Description of the control and measurement system used in the Low Voltage Marine Substation at the Lysekil research site

O. Svensson, C. Boström, M. Rahm and M. Leijon

Division of Electricity,
Uppsala University,
Box 534, SE-751 21 Uppsala, Sweden
E-mail: olle.svensson@angstrom.uu.se

Abstract

This paper gives a description of the control and measurement system inside the Low Voltage Marine Substation at the Lysekil Research site located close to Lysekil on the Swedish west coast. The Lysekil project is run by the Swedish Centre for Renewable Electric Energy Conversion at Uppsala University.

The control and measurement system consists of three PACs, Programmable Automation Controllers, inside the Marine Substation. Each PAC is dedicated to one of the tasks safety and relay-control, DC to AC inversion and data-acquisition. One PAC controls the land based measuring-station. The system has been tested with the control algorithm constant modulation index. The control algorithms constant DC level and constant AC level has been discussed, especial the different behaviour of the algorithms when connected to the grid compared to connected to resistive loads.

Keywords: Control system, Switchgear, Wave power, Inverter.

1 Introduction

The control of a marine substation does not substantially differ from the control of a land-based substation. The land-based substation is remotely operated and the demand for reliability is high, this is also the case for the sea-based substation. But the wave power park is different from a wind power park or a hydro power plant, especially the wave power concept suggested by Uppsala University, which consists of many small units. This makes it hard to use a control and measurement system designed for a land based substation in the national grid which is designed with a few high-power inputs. This paper describes a control system developed on the National Instrument CompactRIO platform.

Research site overview

The Lysekil research site consists of three WECs (Wave Energy Converter), one LVMS (Low Voltage Marine Substation) and one land based measuring-station. Previous studies at the research site are described in [1-5]. The overview of the research site is shown in fig. 1. The LVMS is connected to the measuring-station with one 1 kV three phase cable for energy transfer and one signal cable with 10 twisted pairs, where four of the pairs are used for data communication with the LVMS. The other six pairs are going to be used in other applications at the research site. The cable lengths between the LVMS and the measuring-station is 3.1 km, and the cable length between the WECs and the LVMS is 70 m, the units are placed much closer.

© Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 2009

Figure 1: The parts that the controlled research site consists of April 2009. WEC 3 is red, WEC 2 is blue and WEC 1 is grey. The LVMS are located between the resistive generator loads and land based measuring-station.

Computer system introduction

Generally in the control of industrial processes, Programmable Logic Controllers, PLCs, have been used for automation and an ordinary computer have been used for calculations and measurements. In recent years calculation power has been integrated in PLC's and the merged product is named PAC, Programmable Automation Controller [6]. The PAC from National instruments, CompactRIO [7], consists of three major parts; a real-time controller with a real time operating software; one FPGA chip, Field-Programmable Gate Array [8], and different input output modules. FPGA is a set of programmable logical gates. The main advantage of FPGA is that all calculations are made in one clock cycle; hence, the FPGA is very fast. It is also very stable because it only consists of logical states burned in hardware. The drawback is that it only handles binary values. The FPGA chip is mounted inside a backplane of the CompactRIO system. The backplane can be equipped with different input/output modules which makes it possible to configure the PAC to execute different tasks. If a slot in the backplane is configured with a digital output module, the PAC can control contactors, with a high speed analogue input in one slot, the PAC can be used as an oscilloscope.

The control of the LVMS

The LVMS control system consists of three PACs inside the LVMS and one land-based PAC in the measuring-station. The measured data is stored on the hard disk drive of a land based personal computer. The communication structure is shown in fig. 2.

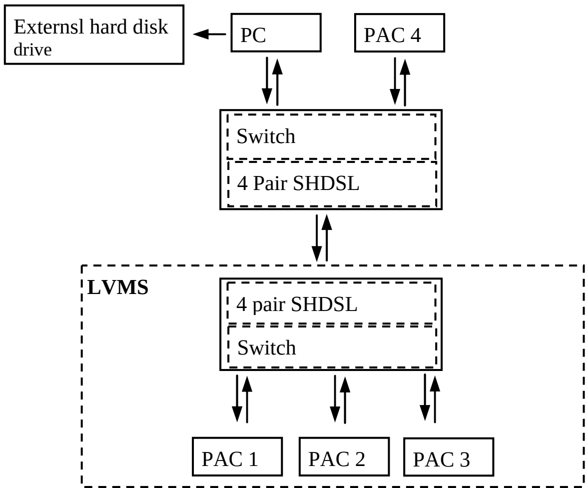

Figure 2: The communication structure including the point to point communication between the LVMS and the measuring-station through the communication cable

