ISSN (Online) 2393-8021
ISSN (Print) 2394-1588

IARJSET

International Advanced Research Journal in Science, Engineering and Technology
National Conference on Emerging Trends in Engineering and Technology (NCETET'16)
Lourdes Matha College of Science & Technology, Thiruvananthapuram
Vol. 3, Special Issue 3, August 2016

Modelling and Control of Grid Connected Wave Energy Converter Using Sliding Mode Controller

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Abstract: Wave energy is one of the most promising renewable energy sources for generating electricity. To extract energy from ocean waves, Wave Energy Converters (WEC) play an important role. One of the WEC types is the Point Absorber which is an oscillating type WEC that extracts the heave, or vertical motion from a wave. It consists of a cylindrical structure which is directly connected to the power takeoff system (PTO) which is connected to the grid through cable. The vertical motions of the point absorber compresses and expands the fluid and make the generator to rotate. The PTO system consists of permanent magnet synchronous generator (PMSG) which transforms the mechanical energy to electrical energy. The time domain simulations of point absorber are performed to evaluate the power take off capabilities of the modeled WEC. The overall system is obtained by connecting the hydrodynamic model to the PTO system. To obtain the maximum power it is required to reduce the voltage fluctuations at the grid side. Sliding Mode Controller (SMC) is implemented at the grid side to generate maximum power by reducing the voltage fluctuations. The output voltage settles at the reference value but due to high switching frequency of SMC, output voltage exhibits disturbances.

Keywords: Wave Energy Converter (WEC), Power Take off (PTO), Permanent Magnet Synchronous Generator (PMSG), Sliding Mode Control (SMC).

I. INTRODUCTION

In a scenario where the safety of fission based nuclear power is questioned and fossil fuels may represent serious threat due to their implication in the climate change, it seems clear that there exists a certain need of developing clean and sustainable power source alternatives. Based on many studies it is possible to obtain 100% of energy from wind, wave and solar power.

Among these kinds of energy ocean energy is expected to play a principal role in the future years. The five categories that come under ocean base physical phenomenon include wave energy, tidal energy, marine currents, temperature gradients, and salinity gradients. Wave energy is generated from wind passing over the sea.

The main characteristics of wave energy are;-

a) High Power Density- when compared to other renewable resources.

b) Large Resource- Estimates for practical potential world wide energy contribution of wave energy is estimated 2,000TWh/yr. These large energy figures are due to vast ocean regions where power density is high.

c) Low Environmental Impact- Wave energy has low negative interaction with surrounding according to Electric Power Research Institute. It has low visual profile.

d) High Availability- Due to storage and transport capacity of ocean waves usable energy remains after wind ceases.

Several WEC with different process of energy conversion are available. According to working principle ,WECs can be classified into OWC systems, overtopping devices or oscillating body systems.OWC have no moving parts in the water and therefore it pose little danger to sea life. It causes too much noise pollution and damage the natural beauty of sea scope.

In oscillating bodies a floating or submerged body that moves along with the waves and PTO system that converts the kinetic energy to electric power and this power is fed to the grid through underwater cable.

II. PRESENTATION OF THE DEVICE

The wave energy converter is the cylindrical shaped point absorber. The Point absorber WEC is a device that has small dimensions relative to the incident wavelength. It can be a floating structure that heaves up and down on the surface of the water or submerged below the surface relying on pressure differential.

Wave direction is not important for these devices (because of their small size and symmetry). An example of point absorber is Ocean Power Technology's Power buoy.

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Fig.1 Point Absorber device

The heaving motion of the buoy is transformed into a rotational motion and generated into electricity by a generator. During the upward motion, the excitation force is used to drive the generator as well as pressurizing the accumulator. On the downwards motion the accumulator is depressurized and the force from that is used to drive the generator.

III. MODELLING OF THE SEA

A simplified way of modelling the sea is to imagine a high, but finite number of sinusoidal waves of different height and frequencies propagating along a plane. The total energy must necessarily be the sum of the energy in all the waves the sea state is made up of. By modelling the sea as energy density as a function of frequency, one can obtain the distribution of energy contribution by different parameter waves. There are various mathematical models that are used for defining the sea spectra. Depending on the conditions such as wind strength, fetch, depth and how fully developed the sea-state can be considered, the different models have their advantages and limitations.

