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Modelling Wave Power by Equivalent Circuit Theory

LING HAI

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Abstract
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The motion of ocean waves can be captured and converted into usable electricity. This indicates that wave power has the potential to supply electricity to grids like wind or solar power. A point absorbing wave energy converter (WEC) system has been developed for power production at Uppsala University. This system contains a semi-submerged buoy on the water surface driving a linear synchronous generator placed on the seabed. The concept is to connect many small units together, to form a wave farm for large-scale electricity generation.

A lot of effort has gone into researching how to enhance the power absorption from each WEC unit. These improvements are normally done separately for the buoy, the generator or the electrical system, due to the fact that modelling the dynamic behavior of the entire WEC system is complicated and time consuming. Therefore, a quick, yet simple, assessment tool is needed.

This thesis focuses on studying the use of the equivalent circuit as a WEC system modelling tool. Based on the force analysis, the physical elements in an actual WEC system can be converted into electrical components. The interactions between the regular waves, the buoy, and the Power Take-off mechanism can be simulated together in one circuit network. WEC performance indicators like the velocity, the force, and the power can be simulated directly from the circuit model. Furthermore, the annual absorbed electric energy can be estimated if the wave data statistics are known.

The linear and non-linear equivalent circuit models developed in this thesis have been validated with full scale offshore experimental results. Comparisons indicate that the simplest linear circuit can predict the absorbed power reasonably well, while it is not so accurate in estimating the peak force in the connection line. The non-linear circuit model generates better estimations in both cases. To encourage researchers from different backgrounds to adapt and apply the circuit model, an instruction on how to establish a non-linear equivalent circuit model is supplied, as well as on how to apply the model to accelerate the decision making process when planning a WEC system.

Keywords: Wave energy, hydrodynamics, electric circuit, electrical analogy, energy absorption, force, system modelling, Simulink, engineering science, renewable energy

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To my dear family

List of papers

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

I **Hai L.**, Svensson O., Isberg J., and Leijon M., ”Modelling a point absorbing wave energy converter by the equivalent electric circuit theory: A feasibility study”. *Journal of Applied Physics*, 117, 164901, April 2015, Copyright 2015, AIP Publishing LLC.

II **Hai L.**, Göteman M., and Leijon M., ”A Methodology of Modelling a Wave Power System via an Equivalent RLC Circuit”. Submitted to *IEEE Transactions on Sustainable Energy*, revision requested.

III **Hai L.**, Ulvgård L., and Leijon M., ”Planning a wave energy conversion system by equivalent circuit modelling method”. *Manuscript*, October 2015.

IV Lejerskog E., Boström C., **Hai L.**, Waters R., and Leijon M., ”Experimental results on power absorption from a wave energy converter at the Lysekil wave energy research site”. Vol. 77, 9-14, *Renewable Energy*, May 2015.

V **Hai L.**, Svensson O., Castellucci V., Lejerskog E., Waters R., and Leijon M., ”Force in the connection line for a wave energy converter: simulation and experimental setup”. Submitted to *Journal of Offshore Mechanics and Arctic Engineering*, Feburary 2015.

VI Ulvgård L., **Hai L.**, and Leijon M., ”Measurement System for Evaluating Wanted and Unwanted Forces on a Point Absorbing Wave Energy Converter during Offshore Operation”. *Proceedings of the 25th International Ocean and Polar Engineering Conference* (peer-reviewed), ISOPE2015, Kona, USA, June 2015.

VII Parwal A., Remouit F., Hong Y., Francisco F., Castellucci V., **Hai L.**, Ulvgård L., Li W., Lejerskog E., Baudoin A., Nasir M., Chatzigiannakou M., Haikonen K., Ekström R., Boström C., Göteman M., Waters R., Svensson O., Sundberg J., Rahm M., Engström J., Savin A., and Leijon M., ”Wave Energy Research at Uppsala University and The Lysekil Research Site, Sweden: A Status Update”. *Proceedings of the 11th European Wave and Tidal Energy Conference* (peer-reviewed), Nantes, France, September 2015.

VIII Lejerskog E., Boström C., Savin A., Strömstedt E., Gravråkmo H., Engström J., Haikonen K., Rahm M., Ekergård B., Svensson O., Waters R., Tyrberg S., Ekström R., Kurupath V., Li W., Sundberg J., Leijon M., Baudoin A., **Hai L.**, and Krishna R., ”Lysekil Research Site, Sweden: Status Update”. *Proceedings of the 9th European Wave and Tidal Energy Conference* (peer-reviewed), Southampton, UK, September 2011.

Other contributions of the author that is not included in the thesis.

IX Castellucci V., Kamf T., **Hai L.**, and Waters R., ”Control System For Mean Sea Level Variation Compensator At The Lysekil Research Site”. *Proceedings of the 2nd Asian Wave and Tidal Energy Conference*, Tokyo, Japan, July 2014.

X Li W., Engström J., **Hai L.**, Bontemps S., Isberg J., Waters R., and Leijon M., ”Optimization of the dimensions of a gravity-based wave energy converter foundation based on the heave and surge forces”. *Proceedings of the 9th European Wave and Tidal Energy Conference*, Southampton, UK, September 2011.

Paper V also appears in the conference preceding:
Hai L., Svensson O., Castellucci V., Lejerskog E., Waters R., and Leijon M., ”Force in the connection line for a wave energy converter: simulation and experimental setup”. *Proceedings of the ASME 33rd International Conference on Ocean, Offshore and Artic Engineering* (peer-reviewed), OMAE2014, San Francisco, USA, OMAE 2014-23147, June 2014.

Contents

Nomenclature and abbreviations

Symbol	SI unit	Quantity
g	m/s^2	Acceleration of gravity
ρ	kg/m^3	Density
T_e or T_{m0-1}	s	Wave energy period
H_s or H_{m0}	m	Significant wave height
h	m	Water depth
λ	m	Wavelength
ω	rad/s	Angular frequency
f	Hz	Frequency
k	1/m	Wave number
η	m	Surface wave elevation
T	s	Wave period
H	m	Wave height
J	W/m	Energy flux
A	m	Wave amplitude
$S(f)$	m$^2/Hz$	Wave power spectrum
T_0	s	Total measured time
ϕ	m$^2/s$	Velocity potential
S_w	m^2	Wet surface of the buoy
P_h	N/m^2	Pressure
f_e	N	Excitation force per unit length
F_e	N	Excitation force
F_r	N	Radiation force
m_a	kg	Added mass
$m_a(\infty)$	kg	Added mass at infinite frequency
B	kg/s	Radiation damping coefficient
$L(t)$	-	Radiation impulse response function
R	Ω	Resistance
Z	Ω	Impedance
I	A	Current
U	V	Voltage
P	W	Power
P_{peak}	W	Peak power
P_{avg}	W	Average power
v	m/s	Velocity

z	m	Displacement
$\dot{z}$	m/s	Velocity
$\ddot{z}$	m/s^2	Acceleration
S	m^2	Cross-sectional area of the buoy
a	m	Radius of the cylindrical buoy
h_b	m	Height of the cylindrical buoy
r_b	m	Minor radius of the toroidal buoy
R_b	m	Major radius of the toroidal buoy
V_{sub}	m^3	Submerged volume of the buoy
b	m	Draft of the buoy when the connection line is tight
b'	m	Draft of the buoy when the connection line is slack
M_b	kg	Mass of the buoy
M_t	kg	Mass of the translator
k_s	N/m	Spring constant of the retracting spring
k_{line}	N/m	Spring constant of the connection line
k_{damper}	N/m	Spring constant of the rubber damper
C_{damper}	kg/s	Damping coefficient of the rubber damper
γ	kg/s	Electromagnetic damping coefficient
A_{act}	%	Active area ratio
l_u	m	Upper free stroke length
l_l	m	Lower free stroke length
l_s	m	Length of the stator
l_t	m	Length of the translator
k_u	N/m	Spring constant of the upper end-stop spring
k_l	N/m	Spring constant of the lower end-stop spring
F_{em}	N	Electromagnetic damping force
F_{PTO}	N	PTO force
F_s	N	Retracting spring force
F_{line}	N	Force in the connection line
$F_{preload}$	N	Preload force from the retracting spring
$F_{endstop}$	N	End-stop spring force
L_g	H	Inductance of the generator
R_g	Ω	Resistance of the generator
R_c	Ω	Resistance of the sea cable
R_l	Ω	Resistance of the load
V_g	V	Voltage over the generator
V_c	V	Voltage over the sea cable
V_l	V	Voltage over the load

Abbreviations

Symbol	Full name	Symbol	Full name
WEC	Wave Energy Converter	OWC	Oscillating Water Column
PTO	Power Take-off	BC	Boundary Condition
AC	Alternating Current	DC	Direct Current

1. Introduction

The world energy consumption has grown rapidly along with the industrialization process. Statistics from the International Energy Agency (IEA) indicate that from 1971 to 2012, the world's primary energy supply has doubled.[1] Fossil fuels such as coal, oil and natural gas were the main sources of energy for this tremendous growth. The heavy reliance on fossil fuels is considered a real danger for national energy security. Furthermore, there is a growing concern about the environmental damage and pollution problems caused by the exploitation, refining, combustion and waste disposal of the fossil fuels.

The concept of capturing natural energy resources and converting them into electrical energy or heat, has gained much attention. It raises the hope of supplying sustainable and environmentally benign energy, as well as promoting energy supply diversity. Renewable energy technologies such as hydro-power, solar photovoltaic energy, wind power, geothermal energy and bioenergy are under fast development. The global renewables-based power generation capacity is estimated to have increased by 128 GW in 2014, a number that was below 40 GW before 2005. [2]

Oceans cover 70% of the earth's surface and contain considerable amounts of energy. There are several renewable energy sources that can be exploited, such as offshore wind, offshore solar energy, wave energy, tidal energy, marine currents, ocean thermal energy and so on. This thesis will focus on the ocean wave energy and its related research.