PAC 1 is a safety system and a relay control system. PAC 2 controls the conversion of DC voltage to AC voltage. PAC 3 is a dedicated data acquisition system that logs WEC data and environmental data from sensors inside the LVMS. The PACs that are mounted inside the LVMS and the PC that is located in the measuring-station are shown in fig. 3. PAC 4 controls the resistive power loads placed outside the measuring-station and measures the voltages and currents on these loads.

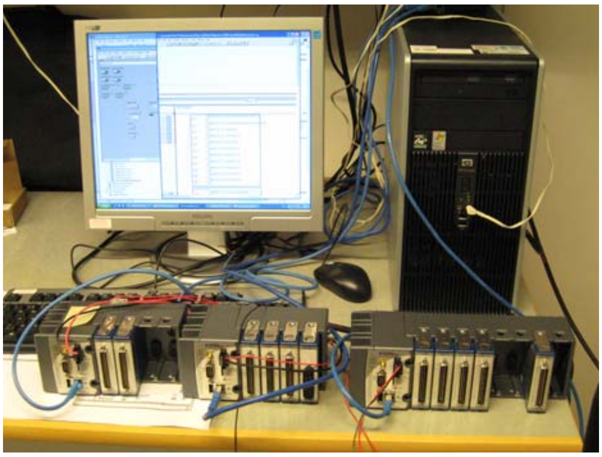

Figure 3: The three PACs inside LVMS 1 and the land based PC.

2 System design

Designing a CompactRIO System

Designing a control system starts with the specification of the controlled device, in this case the LVMS is the controlled device. Listing the number of contactors and relays that the LVMS consists of will give the number of digital outputs needed. The number of measurements that are going to be made will give the number of analogue inputs. Then the modules that have the qualities that are needed are chosen. The modules are placed in the FPGA backplane. The FPGA is then programmed to handle the modules and the signals from the modules

The FPGA is limited to logic and mathematic operations on integer numbers. To convert integer numbers to more user friendly floating point numbers, binary data is transferred to the real time controller where the conversion to floating point numbers takes place. The real time controller communicates with the FPGA and other devices connected to the network.

The Safety system and relay control system.

PAC 1 uses only the FPGA and not the real-time computer; this is to increase system stability. A real-time program consists of many processes that depend on each other. There is always a risk that one process blocks another process and then a hardware reset is the only way to solve the problem. There are different ways to pre-empt deadlock. Traditionally three methods are used to deal with deadlock: deadlock prevention, deadlock avoidance and deadlock detection [9-10]. If only a fraction of the computer power is used, the probability of deadlock decreases, but a real time system can never be 100 per-cent stable.

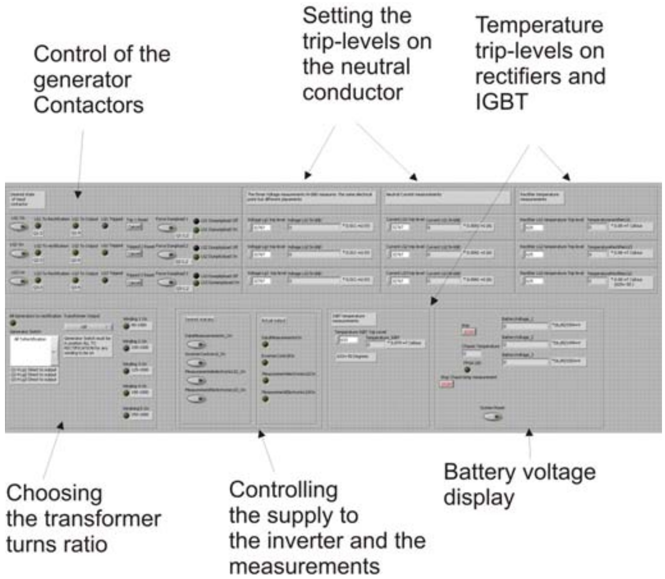

Figure 4: The control interface of PAC 1.

