waves, an end stop spring, visible in the top of the linear generator casing in Fig. 1, decelerate the mass of the buoy and translator near the upper turning point to lower the stress on the line. A set of retracting springs act together with gravity to pull the buoy and translator downward in wave troughs. A first prototype, rated 10 kW, was deployed in March of 2006 and has, at the time of writing, been in operation for a total of more than 12 months. Results from offshore operation are found in [3]-[7].

	Marine current generator	Wind power generator	WEC Linear generator
Power	5 kW	12 kW	10 kW
Voltage, line-to-line	150 V	280 V	200 V
Rotational Speed	10 rpm	127 rpm	
Speed in air gap	0.96 m/s	5.0 m/s	0,67 m/s
Electrical frequency	10 Hz	33.9 Hz	6.7 Hz
Phase resistance	0.475 ohm	0.151 ohm	0.44 ohm
Phase inductance	11.5 mH	0.106 mH	5.2 mH
Inner diameter of stator	1835 mm	760 mm	-
Permanent magnet material	Nd-Fe-B	Nd-Fe-B	Nd-Fe-B
Permanent magnet thickness	13 mm	14 mm	6.5 mm
Air gap width	10.5 mm	10 mm	3 mm
Machine length	270 mm	222 mm	-
Number of poles	120	32	-
No. of stator sides	-	-	4
Pole width	-	-	50 mm
Stator side stack length	-	-	400 mm
Vertical stator length	-	-	1250 mm
Vertical translator length	-	-	1850 mm
Free translator stroke length	-	-	1800 mm

Table 1: Nominal generator ratings.

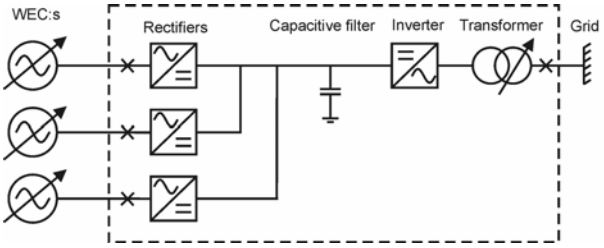

Fig. 3. The main circuit of the substation. The dashed rectangle indicates what is included in the substation.

A substation will be installed at the Lysekil research site. At present, two prototypes similar to the first prototype, described above, have been deployed awaiting the installation of the marine substation. Fig. 2 shows the location of the Lysekil research site some 100 km northwest of Gothenburg.

The choice of technical solutions for the concept results in a direct coupling of the motion of the buoy to the generation of electricity. The WEC has few moving mechanical components to reduce mechanical losses, reduce the need for maintenance and to increase the survivability. Electricity is produced in bursts of varying electrical frequency and voltage amplitude. The voltage from each WEC will therefore be rectified and the power added together with the power from other WECs in a marine substation. The power will be smoothened and the voltage inverted to 50 Hz AC before transformation to a more suitable transmission voltage, which in this case will be 1 kV (line-to-line). A one-line diagram of the substation main circuit is shown in Fig. 3.

The substation is equipped with National Instruments FPGA-based PAC computers for data acquisition (DAQ) and control of power output and circuit breakers. A battery pack feeds the DAQ system and control equipment, power inverter, sensors and circuit breakers. Recharging of the auxiliary battery system will be made by feeding power from the substation main circuit.

The substation presented here will: (1) connect three offshore wave energy converters in an offshore location, (2) directly interconnect generating units that operate at varying voltage amplitude and varying electrical frequency, and (3) be located on the seabed, well below the ocean surface, as opposed to e.g. offshore substations for wind farms that are usually located on platforms above sea level [8]. In addition, in the application with three wave energy converters being interconnected offshore, input power will be delivered intermittently on the time frame of seconds while output power is anticipated to be significantly smoothened. The power fluctuation on the input is due to that the WECs will produce power in bursts as the translator of each linear generator is directly coupled with the motion of the waves. Moreover, no power is produced from a WEC when its translator is at standstill, which e.g. occurs when the translator reaches its upper or lower turning point. Additionally, no power