1.1 Potential and features of wave energy

Ocean waves can be caused by various reasons, such as storms, tsunamis, human activities like shipping, etc. However, wind is the most common cause of wave generation. Waves can be generated by several sources simultaneously, and it is not always easy to distinguish the source. This thesis only concentrates on waves produced by wind. It is interesting to note that energy transformed from winds to waves will be stored inside the waves. Once waves have been created, they do not disappear if the winds stop blowing and they can propagate for thousands of miles with only minor energy losses.

Wave energy has the potential to contribute significantly to the world's energy demand. The wave energy capacity of the world's oceans is estimated to be round 2 TW [3, 4, 5]. The IEA estimates that wave energy can produce enough electricity to meet 10% of world's electricity demand. The wave energy map shown in Fig. 1.1[3, 6], illustrates that the most energy intensive areas are between 40 and 60 degrees latitude in both hemispheres. The most energetic sites in Europe are the ocean area around Ireland and Scotland with an energy flux of around 75 kW/m. [7]

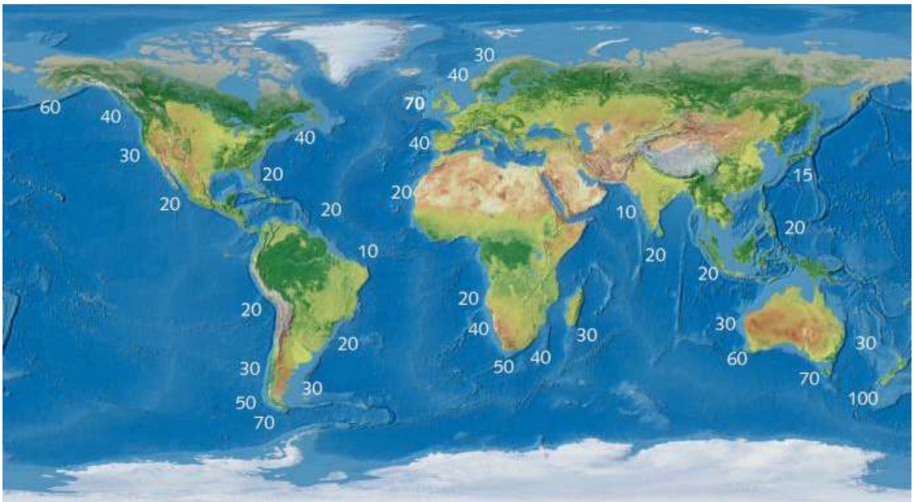

Figure 1.1. Distribution of the global wave energy resources, the numbers represent kW per meter of wave front. [3]

Compared to other renewable energy sources, wave energy has several advantages. It has the highest energy density, high availability (close to 90%), it is stable and predictable, and seasonal changes in intensity are in line with consumption etc. [8] For countries with coastlines or islands, wave power generation is an attractive alternative energy solution.

The main challenge to using wave energy is the harsh marine environment: the seawater is corrosive to metals and big storm waves have a great destructive force. This means that in addition to producing stable electric power under normal wave conditions, the wave power conversion devices also need to be able to resist corrosion and survive large waves.

1.2 Wave energy conversion technology

Unlike the typical three blades of windmills or flat solar panels, devices converting wave energy into electricity do not have a unified style. There are more than 1000 patents on wave energy conversion techniques have been registered by 1980 [9] and this number is still increasing. However, most of these devices are at the small-scale testing stage. Only a few projects have deployed their devices in the ocean, and so far no project has proved to be suitable for a large-scale commercial operation.

In general, the principles of capturing wave energy can be divided into four categories:

- *Point absorbing*. When the oscillating body is much smaller in dimension than the typical wavelength, it is called a point absorber, or *buoy*. Most point absorbers are axis-symmetric.
- *Line absorbing*. When the oscillating body has the same or a larger dimension than the typical wavelength, it is a line absorber, usually called an *attenuator* or *terminator* depending on whether the floater is in parallel with or perpendicular to the predominant wave direction.
- *Oscillating Water Column*. A Water Column has an air chamber in the system. As the air gets compressed or decompressed with the rising or falling water level, it drives a turbine at the exit of the chamber.
- *Over-topping*. This type of WEC is similar to a low-head hydro power system. Water is trapped and accumulated in a reservoir after high waves crossed the 'dam'. A low-head hydro turbine converts the energy from the difference in the water level inside and outside the reservoir.

The Power Take-off (PTO) equipment in wave energy conversion could be mechanical, hydraulic, pneumatic, or completely electric. Figure 1.2 shows four wave energy projects that have been installed in oceans as examples of how diverse the devices in wave energy field can be. Reviews on the wave energy technology can be found in [10, 11, 8, 12].

1.3 Wave energy research at Uppsala University

The wave energy research group of the Division of Electricity at Uppsala University in Sweden, has studied a point absorbing WEC system since 2002. In 2006, the first WEC system was deployed off the west coast of Sweden, and generated electricity successfully [13, 14]. So far, more than 10 types of WECs with different mechanical and electrical designs, and different power ratings have been deployed and tested offshore [15][16]. For simplicity, in the next chapters of this thesis, WEC refers to a point absorbing WEC, if not specified otherwise.

1.3.1 Principle of the system

The WEC system works as Fig 1.3 illustrates. The device consists of a floating buoy on the water surface that drives a linear generator sitting on the seabed. Inside the generator, permanent magnets are mounted on the surface of the translator, and electric coils are wound in the stator. When the semi-submerged buoy floats up and down with the waves, it moves the translator by means of a robust wire, resulting in a changing electromagnetic field, so that the coils in the stator induce voltages. Since the device eliminates the need for gearboxes

Figure 1.2. Examples of wave energy conversion projects based on different principles. (a) Oscillating water column WEC by oceanlinx. (b) Oscillating wave surge converter, Oyster project by Aquamarine Power. (c) Attenuating WEC by Pelamis. (d) Over-topping WEC by Wave Dragon.

and other sensitive and complex systems, a better reliability and efficiency can be expected.

There are four major advantages in using point absorbing wave energy converters:

- the principle of a point absorber means that the device is not sensitive to incident wave directions, which means a higher wave energy absorption ability.
- For a wave energy farm, when multiple point absorbing wave energy conversion devices are connected in a cluster, the total voltage fluctuation will be smaller than the output from one large-scale wave energy converter because the oscillations of the buoys are not synchronized. This means that the requirements for the power electronic devices will be lower.
- Thanks to the relatively small weight and size of the unit, the manufacture, transport and deployment will be easier.
- It is easy to adjust the scale of a wave power plant simply by adjusting the number of devices, there is no need to redesign the device itself for different projects.

1.3.2 Lysekil project

The Lysekil wave energy research site is the area used by Uppsala University to test full scale WECs. The wave energy research project is therefore known as the Lysekil Project. The site is around 2 km from the shore, has a relatively flat seabed and the average water depth is 25 m. A summary of the statistical results of the wave climate, based on 8 year wave data in this area, is shown in Table 1.1 [17].

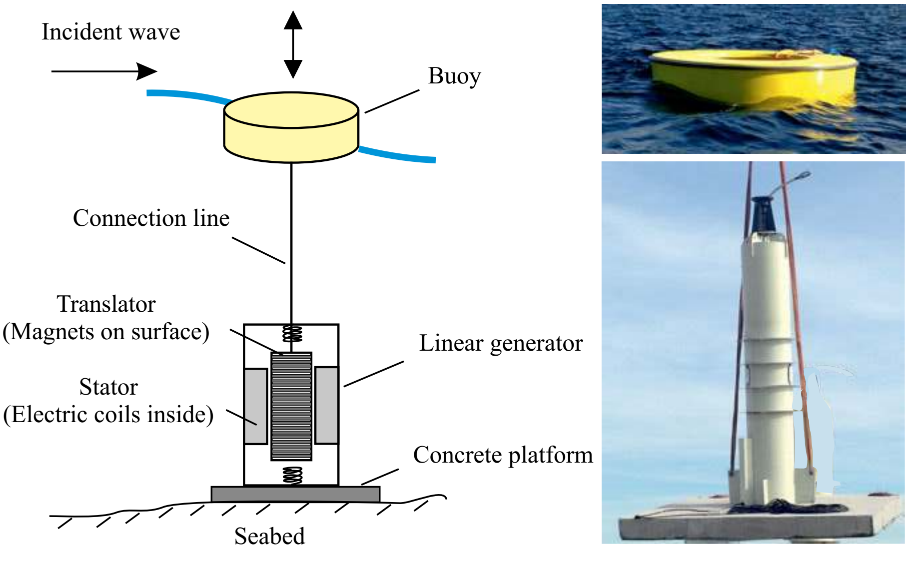

Figure 1.3. The wave energy converter developed by Uppsala University.

Table 1.1. *Summary of the Lysekil test site wave climate.*

	Energy Period	Significant Wave Height
Total range	1 - 12 s	0.1 - 4 m
Medium energy density and occurrence	4 - 8 s	0.8 - 3 m
Most frequent	around 5 s	around 1.5 m

This summary is useful for the design and evaluation of a WEC system. One needs to consider all the possible wave climates. However, the focus will be on the range with medium energy density and occurrence, while the optimal operational mode of a WEC ought to be for the sea states that occur most frequently.