The most widely known energy spectrum for ocean waves is the two parameter Bretschneider spectrum developed in 1959. Its preferred analytical form is as given in the following equation

$$S_{(\omega)} = \frac{5}{16} H_s^2 \frac{\omega_0^4}{\omega^5} e^{-\frac{5\omega_0^4}{4\omega^4}} \qquad (1)$$

where H_s is the significant wave height and ω_0 is the peak frequency. Figure 2 and 3 shows the Bretschneider spectra for varying values of significant height and peak frequencies.

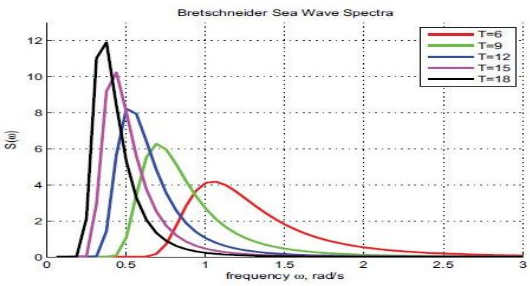

Fig.2 Bretschneider spectra for different values of peak period Tp

The wave spectrum can be used to decompose the sea into waves of different frequencies. The elevation due to each wave is given by

$$\zeta_n(t) = \sqrt{2S(\omega_n)d\omega}\,\sin(\omega_n t + \phi_n) \qquad (2)$$

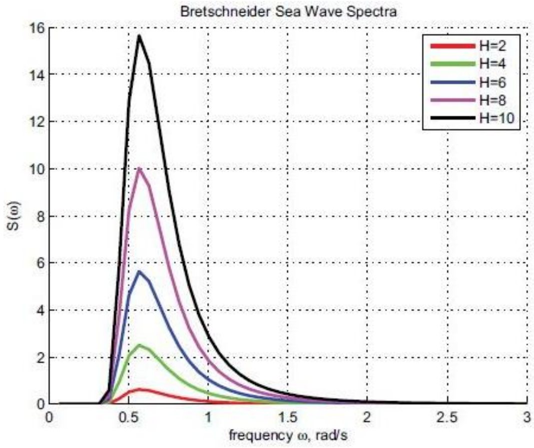

Fig.3 Bretschneider spectra for different values of the significant height Hs

The elevation of the sea is determined by summing all the different waves. These waves of different frequencies need to have random offset in the phase. The equation of the elevation can therefore be given by

$$\zeta_n(t) = \sum_{n=1}^{N} \sqrt{2S(\omega_n)d\omega}\,\sin(\omega_n t + \phi_n) \qquad (3)$$

IV. FORCES ACTING UPON THE SYSTEM

A body submerged in water is considered to have six degrees of freedom. These are along each of the x, y, and z axes. These movements are called surge, sway, heave (along axes) and roll, pitch, and yaw(rotational). The device is defined to move only in a heaving motion it is considered a one degree of freedom system.

The Force balance equation of such a point absorber system can be expressed as

$$M\ddot{\eta} = f_e(t) + f_s(t) + f_r(t) + f_m(t) + f_v(t) + f_l(t) + f_o(t) \qquad (4)$$

where η is the device position and M is the equivalent mass of the system corresponding to the mass of the WEC and added mass due to the inertia of the power take off system. Here f_e is the excitation force, f_m is the machinery force, or the force related to the power take off system. f_s represents the net hydrostatic stiffness or hydrostatic force. The mooring force f_l, the viscous force f_v and the environmental force f_o are neglected.

Hydrostatic Force

Hydrostatic force is the resultant of gravitational forces and forces due acting on the device due to displaced water.

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$$f_S = S_n \qquad (5)$$

where S represents the hydrostatic stiffness

Radiation Force
An oscillating device will create a diffraction wave and force acting on the device due to this wave is known as radiation force. In the frequency domain it is expressed as

$$\hat{F}_R(\omega) = m_r(\omega)\ddot{\eta} + R_r(\omega)\dot{\eta} \qquad (6)$$

where m_r is the added mass of the water oscillating with the device and R_r is the radiation resistance. The equation in time domain can be expressed as

$$F_r(t) = m_r(\infty)\ddot{\eta} + \int_0^t k(t-\tau)\dot{\eta}(\tau)d\tau \qquad (7)$$