The control interface of PAC 1 is shown in fig. 4. PAC 1 either switches the WECs to rectification, or, it bypasses the three phase rectification bridge and connects one single WEC to the land based measuring-station and the other WECs to their resistive loads, see fig. 5. The third alternative is that all WECs are connected to resistive loads. This is the case when there is an error in the land based system or in the LVMS. PAC 1 measures the voltage and current in the WEC neutral conductor and disconnects the WEC from the LVMS if it exceeds a defined value. The transformer in the LVMS has 5 outputs and with PAC 1 it is possible to choose one of these outputs. It also controls the power to the two real-time systems. In this way, it is possible to make a manual reset. It measure temperatures on the rectifier modules and on the IGBTs, Insulated Gate Biplolar Transistors located inside the inverter see fig. 6. If the temperature reaches a critical temperature, the WECs are switched off by PAC 1.

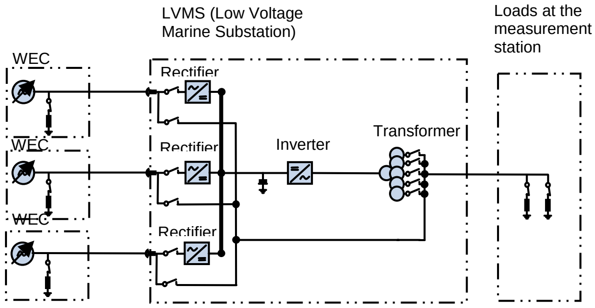

Figure 5: The mains circuit with the contactors controlled by PAC 1.

Inverter Control

PAC number two controls the conversion of the DC voltage to 50 Hz AC voltage. The inverter inside the LVMS consists of a PAC and IGBT driver electronic and 6 IGBTs, fig. 5. The PAC measures the voltages and currents on the DC bus, the IGBT outputs and the transformer output. Based on the measured voltages and currents, it sends pulses to the IGBTs. It also sends the measured values to the land based PC that stores the data on a hard disk drive. The results from the final test of the inverter are shown in fig. 7 [11].

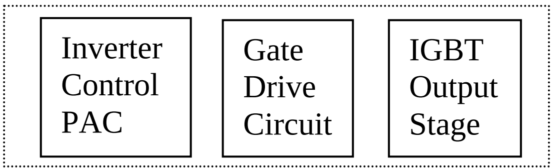

Figure 6: The parts of the inverter

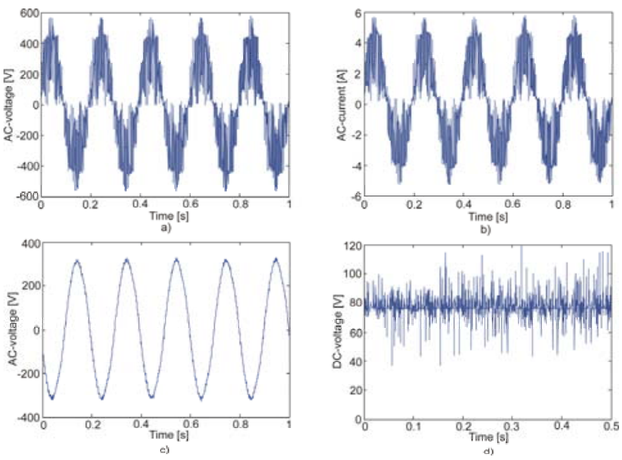

Figure 7: Currents and voltage measurements at the final test in Uppsala. a) AC-voltage measured, load 107 Ohm. b) AC-voltage measured, load 107 Ohm. c) AC-Voltage measured after the transformer, load 36 uF//107 Ohm. d) DC-voltage measured before the inverter.

Dedicated data acquisition system

The third system is a dedicated data acquisition system that measures the voltages and currents from each WEC. Electrical signals from sensors inside two of the WECs are sampled with 256 Hz. The frequency of 256 Hz is chosen because the generator measurements are going to be synchronised with measurements of the buoy. The data logging system inside the buoy have a maximum sampling rate of 16 Hz. The dedicated data acquisition system uses two 16 channel differential analogue input modules to measure the three phase voltages and currents from the three WECs. Two modules are used to measure the sensors in WEC 2 and one module is used to measure the sensors in WEC 3. In both WEC 2 and WEC 3 the position of the translator, the magnetic flux in the generator and the temperature on the stators are measured. There are also indications of water leakage. WEC2 is also equipped with strain gage sensors placed on the metal structure and laser sensors that measure the horizontal movement of the piston. Temperature, pressure and humidity inside the LVMS are also measured by PAC 3. The graphical programming of the input modules in PAC 3 is shown in fig. 8.