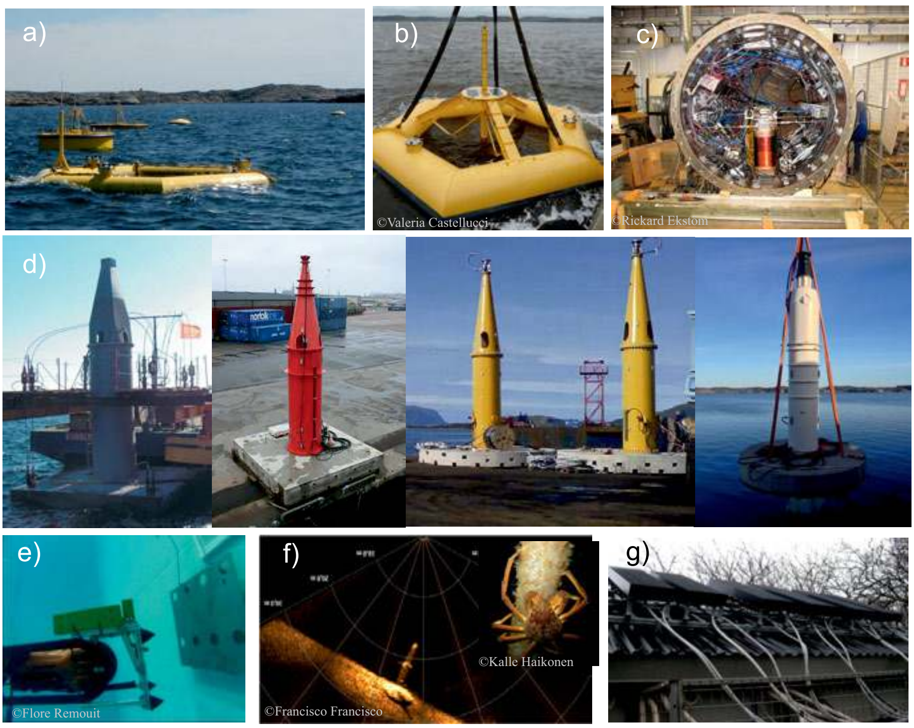

Figure 1.4. Some research activities at the Lysekil research site. (a) Buoys of different sizes and geometries. (b) A buoy with a tidal compensation system. (c) The second generation marine substation. (d) Linear generators. (e) Remotely Operated Vehicle (ROV). (f) An echo-image from a sonar device to study the environmental impacts, the smaller picture shows a crab staying on the buoy line. (g) Resistive loads on the measurement cabin roof.

Current research activities in the Uppsala wave research group include improvements of the WEC system: studies on a better power absorption and survivability, research on grid connection, wave power park studies, environmental studies and the optimization of the deployment method, such as using remotely operated underwater vehicle (ROV), etc. Figure 1.4 shows several research activities from Lysekil, Paper VII and Paper VIII provide thorough descriptions and updates of the Lysekil project research.

1.3.3 Previous work

The wave energy research group in Uppsala University has published 17 Ph.D. dissertations and and 5 Licentiate dissertations to date. The wave - buoy - PTO interaction has been investigated in theses [18, 19, 20, 21, 22, 23]. [18] focuses on the theoretical modelling of the whole WEC system, [19] places a great emphasis on using a camera system for measurements to facilitate the performance study. [20] contains both the research on wave energy transport and a theoretical modelling of the two-body system. [21] studies the hydrodynamic characteristics of the toroidal shaped buoy, [22] looked into the idea of using the equivalent circuit modelling method for the hydrodynamic modelling, and [23] compares the use of COMSOL instead of WAMIT for the hydrodynamic modelling.

The design and improvement of a linear synchronous permanent magnet generator can be found in [24, 25, 26, 27]. [24, 25] present the design and simulation of the first generator. [26] studies the generator using ferrite magnets instead of $Nd_2Fe_{14}B$ magnets, and [27] gives a study of the electromagnetic design of closed stator slots. Thesis [27] also presents an investigation on the relation between power absorption of a WEC in upward and downward motion with the configuration of a WEC system.

The measurement systems for voltage, current, translator position and forces are described in [28, 29, 30]. In addition, [29, 30] include an extensive part on the mechanical design of the generator. Thesis [31] contains the measurement for the air gap width, a study of the Swedish west coast wave climate, as well as experimental results from the first WEC unit deployed at Lysekil.

Thesis [32] presents the design of a transmission system of a wave power farm connected to the grid. The electrical system has been thoroughly studied in [33]. The first and the second marine substations for the control system and the grid connection are included in [34, 35] respectively. The thermal study on the substation is in [36]. One thesis has a focus on power electronics: [37]. Needless to say, the impact of the installation and operation of WECs on the marine ecosystem is of great importance. Research on this topic can be found in theses [38, 39].

1.4 Research questions and aims

After it was proved that the Uppsala WEC concept could produce electricity, the research focused on how to improve the system: how to generate more electric power with a better designed buoy; how to improve the generator and electrical system; how to reduce costs and how to make the mechanical structures more robust and reliable. These improvements are usually made separately, with little attention to the question whether each part of the system matches the others, or whether they will perform in an optimal manner when combined together.

The main cause of this is the interdisciplinary nature of the WEC system modelling. To know the dynamic response of the system, one needs to perform wave-buoy hydrodynamic interaction modelling [40]; finite element modelling of the generator [41] and electrical system simulation [33]. Next, on needs to merge the results from each part. This modelling method can lead to accurate results [18]. However, it requires researchers from different fields using different software to collaborate, which is complex and time consuming.

It would therefore be valuable to have a quick WEC system performance assessment with just one tool. However, this tool needs to be easy to understand and easy to apply, so everyone can use it. This thesis describes the research on using the equivalent circuit as a common modelling language. By extracting the dominating factors from each sub-system, and converting those physical elements into electrical components, one could carry out an analysis of the entire WEC system by simulating one electric circuit model.

The idea of employing the equivalent circuit technique in a WEC system is not new. Many have used the linearised circuit model to improve the understanding of a WEC system, such as [42] and [43]. It has also been applied in control strategy studies which aim to optimise energy absorption in regular [44, 45, 46] and irregular waves [47, 48, 49].

To the best knowledge of the author, the accuracy of the existing linearized model has not been examined thoroughly. There is no non-linear equivalent circuit model established for an actual point absorbing WEC system, nor has the methodology of applying such models on a WEC performance evaluation been addressed. Based on these, the research behind this thesis aims to answer the following questions:

- Is it possible to model a point absorbing WEC system with more details by an electric circuit model? If yes, how reliable is it?
- Which parameters can be simulated in this circuit model, in other words, what can it be used for?
- How can the circuit model be adjusted for a WEC unit with a different design, or can one use the model for other research problems?
- How exactly can one perform a WEC system planning or optimization through the presented modelling method?

1.5 Outline of the thesis

This thesis aims to cover all four aspects above, with an emphasis on developing a framework for the equivalent circuit modelling method and practical guidance on how to master it. The thesis starts with a brief introduction on the research background in this chapter. Chapter 2, Theory, covers basic wave theory and electric circuit theory. It gives a theoretical foundation for the rest of the thesis. Chapter 3 presents the methodology on how to develop an equivalent circuit model, and the studies that can be carried out with the equivalent circuit modelling method. A force measurement system that has been designed and built by the author is introduced in Chapter 4, Experiments. The experimental set-up used for the circuit model validation is described in this chapter as well. Chapter 5, Summary of results, collects the most essential results that have been published in papers attached to this thesis. Chapter 6, Discussions on the circuit model, expounds the performance and characteristics of the equivalent circuit modelling method. Finally, conclusions and suggestions for future work are given in Chapter 7 and 8.

2. Theory

Modelling the dynamic response of a WEC system means studying how the incident waves, buoy and PTO mechanism interact with each other. Establishing an equivalent circuit model builds on understanding the behaviour of an electric circuit. This chapter presents theories that are related to these two aspects.

2.1 Ocean wave theory

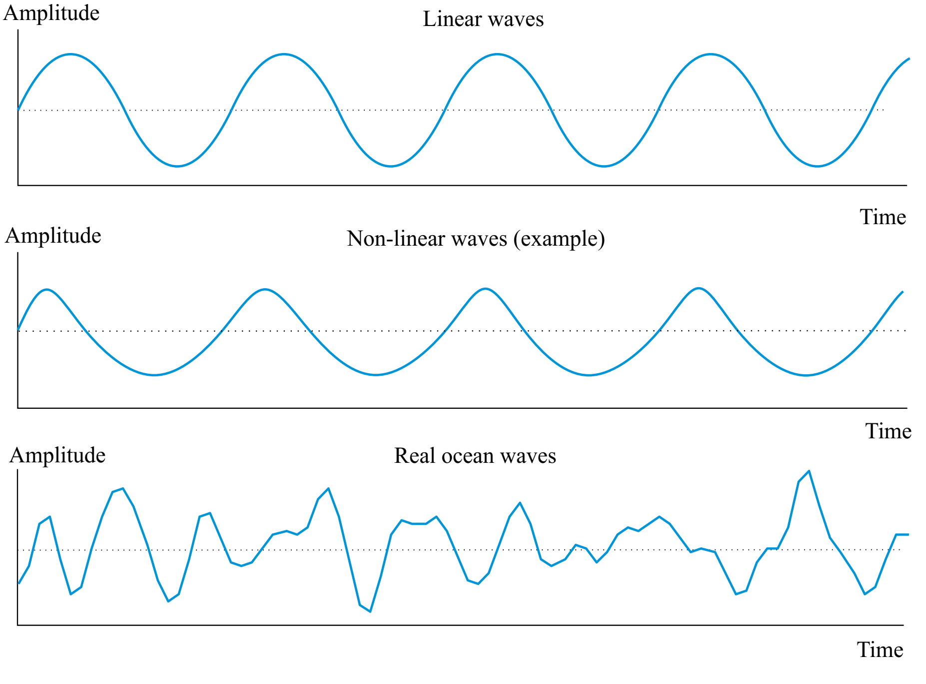

Figure 2.1. Sketch of different wave profiles.

Ocean waves are inherently non-linear and stochastic. However, to analyse how a body interacts with ocean waves, it is convenient to classify waves into linear waves and non-linear waves. For linear waves, the superposition principle can be applied. The linear wave theory is valid most of the time, i.e., when assuming the wave height is much smaller than the wavelength. Non-linear waves, on the other hand, the superposition principle does not generally apply to them. The non-linear wave theory is applicable primarily for extreme wave conditions, e.g. a randomly rough seabed or a transient tsunami [50]. The non-linear wave shown in Fig. 2.1 illustrates a non-linear wave profile close to the shore region, where the seabed has an impact on the shapes of the waves.