$m_r(\infty)$ is the added mass at infinite frequency and $\ddot{\eta}$ is the acceleration of the device. The second term is a convolution integral, where the convolution kernel k_t can be considered the radiation force impulse response. Replacing the convolution term by state space model and equation is expressed as

$$F_r(t) = C_k z(t) + D_k \dot{\eta}(t) \qquad (8)$$
$$\dot{z}(t) = A_k z(t) + B_k \dot{\eta}(t) \qquad (9)$$

There are various methods to identify the state space parameters.
Excitation Force
The force that the incident wave exerts on the WEC body is called excitation force. It is given by the equation

$$F_{e,c}(t) = H_{F,\zeta}(t) * \zeta_{e,c}(t) \qquad (10)$$

The time domain equation of the excitation force become a convolution term and it is given by the equation

$$F_{e,c}(t) = \int_0^t h_{F\zeta}(t-\tau)\zeta(\tau)d\tau \qquad (11)$$

A state space representation of the convolution term is found in the same manner as in the radiation force.

Load Force
The load force or machinery force is the force applied to the system by the power take off system.

$$F_L = B_L\dot{\eta} + M_L\ddot{\eta} \qquad (12)$$

V. SIMULATION RESULTS

Using the equation for the time domain model and assuming constant hydrostatic coefficient, the force balance equation of point absorber can be expressed as

$$(M + m(\infty)) + \int_0^t k(t-\tau)\dot{\eta}(\tau)d\tau + S\eta = \int_0^t h_{F\zeta}(t-\tau)\zeta(\tau)d\tau + F_L(t) \qquad (13)$$

Graphically this is illustrated in the simulink model. In the above equation the convolution term of excitation force and radiation force is replaced by state space models.

TABLE I

Added Damping RL	9000
Added Mass M	5000
Hydrodynamic Stiffness S	19740

The simulation result of point absorber device is shown in the fig 4 and fig 5. From these two figures it is clear that the device should follow the elevation of the wave.

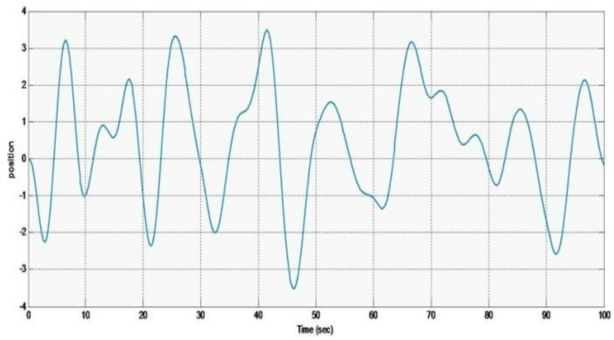

Fig 4 Device Position

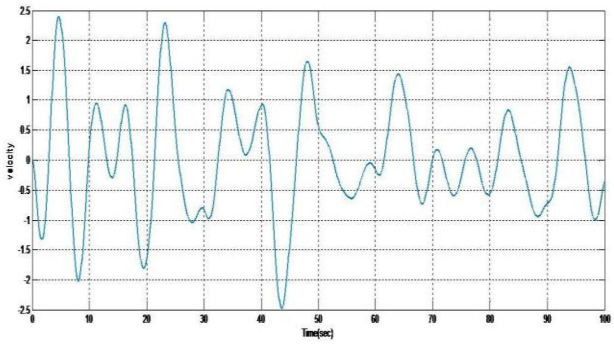

Fig.5 Device Velocity

The output from the point absorber is then fed to the PTO system.fig 4 shows the device position with respect to the wave motion.fig 5 shows device velocity with respect to the wave motion.

VI. PTO SYSTEM

The main part of this work is the PTO system. It converts mechanical power from the point absorber to electric power. The main component present in the PTO system is PMSG. The point absorber with the generator is considered a complete system which only needs to connect to a DC link.

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MODELLING AND CONTROL OF A OF PMSG

The transformation from mechanical to electrical energy is done by Permanent Magnet Synchronous Generator. The main characteristics of PMSG are high efficiency, high power density, and high torque to inertia ratio. In this rotor field is excited by permanent magnets so there are no rotor copper losses and as there are no need for brushes or slip rings. The PMSG is significantly smaller in size than a conventional synchronous generator. There are two types of PMSG, surface mounted and interior mounted permanent magnet machine. The difference lies in the placement of the permanent magnets. The d axis which is defined through the center of magnetic pole while q axis is perpendicular on the d axis. For a surface mounted PMSG the inductances in both the axes are the same.