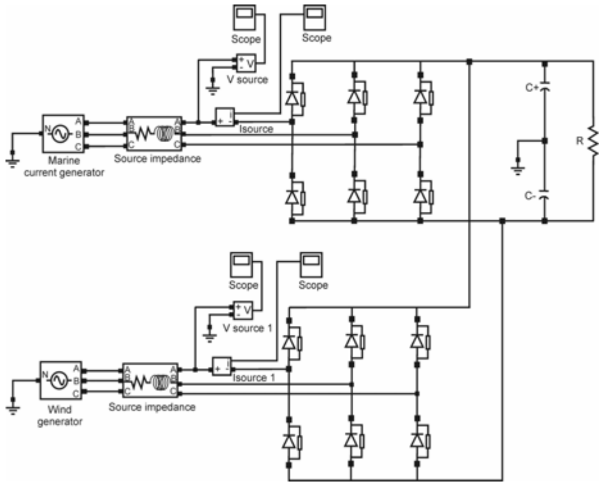

Figure 4. The MATLAB Simulink model.

is extracted from a WEC as long as the amplitude of the voltage from the linear generator is lower than the DC voltage of the substation intermediate DC-stage. This phenomenon is explained in more detail in the *Results* section and analyzed in the *Discussion*.

B. Design choices

In the design, passive diode rectifiers were chosen to reduce complexity. Active rectifiers are often suggested in place of the passive diode rectifiers that the authors have chosen to use so far. However, an active (e.g. thyristor- or IGBT-based) bridge rectifier requires six control signals, one for each semiconductor of the three-phase bridge rectifier. It also requires some input to the controller. In this design, there is really no need to use active rectifiers since the WECs are interconnected to the same DC-bus. Moreover, the WECs will experience the same sea states since they are positioned in the vicinity of each other at the Lysekil Research Site. The optimal damping of one WEC will hence be the same as for the others taken that the same buoy size is used on all three WECs. Optimization of wave energy to electric energy can be implemented using the common inverter of the marine substation.

The choice to design an underwater substation, instead of a platform substation above sea level, was made to make it possible to apply the same solution to future WEC farms installed at greater depths than the present 25 m. Platforms, unless floating, would be difficult to implement at depths of e.g. 150 m. To protect a platform substation from the impact of large waves the platform would have to be elevated from sea level by approximately 10-15 m. The supporting structure would also have to be relatively large to withstand the 50-year and 100-year wave. At the seabed, the environment is stable with low ambient temperatures suitable for cooling of electrical components.

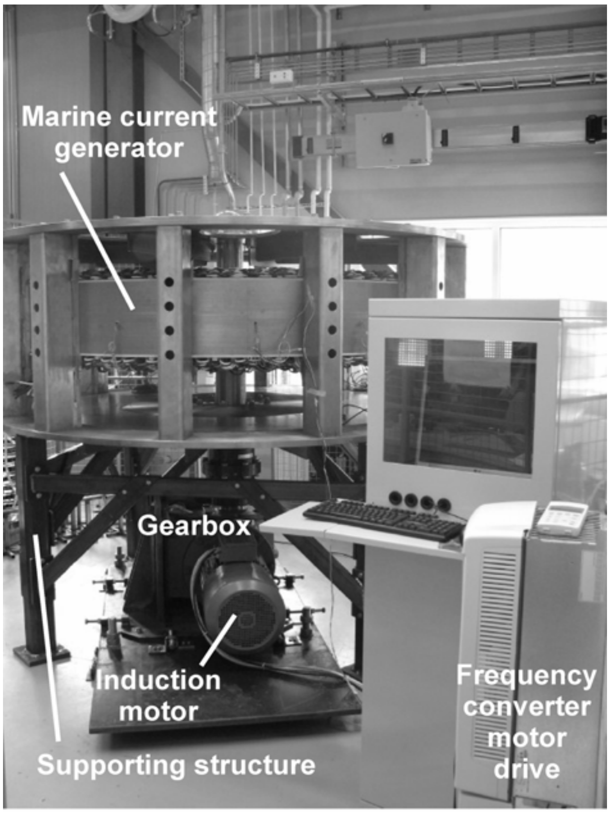

Figure 5. The motor-generator set-up of the marine current generator.