This thesis limits itself to the linear wave theory, i.e., only small-amplitude waves will be taken as incident waves, since earlier research proved it to be valid for normal operation conditions of the WEC system [18]. For further studies on wave theory, Chapter 2 in book [31] is a good start to catch some basic concepts, book [50] states theories on linear and non-linear ocean surface waves, and book [51] is more specific on the interaction between waves and oscillating bodies, mainly from a mathematical perspective. [52] has discussed waves and the response of floating bodies. MIT's open courses also provide a good opportunity to learn about ocean science. One example is a course called Ocean Wave Interaction with Ships and Offshore Energy Systems [53].

2.1.1 Terminologies

The characteristics of a single sinusoidal wave can be defined by the basic parameters illustrated in Fig. 2.2. In addition, if the wave period T which is the time it takes two neighbouring wave crests or troughs to pass a fixed point, is known, we will get the wave frequency f, angular wave frequency ω and wave number k from Eq. (2.1) and Eq. (2.2).

$$\omega = 2\pi f = \frac{2\pi}{T}. \tag{2.1}$$

$$k = \frac{2\pi}{\lambda}. \tag{2.2}$$

Real ocean waves are irregular and composed of many interfering waves of different frequencies, amplitudes, phases and directions of propagation. Irregular waves are of a stochastic nature, and they may be considered as a superposition of many different frequencies [51]. One way to evaluate a sea state over a certain time period is by calculating the power spectrum from an acquired wave surface elevation η data, see Eq. (2.3):

$$S(f) = \frac{2}{T_0}\left| \int_0^{T_0} \eta(t) e^{2\pi f t} dt \right|^2. \tag{2.3}$$

Here T_0 is the total measured time. The spectrum describes how wave energy is distributed along different wave frequencies of different wavelengths. Two important quantities are associated with the wave power spectrum: significant wave height H_s and wave energy period T_e. H_s used to be defined as the mean wave height of the highest one third of the waves. Nowadays it is defined as four times the standard deviation of the surface elevation, or four times the

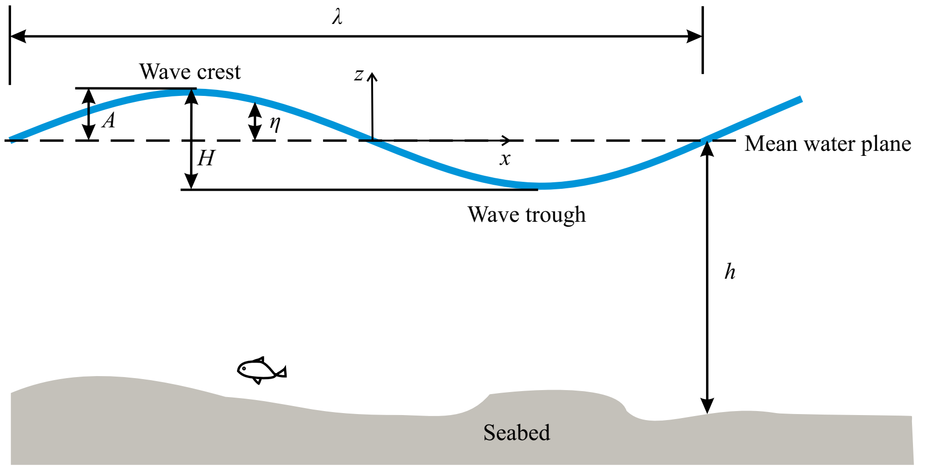

Figure 2.2. Sketch of a single sinusoidal wave and coordinate system.

square root of the zeroth-order moment of the wave spectrum. Eq. (2.4) - Eq. (2.6) present a way to calculate the significant wave height and energy period.

$$m_n = \int_0^\infty f^n S(f) df. \tag{2.4}$$

$$H_s = H_{m0} = 4\sqrt{m_0}. \tag{2.5}$$

$$T_e = T_{m0-1} = \frac{m_{-1}}{m_0}. \tag{2.6}$$

The energy flux for real ocean waves can be calculated if the wave energy period and the significant wave height are known:

$$J = \frac{\rho g^2}{64\pi} T_{m0-1} H_{m0}^2 \quad [\text{W/m}]. \tag{2.7}$$

2.1.2 Potential linear wave theory

An interesting fact is that the paths that water particles move vary for different water depths. In deep water, water particles move in circular orbits and the diameters decrease exponentially with z. In intermediate or shallow water, these particles move in elliptic orbits, and the wave profiles become non-linear, as presented in Fig. 2.3. Ref. [9] has concluded that from the resource estimates, deep water is more feasible for wave energy conversion than coastal water.

To describe a time-harmonic wave motion with a certain frequency, potential linear wave theory is developed. The theory applies when the wavelength is much larger than the wave height, while the fluid motion generated by moving

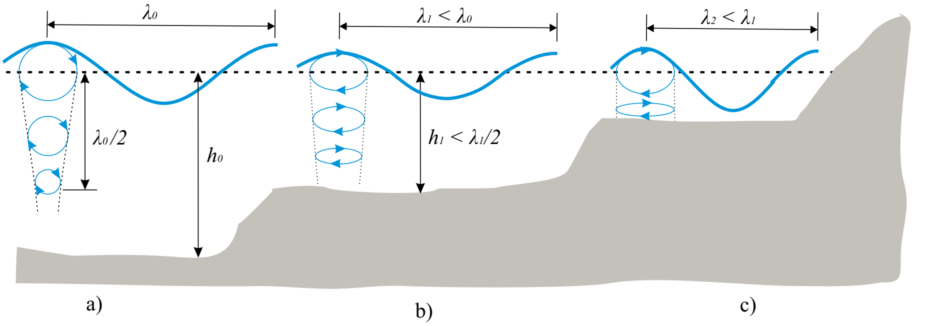

Figure 2.3. Properties of waves for different water depth. (a) deep water, $h > \lambda/2$, (b) intermediate water, $\lambda/2 > h > \lambda/20$, (c) shallow water, $h < \lambda/20$. The picture is adapted from [9].

bodies is small [54]. The potential linear wave theory is based on the Navier-Stokes equation, Eq. (2.8) and the continuity equation, Eq. (2.9), together with several assumptions and boundary conditions.

$$\frac{\partial \bar{v}}{\partial t} + (\bar{v} \cdot \nabla)\bar{v} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \bar{v} + \frac{1}{\rho}\bar{f}. \tag{2.8}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{v}) = 0. \tag{2.9}$$

Here $\bar{v}$ is the velocity vector, ν is the kinematic viscosity, and $\bar{f}$ is the external force on fluid. Basic assumptions include:

- Incompressible fluid: $\rho = constant$.
- Irrational fluid: $\nabla \times \bar{v} = 0$.
- Negligible viscosity: $\nu = 0$.
- Gravity is the only external force: $\bar{f} = g\rho\hat{z}$.
- Small velocity: v^2 can be neglected compared to the velocity v.
- Small amplitude waves.

And the boundary conditions contain:

- Sea floor boundary condition:

$$\left.\frac{\partial \phi}{\partial z}\right|_{z=-h} = 0. \tag{2.10}$$

- Surface boundary condition:

$$\frac{\partial \eta}{\partial t} = \left.\frac{\partial \phi}{\partial z}\right|_{z=0}, \quad \left.\frac{\partial \phi}{\partial t}\right|_{z=0} = -g\eta. \tag{2.11}$$

The resulting derived velocity potential, surface wave elevation and dispersion relation are presented in Eq. (2.12), Eq. (2.13) and Eq. (2.14) respectively. The corresponding terms can be found in Fig. 2.2.

$$\phi = \frac{gH}{2\omega} e^{kz} \sin(kx - \omega t). \tag{2.12}$$

$$\eta = \frac{H}{2} \cos(kx - \omega t). \tag{2.13}$$

Wave angular frequency ω and wave number k are interrelated by the dispersion relation:

$$\omega^2 = gk \tanh(kh). \tag{2.14}$$

For deep water case, Eq. (2.14) can be approximated as

$$\omega^2 = gk. \tag{2.15}$$

2.1.3 Wave-buoy interactions

The hydrodynamic problem regarding the interaction between regular waves and the floating buoy, is normally divided into two sub-problems [55]:

- *scattering problem*, defined as the force and moments on the buoy when it is fixed on the water surface without oscillating. The scattering waves include incident waves and diffracted waves. The resulting hydrodynamic force on the buoy from the scattering problem is called *excitation force*.
- *radiation problem*, defined as the force and moments on the buoy when there is an absence of incident waves, and the buoy oscillates freely in the water. There will be radiated waves generated by buoy's oscillation. The resistive force exerted on the buoy is called *radiation force*.

Figure 2.4 is to facilitate the understanding of the above.

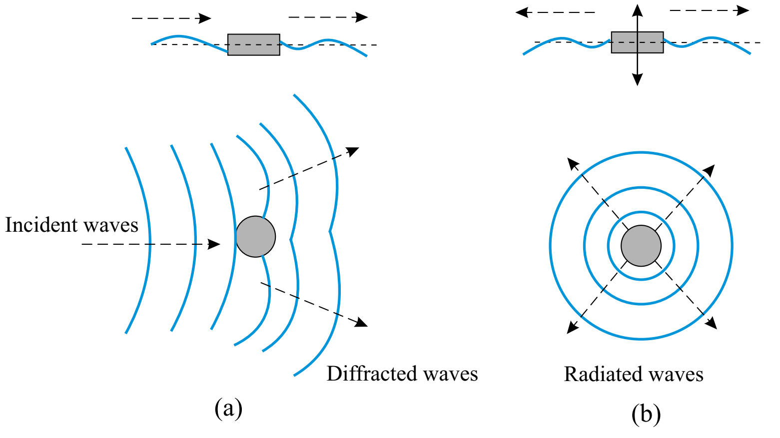

Figure 2.4. Sketch of (a) scattering problem, (b) radiation problem. The solid blue line represents harmonic waves, the dashed line with an arrow represents the wave propagation direction, and the object filled in grey is the buoy.