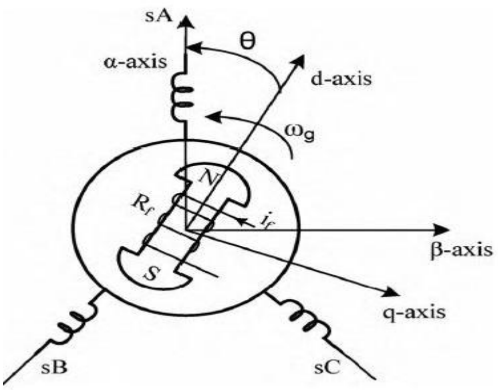

Fig.6 Dynamic model of PMSG

Dynamic model of the PMSG is obtained from the two phase synchronous reference frame, which the q axis is 90 degree ahead of the d axis with respect to the direction of rotation. The synchronization between the d-q rotating frames is maintained by a phase locked loop. Figure 7 shows the dq reference frame used in a salient -pole synchronous machine

where θ is the mechanical angle ,the angle between the rotor d axis and the stator axis. The stator windings are positioned sinusoidal along the air-gap as far as the mutual effect with the rotor. The stator winding is symmetrical, damping windings are not considered, the capacitance of all the windings can be neglected and the resistances are constant. The mathematical model of the PMSG in the synchronous reference frame is

$$u_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_e \varphi_q \quad (14)$$

$$u_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_e \varphi_d \quad (15)$$

u_d is the d axis voltage, u_q is the q axis voltage, i_d is the d axis current, i_q is the q axis current, R_s is the stator resistance, φ_d, φ_q are the d axis and q axis flux linkage respectively, ω_e the electrical speed

$$\varphi_d = L_d i_d + \varphi_m \quad (16)$$

$$\varphi_q = L_q i_q \quad (17)$$

L_d is the d axis inductance, L_q is the q axis inductance, φ_m is the permanent magnet flux linkage

$$u_d = R_s i_d + \frac{d}{dt}(L_q i_d + \varphi_m) - \omega_e L_q i_q \quad (18)$$

$$u_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \varphi_m) \quad (19)$$

The surface mounted PMSG is considered, the inductance are equal for d axis and q axis ,the equation becomes

$$u_d = R_s i_d + \frac{di_d}{dt} L - \omega_e L i_q \quad (20)$$

The general mechanical equation of the machine is

$$\frac{dw_r}{dt} = \frac{T_m - T_e}{J} - \frac{Bw_r}{J} \quad (21)$$

where

$$K_t = \frac{3}{4} P \varphi_m$$

$$T_e = K_t i_q$$

The mathematical model of PMSG is

$$\frac{di_d}{dt} = -\frac{R_s}{L} i_d + \frac{P}{2} i_q \omega_r - \frac{1}{L} u_d \quad (22)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L} i_q - \frac{P}{2}(i_d - \frac{\varphi_m}{L})\omega_r - \frac{1}{L} u_q \quad (23)$$

$$\frac{d\omega_r}{dt} = \frac{T_m}{J} - \frac{k_t i_q}{J} - \frac{B\omega_r}{J} \quad (24)$$

In order to make the PMSG stable we are applying the current and torque control methods. Current control is needed to make sure the actual current follows the wanted current reference values. As it is known from d_q reference analysis there is a cross coupling between the q-axis and the d-axis in equations. This can be avoided by feed forward technique, defining that a reference voltage $v_d = u_d + \omega_e L i_q$ and $v_q = u_q - \omega_e L i_d - e_q$. This gives two independent first order equations in the d_q frame as follows

$$u_d = R_s i_d + L_s \frac{di_d}{dt} \quad (25)$$

$$u_q = R_s i_q + L_s \frac{di_q}{dt} \quad (26)$$

The transfer functions from i to v can therefore be written as

$$\frac{i(s)}{u(s)} = \frac{\frac{1}{R_s}}{1 + \frac{L_s}{R_s} s} \quad (27)$$

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These current loops are controlled using PI regulators. In wave energy large fluctuations in speed is to be expected and consequently a large over rating of the generator will be needed for it not to operate above rated speed. Thus a more practical approach is to allow over-speed operation. In order to extend the operation speed to above rated speed it is necessary to weaken the magnetic field.

It is not possible to directly control the field produced by the permanent magnets, controlling the flux is not as easy as for conventional double excited electrical machines.