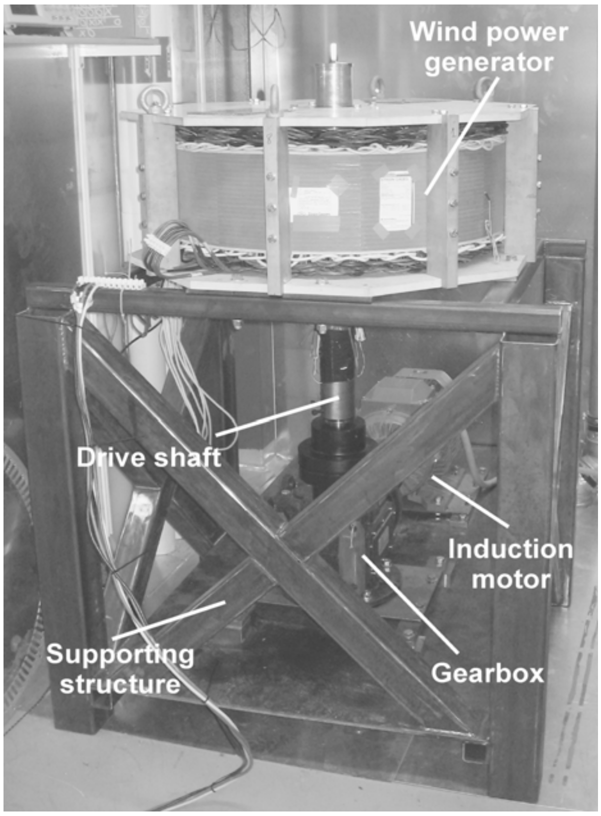

Figure 6. The motor-generator set-up of the wind power generator.

An AC transmission was chosen rather than a DC transmission to shore. The voltage has to be stepped up offshore to reduce transmission losses. An additional rectification offshore and subsequent conversion to 50 Hz AC onshore was ruled out as an expensive and more complex solution.

2 Simulation

A model was implemented in MATLAB Simulink to simulate the voltage and current wave forms as two variable-speed, direct-driven PMSGs are interconnected on a common DC-bus of a marine substation for wave power. The standard solvers in Simulink were used. The simulation model is depicted in Fig. 4. The measured no-load voltage, phase inductance and phase resistance of each generator, as seen in Table 1, was set in the Simulink model. The load resistance between the positive and negative terminals of the DC-bus was set to 9.4 ohms, which was the value of the load resistance in the experiments. Phase voltage and current waveforms were calculated for 5 s to allow for transients at start up to be fully dampened. In the Results section, Fig. 9-10, snapshots of 0.25 s to 0.5 s are shown for comparison with measurements.

3 Experimental set-up

The practical challenges of making laboratory tests of the substation using the linear generators of the WECs are comprehensive. The casings of the WECs alone are 5 m tall and horizontal testing was not possible. Above all, the vertical clearance of the laboratory where the substation and WECs are being assembled is too low to operate the WECs. Similar problems were encountered by the developers of the wave energy converter Archimedes Wave Swing (AWS) upon the initial testing of their 2 MW prototype of the AWS linear generator [9]. Here, instead, the substation is tested using two grid-fed motor-generator systems with rotating generators. Thus, the test set-up consists of two motor-generator systems for generation of power, the marine substation, and a resistive load connected to the DC-bus. Both generators of the motor-generator systems are of the PMSG, direct-drive topology.