Applying superposition, the total velocity potential contains the incident wave velocity potential ϕ_{in}, the diffraction velocity potential ϕ_d and the radiation velocity potential ϕ_r:

$$\phi = \phi_{in} + \phi_d + \phi_r. \tag{2.16}$$

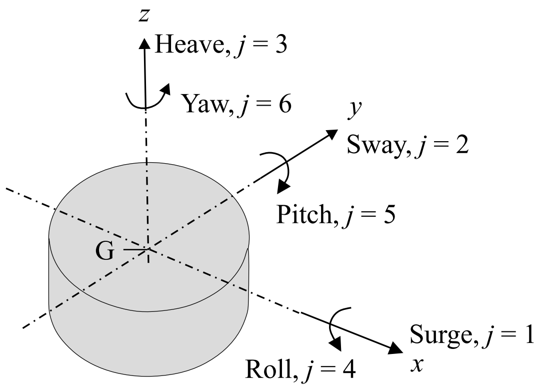

Figure 2.5. Sketch of six modes of motion of a rigid body.

There are six degrees of freedom or modes of motion can be used to describe the oscillation status of a rigid body, see Fig. 2.5. In general, the hydrodynamic force acting on a body can be calculated from the pressure integrals, the corresponding wet surface S_w on its normal n_j for the oscillating mode j, as well as the velocity potential:

$$F_j = \iint_{S_w} P_h \, n_j \, dS = -\rho \iint_{S_w} \frac{\partial \phi}{\partial t} \, n_j \, dS. \tag{2.17}$$

$$F_{e,j}(\omega) = i\omega\rho \iint_{S_w} (\phi_{in} + \phi_d) \, n_j \, dS = f_{e,j}(\omega)\eta(\omega). \tag{2.18}$$

$$F_{r,j}(\omega) = i\omega\rho \iint_{S_w} \phi_r n_j \, dS = [i\omega m_{a,j}(\omega) + B_j(\omega)]\dot{z}_j(\omega). \tag{2.19}$$

In the time domain, the excitation force and the radiation force become:

$$F_e(t) = f_e(t) * \eta(t). \tag{2.20}$$

$$F_r(t) = m_a(\infty)\ddot{z}(t) + L(t) * \dot{z}(t), \tag{2.21}$$

where the asterisk * denotes the convolution product, $m_a(\infty)$ is the infinite frequency limit of the added mass, $L(t)$ is the radiation impulse response function (IRF), which could be calculated by either Eq. (2.22) or Eq. (2.23) [51].

$$L(t) = \frac{2}{\pi} \int_0^\infty \omega[m_a(\infty) - m_a(\omega)] \sin(\omega t) d\omega. \tag{2.22}$$

$$L(t) = \frac{2}{\pi} \int_0^\infty B(\omega) \cos(\omega t) d\omega. \tag{2.23}$$

2.2 Electric circuit theory

2.2.1 Basic concepts

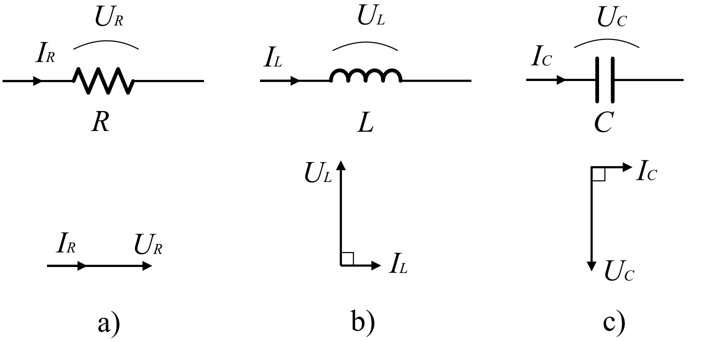

Figure 2.6. The relation between the voltage and current for a constant (a) resistor R, (b) inductor L, (c) Capacitor C, with sinusoidal steady-state excitation.

The circuits introduced in this thesis are composed of AC or DC voltage sources, electric switches, and passive elements - resistors R, inductors L, and capacitors C. The impedance of the RLC components are:

$$Z_R = R, \quad Z_L = j\omega L, \quad Z_C = \frac{1}{j\omega C}, \tag{2.24}$$

where $j = \sqrt{-1}$. For a purely resistive load, the current through this load I_R is in phase with the voltage drop U_R. For a purely inductive load, the current I_L lags the voltage U_L for 90 ^{o}, and for a purely capacitive load, the current I_C leads the voltage U_C for 90 ^{o}, the phase relation has been summarized in Fig. 2.6 in phasor forms and in a time scale in Fig. 2.7 (a).

The average power absorbed by a resistive load is called *active power* or *real power*, denoted as P. For inductive or capacitive loads, the time-average of the instantaneous power absorbed by them is zero, meaning they do not consume any electric energy. The amplitude of this instantaneous power is named *reactive power*, denoted as Q. Figure 2.7 (b) draws the instantaneous power curve for each element in a series connected RLC circuit, to aid the understanding of the active and reactive power concept.

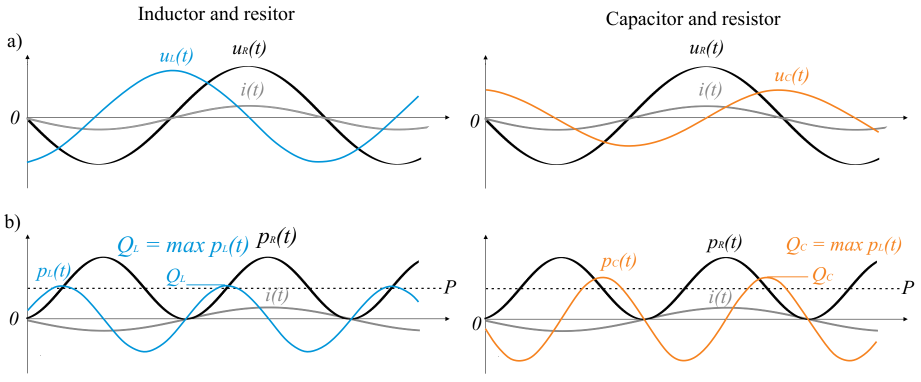

Figure 2.7. Illustration of the (a) phase shift between the voltage and the current. (b) Active power and reactive power. The simulation is done for a series connected RLC circuit, amplitudes have been rescaled.

2.2.2 Circuit analysis techniques

Ohm's Law lays the basis for the electric circuit analysis. It can be written in a general form:

$$U = IZ. \tag{2.25}$$

Figure 2.8 presents five different topologies of the electric circuit. For plot (a), a *series connected* electric circuit, the current passing every component is the same. Plot (b) is a *parallel connected* electric circuit, the voltage drop over each branch is the same. Plot (c) containing two voltage sources and two meshes, is a more complicated circuit to analyse. The *mesh analysis* which is based on Kirchhoff's Voltage Law (KVL) can be applied to analyse the circuit. The equations for two meshes are:

$$U_1 - I_1 Z_1 - (I_1 - I_2) Z_2 - I_1 Z_5 = 0, \tag{2.26}$$

$$U_2 - I_2 Z_3 - I_2 Z_4 - (I_2 - I_1) Z_2 = 0. \tag{2.27}$$

Circuits in Fig.2.8 (d) and (e) can have a *Y-* Δ *transformation*, if three impedances are identical in one diagram, $Z_Y = \frac{1}{3} Z_\Delta$.

The circuit analysis techniques introduced above are the main ones applied in this thesis. Other techniques such as the node analysis based on Kirchhoff's Current Law, the Thevenin and Norton theorems, superposition etc can also be useful tools. They can be found in university level electric circuit theory books such as [56].

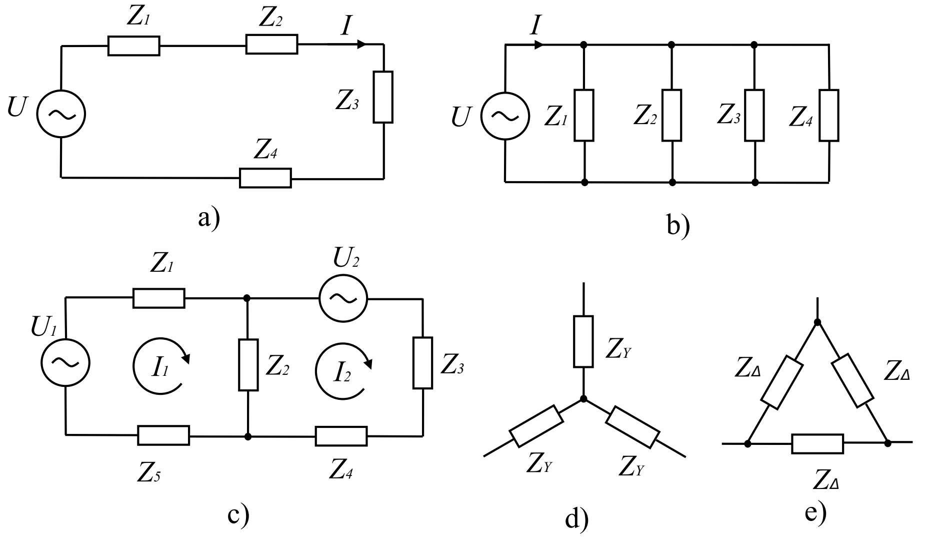

Figure 2.8. Different electric circuit topologies: (a) series connected, (b) parallel connected, (c) unbalanced circuit with two meshes, (d) Y connection, (e) Δ connection.

2.3 Power Take-off mechanism

PTO refers to the method of extracting energy from an energy source. The synchronous linear generator together with the electrical system is the PTO unit in this study. By damping the motion of the translator through the electromagnetic force in the generator, kinetic energy gets converted into electric energy.