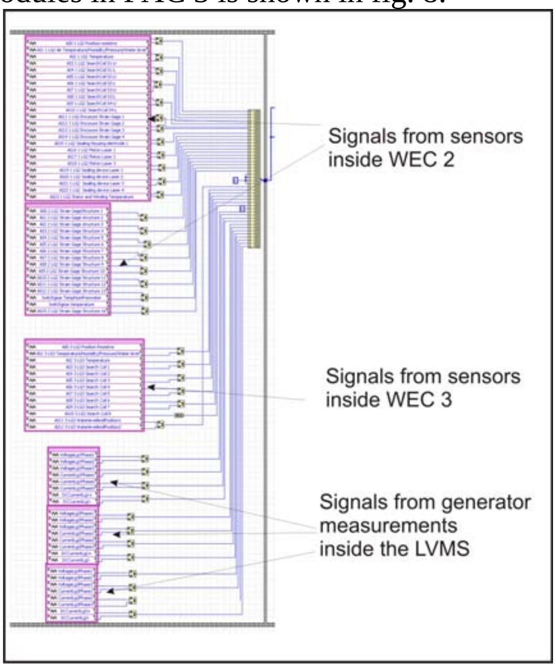

Figure 8: The picture shows a part of the Labview program. The digital data from the analogue input modules are merged to an array of data. The array represents one sample and is then transferred from the FPGA to the real time controller.

3 Energy control algorithms

Current flow on a transmission line

The current flow on a transmission line from bus S to bus R is generally described with equation 1. The transmission-line is shown in fig. 9. The shunt capacitor is neglected to simplify the system. The capacitor would influence the imaginary value of the impedance and the resonant behaviour of the transmission-line. The frequency domain is not discussed in the paper hence the shunt capacitor is not essential. The current depend on the voltage at S, the voltage at R and the impedance in the transmission line [12].

$$I_{Line} = (\bar{V}_S - \bar{V}_R)\left(\frac{R}{R^2 + X^2} - j\frac{X}{R^2 + X^2}\right) \quad (1)$$

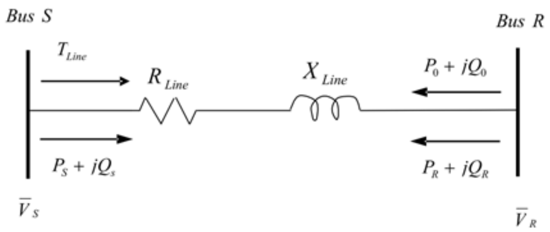

Figure 9: The transmission line modelled with a lumped series impedance.

The wave power park and the transmission line

The experimental set-up is modelled in fig 10. Two transmission lines are added to the circuit diagram of the LVMS. One transmission line is added from the LVMS to the measuring-station and one that represents the grid is added after the measuring-station. In the experimental set-up Vs is the voltage over the resistive loads and the current in the circuit shown in fig. 10 can be modelled with equation 2. The values of the resistances in the park are shown in table 1.

$$I_{Line} = (\bar{V}_{LVMS})\left(\frac{R_{Seacable}}{R_{Seacable}^2 + X_{seacable}^2} - j\frac{X_{Seacable}}{R_{Seacable}^2 + X_{Seacable}^2} + R_{R\ MeasStatio}\right) \quad (2)$$

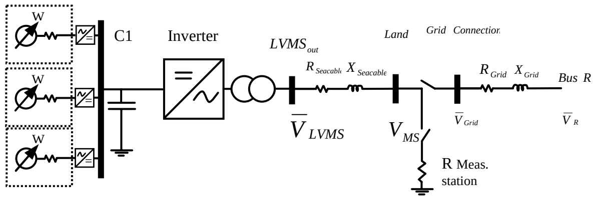

Figure 10: The three WECs the LVMS the transmission line to the measuring-station the resistive loads at the measuring-station and the grid transmission line.

Impedances	
$R_{Seacable}$	0.5 [Ω]
$R_{Meas\ .station}$	100 [Ω]
$X_{Seacable}$	Ignored
R_{Grid}	0. 1- 0.5 [Ω]
X_{Grid}	0.001 - 0.1 [Ω]

Table 1: The impedances in the transmission-lines and the load resistances at the measuring-station. R grid and X grid are general values, not the values of the grid connection point at the research site.