The first generator is intended for use in a marine (tidal) current energy converter with a straight-bladed, vertical-axis turbine, a so-called H-rotor [10-11]. The specifications of the marine current generator are shown in Table 1. The marine current generator experimental set-up is shown in Fig. 5.

The second motor-generator system is based on a laboratory version of the generator of an H-rotor-based windmill operated in Marsta, north of Uppsala [12]. Some of the specifications of the wind power plant

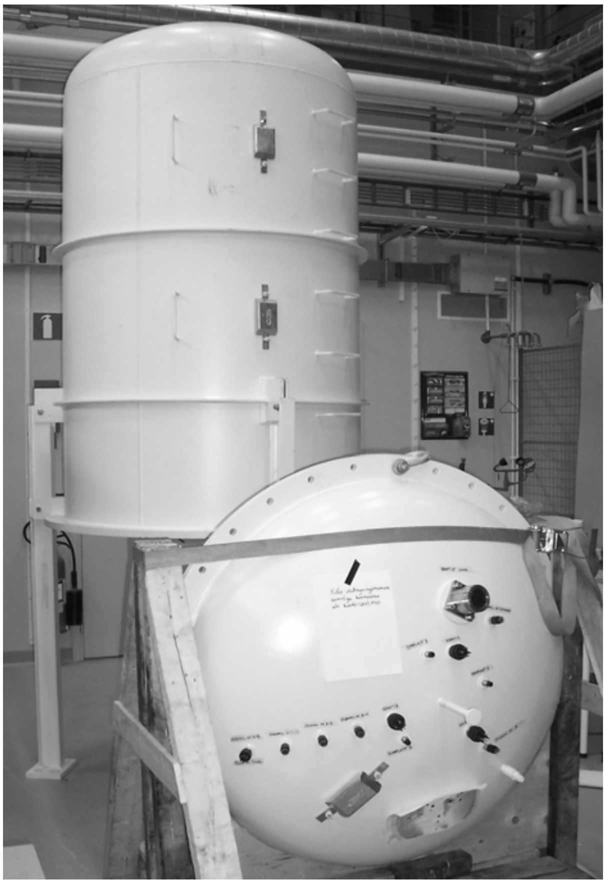

Figure 7. The marine substation pressure vessel with lower dished end, with its underwater connectors, in front of the main hull.

generator are shown in Table 1. The motor-generator set-up of the wind power generator is shown in Fig. 6. More detailed information on the performance of the wind power generator can be found in [13]. For comparison, the specifications of the linear generator of the first WEC prototype, submerged in March 2006, are shown in Table 1. More detailed information on the ratings and construction of the linear generator can be found in [3]-[6].

As can be seen in Table 1, many similarities can be found in the specifications of the generators. All three generators are multi-pole machines with surface mounted permanent magnets that operate at low rotational and linear speed respectively. All three machines are designed to operate at variable speed and are therefore designed to have flat efficiency curves in order to generate power at high efficiency at part load as well as at rated power. The stator winding current density is kept low to allow over-load capacity. This is important since the momentary power in the waves can vary significantly on the short time scale (tenths of seconds). Additionally, the overload capacity of the linear generator is vital for the survivability of the WEC. The output power of an isolated linear generator will vary from zero to several times the nominal power as one sufficiently large wave passes the WEC buoy.

The marine substation is designed for installation at 25 m water depth at the Lysekil Research site and consists of a 3 bar pressure vessel with a volume of 3 m^3, see Fig. 7.

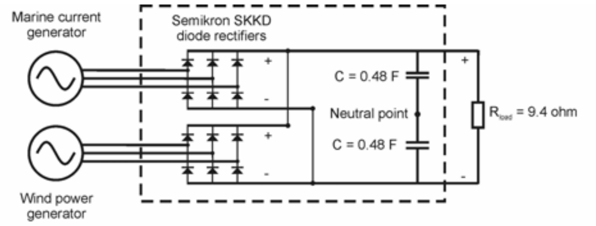

Figure 8. Circuit diagram of the experimental set-up. The dashed rectangle indicates what is included in the marine substation. Note that the inverter and transformer of the substation were not used in the experiments presented here.