Generally, the damping force from a PTO unit can be decomposed into two parts. One is proportional to the velocity $\dot{z}$ and the other is proportional to the displacement z, i.e., $F_{PTO} = \gamma\dot{z} + Kz$. [57] The coefficient γ relates with the electromagnetic damping force, and the coefficient K can either be in a mechanical form using retracting springs, or in an electrical form through the control system, for instance, the reactive control.

For a passive loading system, if there are no retracting springs pulling down the translator, the PTO damping force would come purely from the electromagnetic damping force F_{em}, which in our case is calculated by:

$$F_{em} = \gamma\, A_{act}\, \dot{z}_t, \tag{2.28}$$

where A_{act} is the overlap ratio between the translator and stator. For simplified models, A_{act} is usually approximated as 1, meaning the stators are fully covered be the translator.

The relation between the absorbed power P, the damping force F_{em} and the translator velocity $\dot{z}_t(t)$ is:

$$P = F_{em}\dot{z}_t, \tag{2.29}$$

as a result, γ can be determined with Eq. (2.30):

$$\gamma = \frac{P}{A_{act}\,\dot{z}_t^{\,2}}. \tag{2.30}$$

A circuit diagram of the generator connected with three identical resistive loads is presented in Fig. 2.9 (a). [58] It is worth mentioning that there can be different types of electrical system connected at the 'Load' part, the resistive load is just one option. Fig. 2.9 (b) shows an example that a passive rectifier together with a capacitor are placed before a load, so that a DC voltage drop over the load can be achieved. Ref. [59] studied different loads connected to a linear generator. Ref. [57] has summarised the electrical damping systems that have been applied on the wave energy converters.

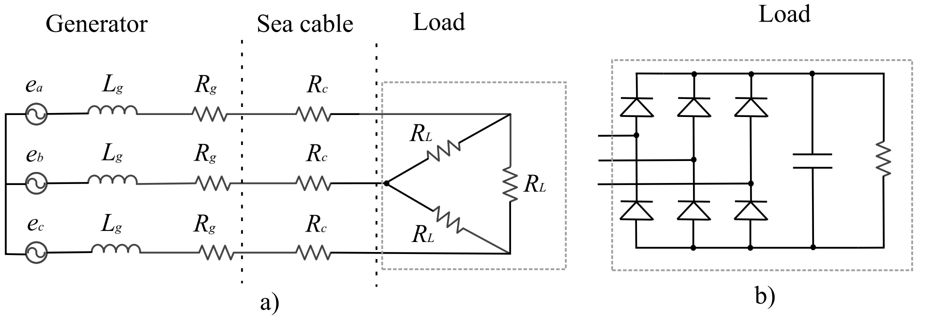

Figure 2.9. Sketch of (a) a simplified 3 phase generator connected to resistive loads. Adapted from Paper I. [60] (b) A diode bridge rectifier and a DC capacitor, connected with a load.

The absorbed power P in this case refers to the active power consumed by the resistances of generator, the sea cable and the loads. It can be calculated by [61]:

$$P = 3\Big(\frac{V_g^2}{R_g} + \frac{V_c^2}{R_c} + \frac{3V_L^2}{R_L}\Big). \tag{2.31}$$

2.4 Time domain and frequency domain

The time domain and the frequency domain are two modes of analysis. The two modes can be converted into each other via various transformation methods, such as the Fourier transform or the Laplace transform.

For regular waves, it is common to keep the analysis in the frequency domain with the aid of the Fourier transform. The definition of the Fourier transform and the inverse Fourier transform can be found in Eq. (2.32) and Eq.(2.33). The frequency domain analysis is appropriate on the assumption that incident waves are a supposition of many sinusoidal waves, and that oscillating bodies have linear constraints for a sufficiently long time to achieve steady state [62], [45].

$$f(t) \xrightarrow{F} \hat{f}(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt, \tag{2.32}$$

$$\hat{f}(\omega) \xrightarrow{F^{-1}} f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{f}(\omega)e^{i\omega t}d\omega. \tag{2.33}$$

One great advantage of applying the Fourier transform is that many complicated mathematical operations in the time domain can be simplified. Convolution integrals and differential equations can be simplified a great deal by the Fourier transform as Eq. (2.34) and Eq. (2.35) illustrate.

$$f(t) * g(t) = \int_{-\infty}^{\infty} f(\tau)g(t-\tau)d\tau \xrightarrow{F} \hat{f}(\omega)\hat{g}(\omega). \tag{2.34}$$

$$f'(t) \xrightarrow{F} i\omega\hat{f}(\omega). \tag{2.35}$$

The prime $'$ denotes differential and $\xrightarrow{F}$ denotes Fourier transform.

The time domain analysis is normally used when a transient analysis is needed in the electric circuit field. For a WEC system analysis, it is usually conducted when non-linear effects need to be considered, e.g., end-stops, or to evaluate a WEC performance with experimental data from a real wave climate, i.e., irregular waves.

3. The equivalent circuit modelling method

The equivalent circuit model for a point absorbing WEC system is built based on the system force analysis. Paper II has presented the methodology of deriving a non-linear electric circuit model in detail. Paper I introduced the method of determining the circuit parameters. The following sections will briefly outline the method.

3.1 Force analysis for the system

Figure 3.1 illustrates the scenarios of the linear and the non-linear force analysis in this thesis. In the heave direction, if looking at the buoy and the translator separately, a group of *non-linear* equations of motions can be derived.

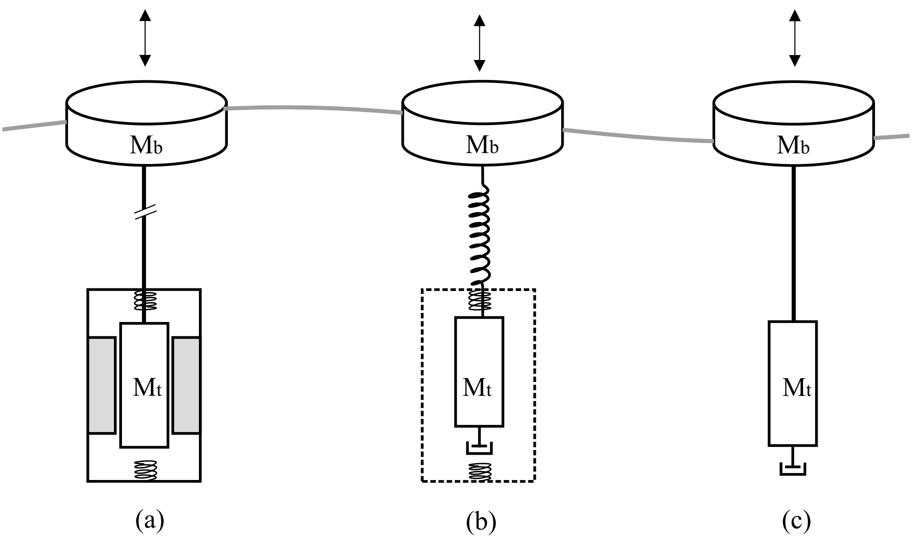

Figure 3.1. Sketch of the (a) physical WEC model, (b) non-linear WEC model for force analysis, (c) linear WEC model for force analysis.

When the connection line is tight, the equations are:

$$M_b\ddot{z}_b(t) = F_e(t) - F_r(t) - F_{line}(t) + \rho g V_{sub} - M_b g - \rho g S z_b(t), \quad (3.1)$$

$$M_t\ddot{z}_t(t) = F_{line}(t) - F_{endstop}(t) - F_{PTO}(t) - M_t g, \quad (3.2)$$

here, V_{sub} is the submerged volume of the buoy. For most cases in this thesis, the cross-sectional area of the buoy is constant, then $V_{sub} = Sb$.

When the connection line is slack, the equations of motion take the form

$$M_b \ddot{z}_b(t) = F'_e(t) - F'_r(t) - \rho g S z_b(t). \tag{3.3}$$

$$M_t \ddot{z}_t(t) = -F_{endstop}(t) - F_{PTO}(t) - M_t g. \tag{3.4}$$

The prime $'$ here denotes the force corresponding to the decreased draft b'. The connection line is modelled as a very stiff spring:

$$F_{line} = \begin{cases} k_{line}(z_b - z_t) & if\, z_b > z_t \\ 0 & else. \end{cases} \tag{3.5}$$

The $F_{endstop}$ is the spring force from the compression of either the upper or lower end-stop springs,

$$F_{endstop} = \begin{cases} k_u(z_t - l_u) & if\; l_u < z_t < l_{u,\max} \\ k_l(z_t + l_l) & if\; -l_{l,\max} < z_t < -l_l \\ 0 & else. \end{cases} \tag{3.6}$$

For a *linear* WEC system, the buoy and the translator are connected by a stiff wire with no elasticity, and moving together. The equations of the motion for the buoy and the translator become:

$$M_b \ddot{z}(t) = F_e(t) - F_r(t) - F_{line}(t) + \rho g V_{sub} - M_b g - \rho g S z(t), \tag{3.7}$$

$$M_t \ddot{z}(t) = F_{line} - F_{PTO}(t) - M_t g. \tag{3.8}$$

These two equations can be merged into one:

$$(M_b + M_t)\ddot{z}(t) = F_e(t) - F_r(t) - \rho g S z(t) - F_{PTO}(t). \tag{3.9}$$

3.2 From force equation to electric circuit

Besides the circuit layout, one of the most important steps is to decide the corresponding equivalent electrical component. By comparing each force term with the voltage drop over the different RLC components, the conversion relations can be derived, they are summarized in Table 3.1.

3.3 Circuit parameters

3.3.1 System configuration parameters

Parameters like the mass of the buoy and the translator, the spring stiffness, the free stoke length, or the cross-sectional area of the buoy are the fixed parameters for one set of a WEC unit. They can be put directly into the electric circuit model with the same value in the SI unit.