Implemented control algorithms

PAC 2 controls the transformation from DC voltage to 50 Hz AC voltage. Three simple control algorithms are implemented in PAC 2; Manual control of the (pulse width) modulation index, constant DC level and constant AC level. The changing of the control values of the algorithms are made in the control interface shown in fig. 11.

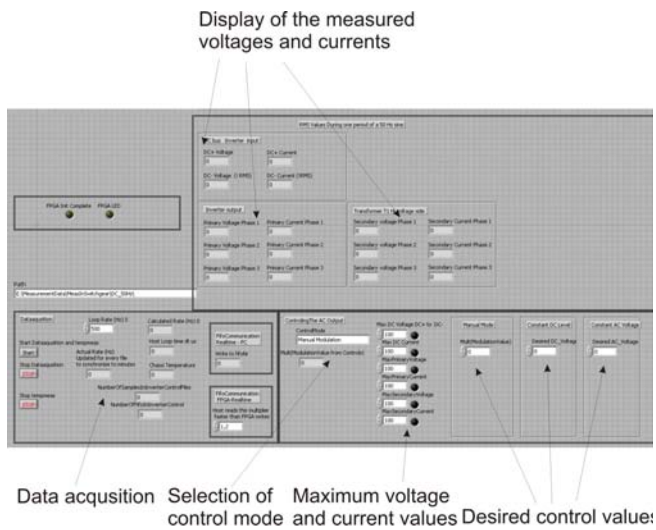

Figure 11: The control interface of PAC 2

Constant modulation index

When the modulation index is set constant by the manual control algorithm, the LVMS output AC voltage is directly proportional to the DC voltage. Hence the power output is directly proportional to the square of the AC voltage over the resistive loads. The capacitors will work as energy storage for the energy peaks from the wave power park, resulting in variations in the DC level.

Constant DC level

Constant DC level is an algorithm that is implemented to evaluate the WEC within the experimental set-up. Since a constant modulation index will result in varying DC level when the switchgear is connected to resistive loads, the output power must be controlled by varying the modulation index based on the measured DC level.

Constant AC level

Constant AC level varies the modulation index to maintain the output voltage constant. With resistive loads connected to the output, the power will also be constant as long as energy is produced and the DC voltage is within the specified values.

4 Discussion

The control algorithms and grid connections

Manual control of the pulse width modulation index will result in a different behaviour of the power output and the input DC voltage level if the LVMS is connected to the grid; instead of to resistive loads. In the experimental set-up, where resistive loads are connected to the output of the LVMS, increased DC voltage will result in power output proportional to the square of the DC voltage. The power output change will be moderate. If the DC voltage is decreased, the power output will decrease, but it will never be zero, unless the DC voltage is zero.

If the LVMS is connected to the grid and a fixed pulse width control algorithm is used, the power output will fluctuate much more due to the very low impedance of the grid and that the LVMS output works towards a grid voltage, this is generally described in equation 1. In the ideal case when the transmission line and all the components in the LVMS have no losses, the energy absorbed in the wave park will instantly be transferred to the grid. The DC level will be fixed at a voltage that depends of the modulation index and the turns-ratio of the transformer. In the real case with components that have losses, the power output will be limited by the inverter, and the grid impedance. The energy will not flow directly from the park to the grid. Some energy will be stored in the capacitors, resulting in fluctuating DC level and smoothening of the power peaks.

The control algorithm Constant AC level will not have constant power output when it is connected to the grid because the variations in the grid voltage. This may be advantageous to strengthen up a poor grid but the variations of the DC level may make the wave power park absorb less power.

When the park is connected to the grid a combination of control algorithms will be necessary to maximize the power absorption within the demands of the owner of the grid.