The substation rectifies the voltage of each of the generator input sockets in accordance with Fig. 8. The rectification is made using passive diode rectifiers. The filter, which consists of Aluminum electrolytic capacitors, smoothens and stabilizes the DC-voltage. The capacitance of the filter determines the time constant of the discharging of the filter. Hence, the stability of the DC-voltage level during operation is determined by the filter capacitance, the intermittency of the input power and by the changes in power output. The latter will be set via the control system. It is anticipated that the filter capacitance required to smooth out the power output variations in the time frame of seconds to minutes can be significantly reduced by interconnection of several linear generator WECs on a common DC-bus. A simulation on the effect of farm size on the smoothing of output power was made in [14].

4 Experiment

In the experiments carried out in this study, power was extracted on the DC-side of the rectifier, see Fig. 8. At the time of taking the laboratory measurements, the substation inverter was still being tested. Therefore, the DC-to-AC conversion step and transformer, seen in Fig. 3, have been excluded from this study.

The substation was tested in a laboratory environment. The absence of the cooling effect of the seawater, which would otherwise surround the substation hull, therefore limited the amount of power that could be transmitted through the substation main circuit. Hence the relatively small power output compared to the substation nominal power of 30 kVA.

5 Results

Phase voltage and line current of each of the two generators were simulated and measured to demonstrate how the substation main circuit will operate. Measurements show reasonable agreement

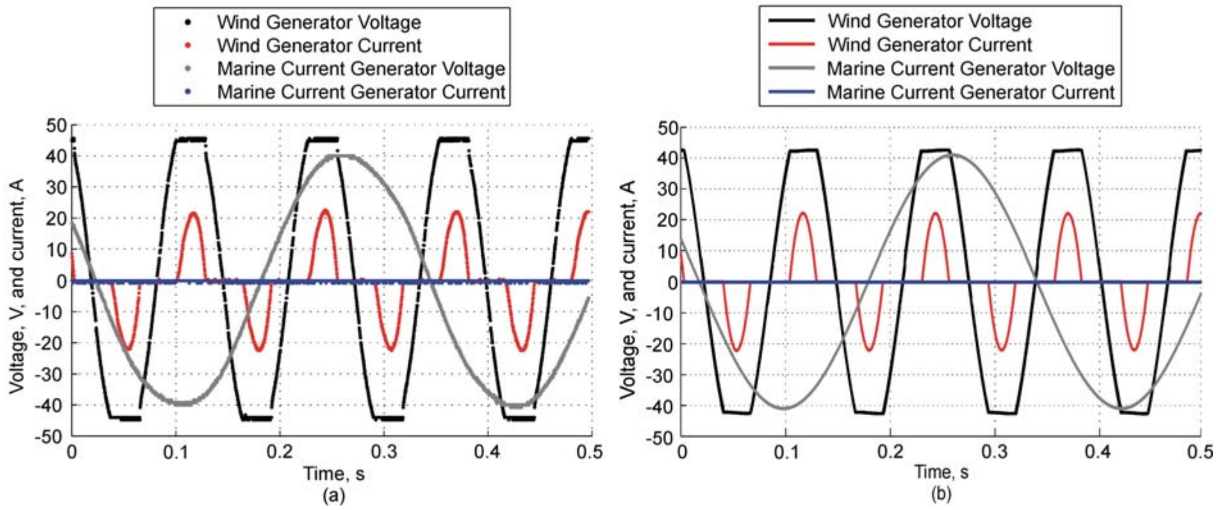

Figure 9. Measurements (a) and simulations (b) of voltage and current of the generators for the wind power and marine current power applications.