Table 3.1. *Major conversion relations.*

Terms appeared in force equations	Electrical equivalents
Force	Voltage source
Velocity	Current
Mass	Inductor
Spring	Capacitor
Hydrostatic stiffness $1/\rho g S$	Capacitor
Electromagnetic damping coefficient	Resistor

3.3.2 Hydrodynamic coefficients

The hydrodynamic parameters in the circuit model are computed by the numerical code WAMIT [63] in this thesis. For buoys with simple geometries, the coefficients can also be calculated analytically [64, 65, 66, 67, 68, 69]. Fig. 3.2 gives an example on how to read the parameters. The values at the red spots will be taken as the input for the electric circuit, to simulate a monochromatic sinusoidal incident wave interacting with a buoy.

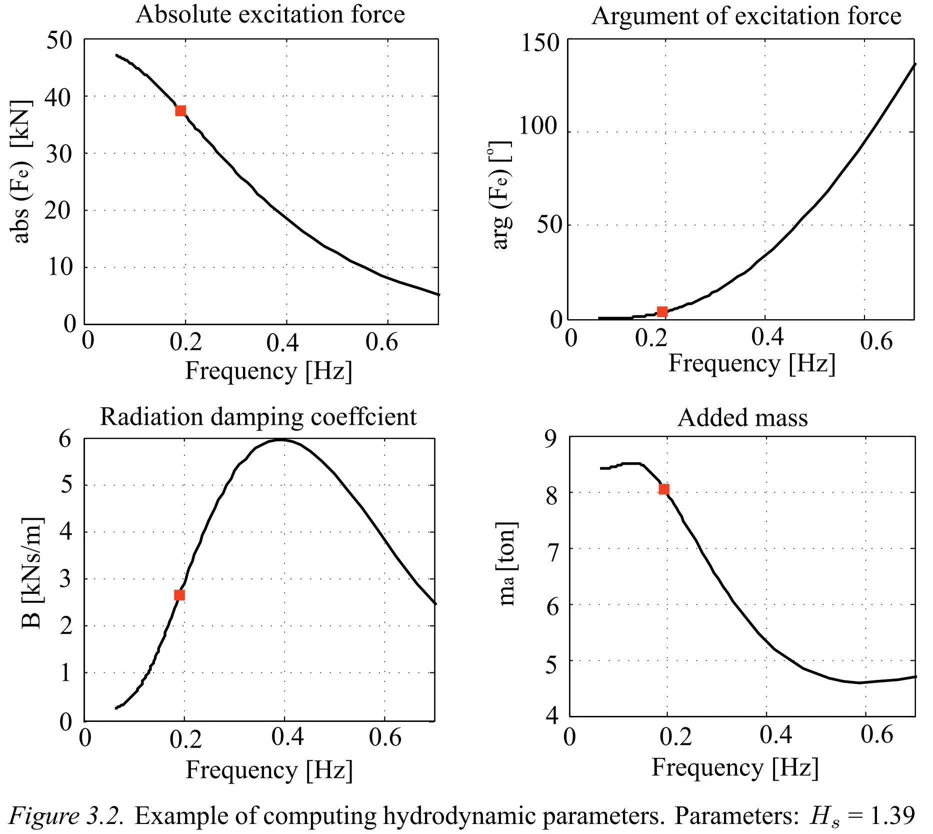

Figure 3.2. Example of computing hydrodynamic parameters. Parameters: H_s = 1.39 m, cylindrical buoy a = 1.5 m, b = 0.4 m, h = 25 m.

3.3.3 Power Take-off damping coefficients

If the generator was equipped with a retracting spring, the spring constant k_s can be read from the product specification.

The electromagnetic damping coefficient γ can be plotted versus the translator velocity, based on a finite element modelling of the linear generator, or from the on-shore test data. If the characteristic parameters of the generator are known, it can also be plotted by simulating the equivalent circuit diagram formed by the generator, the transmission network and the loading system. Fig. 3.3 gives an example of how the γ - $\dot{z}_t$ relation varies when different resistive loads are connected.

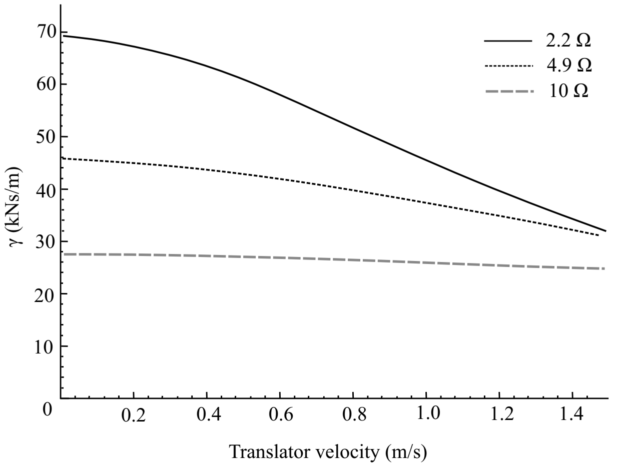

Figure 3.3. Example of computing the electromagnetic damping coefficent. Figure adapted from [61].

3.4 System analysis via circuit model

3.4.1 Monitor instantaneous performance

If using circuit simulation software like Matlab Simulink, the quantities that have been transformed directly from the force equation can be read through measuring the voltage or the current, and viewed by the oscilloscope during the simulation. Typical quantities are the velocity, the PTO force or the force in the connection line.

By placing some simple modules like multiplication, integral, differential etc., we can monitor more parameters like the absorbed electric power, the displacement, and the acceleration in the oscilloscope. The inspection can be for the buoy and the translator separately, and for as many types of sea states as required.

3.4.2 Long term performance evaluation

The figure every investor wants to know is the annual electricity production from a WEC device. The relation between the energy and power is:

$$E = \int_0^{T_0} P(t)dt. \tag{3.10}$$

With measured wave data of the chosen location, the absorbed electric energy can be calculated from Eq. (3.11):

$$E = \sum_{i=1}^{n} \sum_{j=1}^{m} P_{_{RMSij}} t_{ij}, \tag{3.11}$$

where $P_{_{RMSij}}$ is the simulated average power when the wave energy period is T_{ei}, and the significant wave height is H_{sj}. t_{ij} is the accumulated time for this sea state. Here, the assumption is that the wave energy period at the investigated site ranges from T_{e1} to T_{en}, and that the significant wave height ranges from H_{s1} to H_{sm}.

4. Experiments

Two full scale offshore experiments are included in this chapter. The first one is used for validating the equivalent circuit modelling method. Descriptions on how the experimental data gets processed can be found in Paper I. In the second experiment, the author has designed and implemented the force measurement system to measure the force in the connection line. The system design and test information can be found in Paper V and Paper VI.

4.1 Offshore experiment for model validation

The average absorbed power and the peak force in the connection line are the parameters that have been validated by the equivalent circuit models. Simulation results have been compared with the experimental results.

Below is the first WEC unit deployed by Uppsala University, more details on the experiment can be found in Ref. [70]. The WEC is composed of a cylindrical buoy, a linear generator L1 and a resistive loading system. The sketch of the experimental set-up is drawn in Fig 4.1, and the main features of the WEC are listed in Table 4.1.

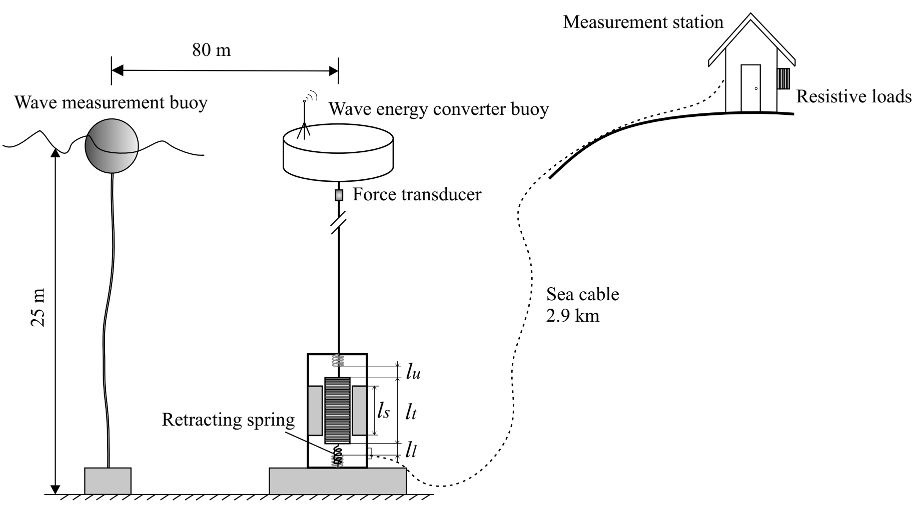

Figure 4.1. Illustration of the first experimental set-up.

The experimental results used in this thesis were collected between 2007-03-08 and 2007-03-14. This period was chosen because the wave climate varies

Table 4.1. *Main features of the WEC system for model validation [61].*

Buoy radius a	1.5 m
Buoy height h_b	0.8 m
Buoy mass M_b	1000 kg
Draft at mean water level b	0.4 m
Nominal power P_{nom}	10 kW
Nominal speed v_{nom}	0.67 m/s
Translator mass M_t	1000 kg
Nominal voltage V_{nom}	133 V
Stator length l_s	1264 mm
Translator length l_t	1867 mm
Free stroke length	± 900 mm
Spring constant of the connection line k_{line}	450 kN/m
Upper end-stop spring constant k_u	243 kN/m
Lower end-stop spring constant k_l	215 kN/m
Retracing spring constant k_s	6.2 kN/m
Initial retracting spring force $F_{preload}$	8.12 kN
Per phase generator resistance R_g	0.45 Ω
Per phase generator inductance L_g	7.8 mH
Per phase sea cable resistance R_c	0.54 Ω
Resistive load R_l	2.2 Ω in Δ connection

considerably, and there are force measurement data available. One major difference between L1 and the later generators is that the later models no longer have retracting springs attached between the translator and the bottom of the generator. The translator is now designed to have a big weight that can pull itself back.