Under rated conditions the d-axis current is kept at zero in order to slow as possible current under constant torque operation. However, in order to weaken the resultant magnetic field a negative d-axis current is needed. This is called field weakening control, and is a well known subject for PM-machines.

The electromagnetic torque which is proportional to the q axis current. The relation between the current and torque is given by

$$i_{q,ref} = \frac{T_{e,ref}}{\frac{3}{2} n_{pp} \Psi_{PM}} \qquad (28)$$

Therefore the reference current is obtained as

$$i_{q,ref} = -\frac{\omega_e R_s \Psi_{PM}}{R_s^2 + \omega_e^2 L^2} \qquad (29)$$

A PWM and converter bridge is also used here in order to connect the overall system to the grid.

VII. SIMULATION RESULT OF THE SYSTEM

In this simulation is done by combining the hydro dynamical model and the PTO system model. The parameters used for the simulation of PMSG are shown below.

TABLE II

Description	Symbol	Units	Values
Air density	ρ	Kg/m3	1.025
Rotor radius	R	M	38
Stator resistance	Rs	Ω	0.08
d-axis inductance	Ld	H	0.334
q-axis inductance	Lq	H	0.217
Permanent magnet flux	φ_m	Wb	0.4832
Pole pairs	P	-	3

The irregular wave pattern is considered and the output from the PTO system is shown in fig 8 & 9.

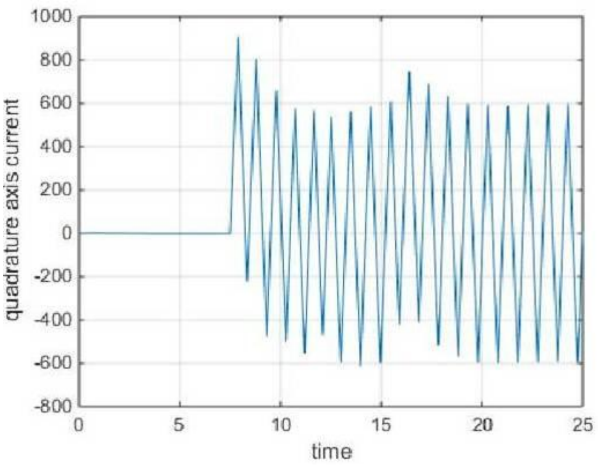

Fig.7 Quadrature axis current

This figure shows the quadrature current corresponding to the irregular wave pattern.

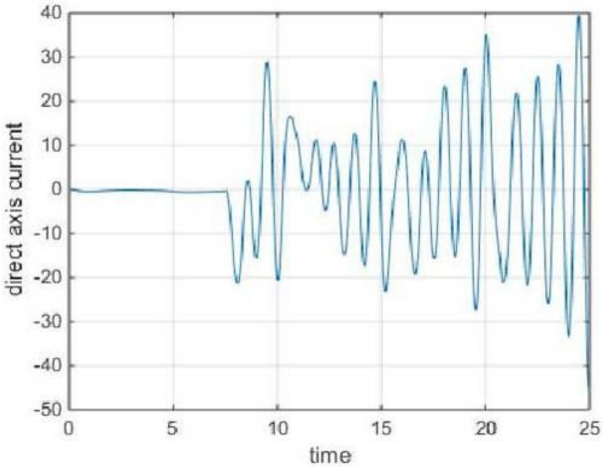

Fig.8 Direct axis current

This fig shows the direct axis current corresponding to the irregular wave pattern. The current and torque control is also implemented in order to obtain a better output current waveform. By analyzing these two graphs it is clear that the overall PTO system is stable.

VIII. GRID SIDE CONVERTER CONTROL

The main objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The control of the grid-side converter are organized in two loops; a DC-link current control loop, which controls the current through the grid filter, and DC-link voltage control loop that controls the dc-link voltage. In this work injection of DC voltage to the grid is considered. The controller is implemented at the rectifier side to regulate voltage fluctuations. The actual DC voltage is compared with its reference value to form error signal which is passed through the controller to generate the reference signals for the PWM generator. The pulses from the PWM generator are then fed to the gate of the rectifier to generate the regulated DC voltage

IX. SLIDING MODE CONTROLLER

Sliding mode control (SMC) is a technique derived from Variable Structure Theory. The basic idea of SMC controller is to force the tracking error e(t), after a finite time of reaching phase, to approach the sliding surface S(t) containing the system operating point and and then move along the sliding surface to the origin. SMC controllers proved their capability to handle nonlinear and time varying systems, high accuracy and robustness with respect to various internal and external disturbances.