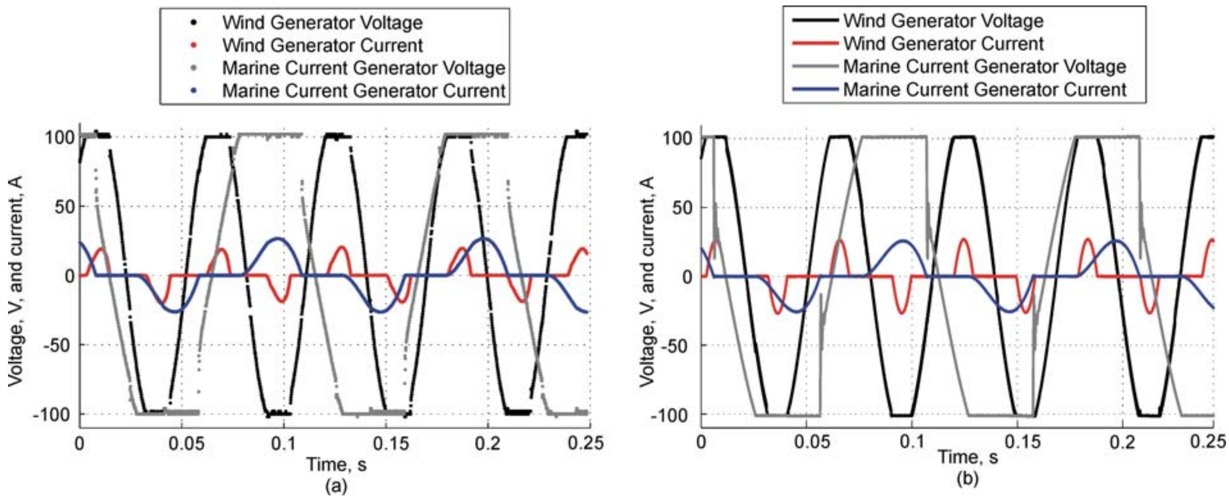

Figure 10. Measurements (a) and simulations (b) of voltage and current of the generators for the wind power and marine current power applications.

with simulations. In each simulation/experiment, the generators are run at constant speed. As was shown in Table 1, the generators have different nominal voltage, speed and power. Therefore, running the generators so that approximately the same voltage is generated from both generators, they will be run at different part load conditions. Extraction of 500 W electric power from each generator will e.g. correspond to a part load of 10% for the marine current generator, but only a part load of 4.2% for the wind power generator.

In the following, note that there is a slight difference between the positive DC-bus voltage and the amplitude of the phase voltages in both a) and b) of Fig. 9 to Fig. 10. The difference is the voltage drop of around 1 V of the Semikron SKKD diode rectifier.

In Fig. 9, measurements and simulations show the wind power generator running at a frequency of 30 rpm, corresponding to an electrical frequency of 7.9 Hz. Here, the voltage amplitude of the marine current generator at its speed of 3.1 rpm (electrical frequency of 3.1 Hz) is lower than the measured DC-voltage, which is ±43.6 V. This results in that only the wind power generator feeds current into the common DC-bus. The voltage amplitude of the wind power generator is limited to the DC-voltage plus the diode rectifier voltage drop. The red data points in Fig. 9 illustrate the intermittent current pulses, which are drawn from the wind power generator by the capacitive filter and resistive load on the DC-side. An electric power of 810 W is dissipated in the resistive load.

In Fig. 10, both generators deliver current to the common DC-bus. Note that the time period in the figures now, for clarity, is 0.25 s instead of 0.5 s. The measured DC-voltage is now ±98.6 V. Both generators deliver a significant current to the DC-bus, the wind power generator current peaking at about 20 A and the marine current generator current peaking at about 25 A. A total of 4.2 kW is being dissipated in the resistive load. As can be seen comparing the length of the diode conduction time periods of the voltage curves and the integral of the current pulses of each of the generators, the marine current generator delivers more power to the

DC-bus than the wind power generator. Here, the electrical frequencies of the wind power generator and marine current generator are 17.0 Hz and 9.9 Hz respectively.