Placement of the Data Acquisition System

There could have been a different approach regarding the placement of the data acquisition system that samples the sensors inside the WEC. One would have been, to place the data acquisition system inside the WEC. The benefit of this would have been a signal cable with fewer conductors between the switchgear and the WECs and data conversion in a better EMC environment. The decision to place the measurement computer inside the switchgear was made based on the fact that every computer sooner or later needs service. The switchgear is possible to lift up to the ocean surface and take to a harbour for service. The procedure to lift up one WEC is much more complicated. Another alternative would have been to place the data logging equipment outside of the WEC in a separate pressure vessel close to the WEC. This is also a solution that makes it possible to service the data logging system. During the process of evaluating measured data the problem of time synchronisation have risen. Computer clocks and data logging system clocks are accurate within seconds. To evaluate data from a WEC the sensors must be synchronised on a millisecond level. This is of course possible to implement with the clock synchronization protocol IEEE-1588 [13], but if the same data logging system is used the sensors inside the WEC are always synchronised with the WEC voltages and currents. Because of this it was a very good choice to transferee analogue signals from the WECs.

5 Conclusion

A control and measurement system have been implemented in a LVMS; Consisting of four distributed CompactRIO. It has been shown that it is possible to control the DC to AC conversion with an inverter-design based on a PAC. Three control algorithms have been implemented and the control algorithms have been discussed. The status of the wave energy park at the Lysekil research site 2009 has been described.

6 Acknowledgements

The Lysekil Project is supported by Vattenfall AB, Statkraft AS, Fortum oy, The Swedish Energy Agency, Draka Cable AB, The Gothenburg Energy Research Foundation, Falkenberg Energy AB, The Wallenius Foundation, Helukabel, ProEnviro, Seabased AB, The Olle Engkvist Foundation, The J. Gust. Richert Foundation, Ångpanneföreningen's Foundation for Research and Development, CF Environmental Fund. The Göran Gustavsson Research Foundation, Vargöns Research Foundation.

I would also like to thank Tobias Semberg that soldered the major part of the cables and electronics in the control system. A would also like to thank Lisa Bolin and Hjalmar Nyström for mounting the parts in the LVMS together.

7 References

[1] Leijon M, Boström C, Danielsson O, Gustafsson S, Haikonen K, Langhamer O, Strömstedt E, Rahm M, Sundberg J, Svensson O Tyrberg S Waters R. Wave Energy from the North Sea: Experiences from the Lysekil Research Site. Surveys in Geophysics Volume 29, Number 3/ May 2008

[2] Waters R, Stålberg M, Danielsson O, Svensson O, Gustafsson S, Strömstedt E, Eriksson M, Sundberg J Leijon M. Experimental results from sea trials of an offshore wave energy system. Appl. Phys. Lett. , 90(1), 034105

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

[4} Bostrom, C.; Waters, R.; Lejerskog, E.; Svensson, O.; Stalberg, M.; Stromstedt, E.; Leijon, M. **Study of a Wave Energy Converter Connected to a Nonlinear Load** IEEE Journal of Oceanic Engineering, Volume 34, Issue1.

[5] Leijon, M.; Waters, R.; Rahm, M.; Svensson, O.; Bostrom, C.; Stromstedt, E.; Engstrom, J.; Tyrberg, S.; Savin, A.; Gravrakmo, H.; Bernhoff, H.; Sundberg, J.; Isberg, J.; Agren, O.; Danielsson, O.; Eriksson, M.; Lejerskog, E.; Bolund, B.; Gustafsson, S.; Thorburn, K.;, **"Catch the wave to electricity"**, IEEE Power and Energy Magazine, Volume 7, Issue 1, January-February 2009, Page(s): 50-54.

[6] John Wilhite. The rise of the programmable automation controller. http://www.automation.com/pdf_articles/pac.pdf. May 2009.

[7] http://www.ni.com/compactrio May 2009.

[8] S. Brown and J. Rose, FPGA and CLPD architectures: a tutorial, IEEE Design & Test of Computers, vol. 13, 1996

[9] Sanches C, Sipma H, Manna Z, Gill C. Efficient distributed deadlock avoidance with liveness guarantees. Proceedings of the 6th ACM & IEEE International conference on Embedded software.

[10] Tannenbaum A. Modern Operating Systems. Prentice Hall; 3 edition (11 Feb 2008) **ISBN-10:** 0136006639

[11] Boström C. Electrical System of a Wave Power Plant. Licentiate thesis, Uppsala University, Sweden 2009.

[12] Skvarenina T. The power electronic handbook. Crs Press chapter 20-2 ISBN 0-8493-7336-0

[13] Eidson C, Fischer M, White J. IEEE-1588 Standard for a precision clock synchronization protocol for networked measurement and control systems. Proceedings of the 34'th Annual Precise Time and Time Interval (PTTI) Meeting.