The sliding surface S(t) is defined with the tracking error e(t) and its integral (∫edt) and rate of change ($\dot{e}$)

$$S(t) = \frac{de(t)}{dt} + \lambda_1 e(t) + \lambda_2 \int e(t)dt + \lambda_0 \quad (30)$$

Here $\lambda_0, \lambda_1, \lambda_2 > 0$ are positive real constants. These values are obtained by using trial and error method.

X. SIMULATION RESULTS

The overall model is then connected to the grid side and implementing SMC controller in the grid side to regulate the voltage fluctuations.

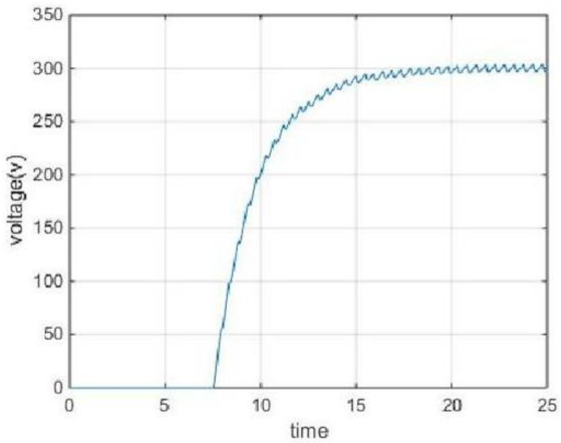

Fig.9 Output voltage using SMC

This graph shows the regulated DC output voltage by using SMC. The voltage settles the reference value of 300 at a time of 20 sec. Due to the high switching frequency of SMC, the output voltage exhibits some disturbances.

XI. CONCLUSION

The point absorber based wave energy converter is modeled in the time domain and then this hydro dynamical model is connected to the overall PTO system. The main function of the PTO system is to transform the mechanical power to the electrical power. The overall system is connected to the grid side .By implementing SMC controller at the grid side, the output voltage settles at the reference value and thus the voltage is regulated.

REFERENCES

[1] T.W. Thorpe. 2010 survey of energy resources. Technical report, World Energy Council, 2010.

[2] A. Babarit, J. Hals, M.J. Muliawan, A. Kurniawan, T. Moan, and J.Krokstad. Numerical benchmarking study of a selection of wave energy converters. Renewable Energy, (0):–, 2011.

[3] J. Falnes J. Hals, T. Bjarte-Larsson. Optimum reactive control and control by latching of a wave-absorbing semisubmerged. heaving sphere. In Proc. of the 21th Int.l Conf. on Offshore Mechanics and Arctic Eng., volume 3, pages 343–350, 2002.

[4] E.Tedeschi and M. Molinas. Control strategy of wave energy converters optimized under power electronics ratings constraints.In Proceedings of the International Conference on Ocean Energy, volume 3, pages 343–350, 2010

[5] Ida Kathrine Bjerke, Jonas Sjolte, and Gaute Tjensvoll. Experiences from field testing with the bolt wave energy converter. In .

[6] W. H. Mitchell. Sea spectra revisited. I Marine Technology, volume 4, pages 211– 227, 1999.

[7] R.G. Dean and R.A. Dalrymple. Water wave mechanics for engineers and scientists, volume 2. Prentice Hall, 1984.

[8] J. Hals. Modelling and phase control of wave-energy converters. diploma thesis, Norwegian University of Science and Technology.

[9] W. E Cummins. The impulse response functions and ship motions. Schiffstechnik, 1962.

[10] Reza Taghipour, Tristan Perez, and Torgeir Moan. Hybrid frequencytime domain models for dynamic response analysis of marine structures. Ocean Engineering, 35(7):685 – 705, 2008.

[11] S. Kung. A new identification and model reduction algorithm via singular value decompositions. In Proc. of the 12th Aslilomar Conf. on Circuits, Systems and Computers, pages 705–714, 1978.

[12] E. Tedeschi and M. Molinas. Impact of control strategies on the rating of electric power take off for wave energy conversion. In Industrial Electronics (ISIE), 2010 IEEE International Symposium on, pages 2406 –2411, july 2010.

[13] J. Falnes. Ocean Waves and Oscillating Systems. April 2002