The length of the diode conduction time periods of the two voltage curves in Fig. 10 is determined by the DC-voltage level. This in turn can be altered by changing the resistance of the load, which is connected to the positive and negative terminals of the DC-bus. An increased load resistance would increase the DC-voltage and hence shorten the length of the diode conduction time periods and the power dissipated in the resistive load would decrease. A decreased load resistance would increase the length of the diode conduction time periods, i.e. the power dissipated in the resistive load would increase.

6 Discussion

There is reasonable agreement between simulations and experiments. However, some deviations exist. In Fig. 9, the amplitude of the phase voltage of the wind power generator is slightly lower in the simulation than in the experiment. This could be due to heating of the load resistors in the experiment, causing an increase in resistance and hence a decrease in power output and increase in DC-voltage.

The voltage of the DC-bus is nearly constant during each experiment. Power is continuously drawn from the capacitor bank to the resistive load while power is intermittently supplied only from the wind power generator (Fig. 9) or from both of the generators (Fig. 10). The output power was passively controlled by means of the resistive load connected to the DC-bus of the substation. An expected increase of the DC-voltage is seen as the speed, and hence the terminal voltage, of each generator is increased. The output power then increases according to the increased DC-voltage.

When connecting three WECs to the marine substation in the Lysekil Research site, the input power will fluctuate to a greater extent than in the experiments conducted in this paper. The DC-voltage will, however, be possible to maintain at a constant level (e.g. in the time frame of minutes) using the inverter. The substation output power will then be a result of the added input power of the three WECs (with losses subtracted). This will result in an increased generator current rather than voltage (the latter was the case in the laboratory experiment with a purely resistive load) as a large wave interacts with the WEC buoy.

In this study, in order for both machines to start delivering power to the DC-bus, the amplitude of the voltage of each generator has to exceed the DC-bus voltage by the diode forward voltage drop. If, for one of the generators, that is not the case, the generator will continue to run at no-load.

A generating unit operating at a mean speed, and hence a mean output voltage, which has an amplitude that is lower than the voltage of the DC-bus will not contribute to the system power output. If more and more generators stop contributing to the system power output due to a reduction in the present sea state, the DC-voltage will decrease if the power output is maintained. A new, lower, DC-level and output power should then be set. The resulting absorption width, which should be calculated continuously, could be used as an input parameter to the control system. The output power can again be altered and the resulting absorption width calculated until an optimum power point has been found. It is the intention of the authors to implement such a maximum power point tracking (MPPT) algorithm in the future.

7 Conclusion

A marine substation designed for offshore operation of three WECs has been validated in a laboratory environment. Measured voltage and current wave forms were compared with simulations in MATLAB Simulink. The main circuit was tested regarding rectification of incoming power and filtering (DC-voltage smoothing) of added power from two of three possible WEC generator inputs.

This study shows that there is reasonable agreement between measured values and the expected performance according to the simulated voltage and current wave forms. Furthermore, it is shown that although the electrical frequency of the two power sources is different and although input power is delivered intermittently from these sources, they can be added together in parallel to form a constant power flow to a resistive load on the DC-side of the substation main circuit. The DC- voltage is stable and is smoothened by the capacitors on the DC-bus. A stable DC-voltage is a good condition for an inverter to operate satisfactorily and the DC-voltage may therefore be inverted to 50 Hz at a later stage.

We have shown that parallel connection of voltage sources with varying electrical frequency and amplitude, as will be the case in the offshore experiments of the WEC array of the Lysekil project, can be made. In the present study, the voltage on the DC-busbar automatically adjusts to a new level when the speed, and hence the output voltage, of the generating units are altered. The mean output voltage, which is proportional to the mean translator speed (except for non-linear effects in the stator steel and the fact that the translator has a finite length and might not entirely overlap the stator at all times), of the linear generators of the WECs, will determine the appropriate voltage of the DC-bus. This voltage will be possible to set and maintain by means of a controlled three-phase inverter. The mean speed of the WEC linear generator translators in turn is dependent upon the sea state and the level of electromagnetic damping.

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References

[1] J. Falnes and J. Løvseth, Ocean wave energy, Energy Policy, pp. 768-775, October 1991.

[2] A. Clément, P. McCullen, A. Falcão, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M. Teresa Pontes, P. Schild, B-O. Sjöström, H-C. Sorensen and T. Thorpe, Wave energy in Europe: current status and perspectives, Renewable & Sustainable Energy Reviews, No. 6, pp. 405-431, 2002.

[3] R. Waters, M. Stålberg, O. Danielsson, O. Svensson, S. Gustafsson, E. Strömstedt, M. Eriksson, J. Sundberg, and M. Leijon, Experimental results from sea trials of an offshore wave energy system, Applied Physics Letter 90, 034105, 2007.

[4] Stålberg, R. Waters, O. Danielsson, and M. Leijon, Influence of generator damping on peak power and variance of power for a direct drive wave energy converter, Journal of Ocean Mechanics and Arctic Engineering, Vol 130, No. 031003, August 2008.

[5] M.Eriksson, R.Waters, O.Svensson, J.Isberg and M.Leijon, Wave power absorption: Experiments in open sea and simulation, Journal of Applied Physics 102, 084910, 2007.

[6] M. Leijon, C. Boström, O. Danielsson, S. Gustafsson, K. Haikonen, O. Langhamer, E. Strömstedt, M. Stålberg, J. Sundberg, O. Svensson, S. Tyrberg, and R. Waters, Wave energy from the North Sea: experiences from the Lysekil Research Site, Surv. Geophys, Vol. 29, pp. 221-240, 2008.

[7] C. Boström, E. Leijerskog, M. Stålberg, K. Thorburn, and M. Leijon, Experimental results of Rectification and Filtration from an Offshore wave Energy System, Renewable Energy, Vol. 34, No. 5, pp. 1381-1389, 2009.

[8] M. Bazargan, Renewables offshore wind - offshore substation, Power Engineer, Vol. 21, Iss. 3, pp. 26-27, June-July 2007.

[9] H. Polinder, M. E. C. Damen and G. Gardner, Design, modeling and test results of the AWS PM linear generator, European Transactions on Electrical Power, pp. 245-256, No. 15, 2005.

[10] K. Thomas, M. Grabbe, K. Yuen, and M. Leijon, A low-speed generator for energy conversion from marine currents – experimental validation of simulations, Journal of Power and Energy (Part A of the Proc. of the Institution of Mechanical Engineers), Volume 222, Number 4 / 2008, Pages 381-388

[11] K. Nilsson, M. Grabbe, K. Yuen and M. Leijon, A direct drive generator for marine current energy conversion - first experimental results, in Proc. of the 7th European Wave and Tidal Energy Conference, , September 11-13, Porto, Portugal, 2007.

[12] P. Deglaire, S. Eriksson, J. Kjellin, and H. Bernhoff, Experimental results from a 12 kW vertical axis wind turbine with a direct driven PM synchronous generator, in 2007 Proc. of European Wind Energy Conference, May 7-10, Milan, Italy, 2007.

[13] S. Eriksson, A. Solum, M. Leijon, and H. Bernhoff, Simulations and experiments on a 12 kW direct driven PM synchronous generator for wind power, Renewable Energy, Vol. 33, No. 4, pp. 674-681, 2008.

[14] K. Thorburn, M. Leijon, Farm size comparison with analytical model of linear generator wave energy converters, Ocean Engineering, Vol. 34, Issues 5-6, pp. 908-916, April 2007.