4.2 A force measurement project

To know the hydrodynamic characteristic of a toroidal buoy [71], as well as to validate the circuit model with more offshore experimental data, a new force measurement system has been designed. In this experiment, the toroidal buoy is 24 m^3 larger in volume than the above cylindrical buoy, the translator is almost 7 tons heavier than for the L1, and there is a rubber damper placed in the middle of the buoy to protect the system from snatch loads. A 50 ton force transducer was selected for this experiment. Table 4.2 summarizes the main parameters of this WEC. [72]

Fig. 4.2 shows how the measurement system and the buoy get assembled. Fig.4.3 shows the offshore deployment of the generator and the buoy.

This force measurement experiment, unfortunately, did not manage to collect any offshore force measurement data when there were waves. Several days later, high waves up to 5 meters damaged a welding point of the buoy structure, which has taken away the chance to repair the system. Another force measure-

Table 4.2. *Main features of the WEC system for the force measurement project.*

Equivalent minor radius r_b	0.75 m
Equivalent major radius R_b	2.7 m
Buoy weight M_b	8000 kg
Draft at mean water level b	1 m
Nominal power P_{nom}	20 kW
Nominal speed v_{nom}	0.67 m/s
Translator weight M_t	7800 kg

ment system is being built now, with a hope to conduct the experiment in the next deployment.

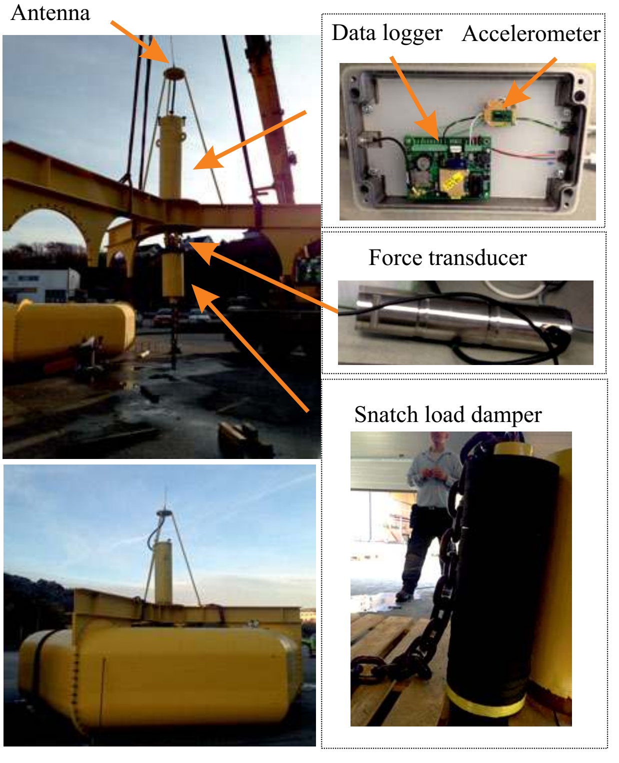

Figure 4.2. The process of assembling the force measurement system and the buoy. Adapted from Paper VI. [73]

a) b)

Figure 4.3. Offshore deployment of the (a) linear generator, (b) buoy.

5. Summary of results

The results presented in this chapter contain the validation of the electric circuit models, the different electric circuit forms that are derived according to either different WEC configurations, or different requirements for the system analysis, as well as the annual electric energy production estimation from different WEC units. Information on the linear circuit model and its validation can be found in Paper I, the process of deriving different non-linear circuit models is included in Paper II, and the procedure for using the equivalent circuit model in WEC system planning process is included in Paper III.

5.1 Linear and non-linear equivalent circuit models

Based on the linear force analysis, if taking Eq. (3.7) and Eq. (3.8), the equivalent circuit model presented in Fig. 5.1 (a) can be derived. This circuit is useful when the force in the connection line needs to be measured. Otherwise the simplest form of the equivalent circuit model shown in Fig. 5.1 (b) can be derived from Eq. (3.9). This circuit is the one that is normally used to facilitate the control system study, or to illustrate the WEC system.

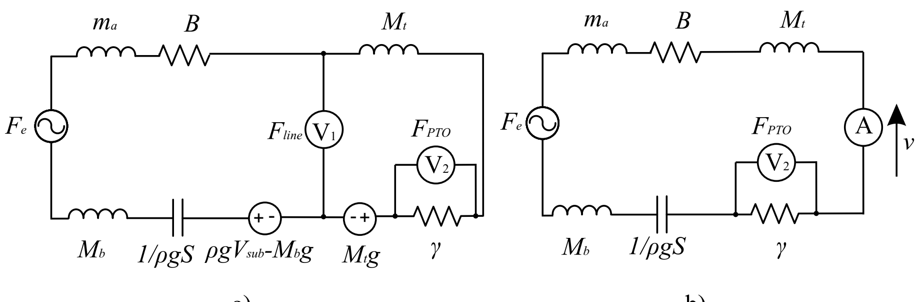

Figure 5.1. The linear equivalent circuit model for a WEC system only considering heave motion. (a) The complete linear circuit when the force in the connection line needs to be simulated. (b) A further simplified circuit if only the absorbed power needs to be simulated. Adapted from Paper I. [60]

Since the impedance of the voltage meter is considered infinitely large, the above two linear circuits will yield identical results for the velocity, the PTO force or the absorbed power.

Based on the non-linear force analysis, according to Eq. (3.1) - Eq. (3.4), an equivalent circuit shown in Fig. 5.2 can be derived. It has taken the tightened line case and the slack line case into consideration, as well as the elasticity of the connection line, the limited stroke length and the compression of end-stop springs. There are controlled switches in this circuit model, aiming to form a new circuit layout when the system's operational status changes. This circuit is useful when a more precise simulation result is needed.

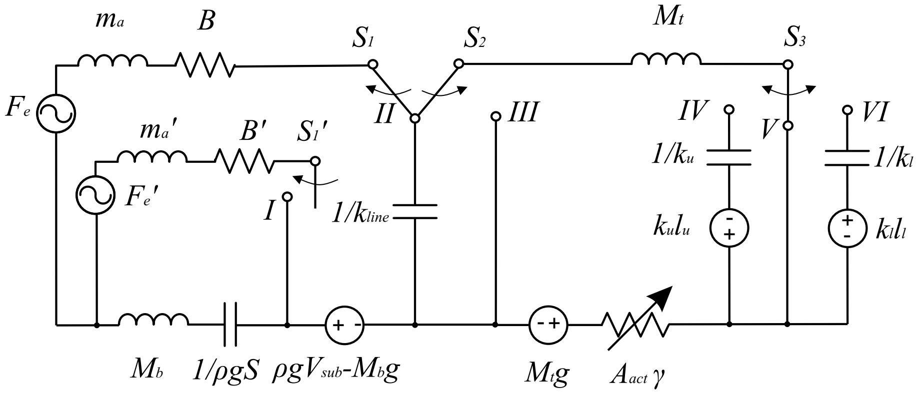

Figure 5.2. The non-linear equivalent circuit model for a WEC system only considering heave motion. Adapted from Paper III.

5.2 Equivalent circuit model for different cases

Three case studies including a generator with a retracting spring, a connection line with a rubber damper [74], or a buoy moving in both the heave and surge motions are given in Paper II. Fig. 5.3 demonstrates what the combined circuit looks like.

The phase shift on the excitation force has been introduced in this circuit, to discriminate between the direction of the surge motion and the heave motion. The rubber damper undergoes a force of the same magnitude as the ordinary connection line. Therefore its electrical equivalence is in parallel with the connection line part. The dashed line implies that the switches need to act simultaneously.

During the derivation process, a modular approach has been applied. The modification of the circuit is still based on the force analysis for each case, but a faster decision can be made if figuring out which part of the WEC system will be influenced by the new element.

5.3 Validation of the circuit model

The linear equivalent circuit model has been verified with the full-scale offshore experiment described in Chapter 4. The experimental power and the

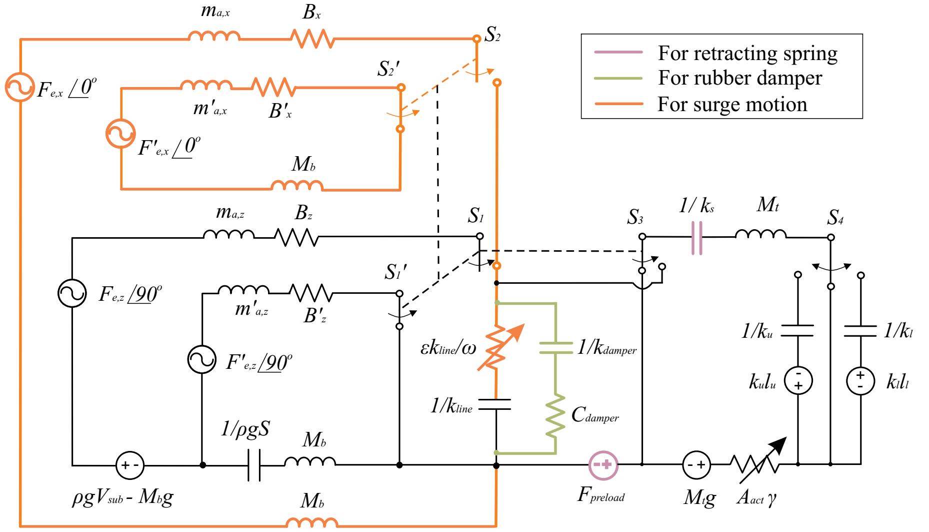

Figure 5.3. The equivalent circuit model for a WEC system with more factors considered. Adapted from Paper II.

force data for around 144 sea states have been analysed. Each sea state is extracted from 10 min of measured wave data. The input sinusoidal wave for the circuit model is characterised by the wave energy period T_e and the significant wave height H_s from the corresponding 10 min sea state.

The results for the average power display a good fit between the simulation results and the experimental results, as indicated in Fig. 5.4 (a). However, the simulated peak force in the connection line exhibits a big deviation from the experimental results.

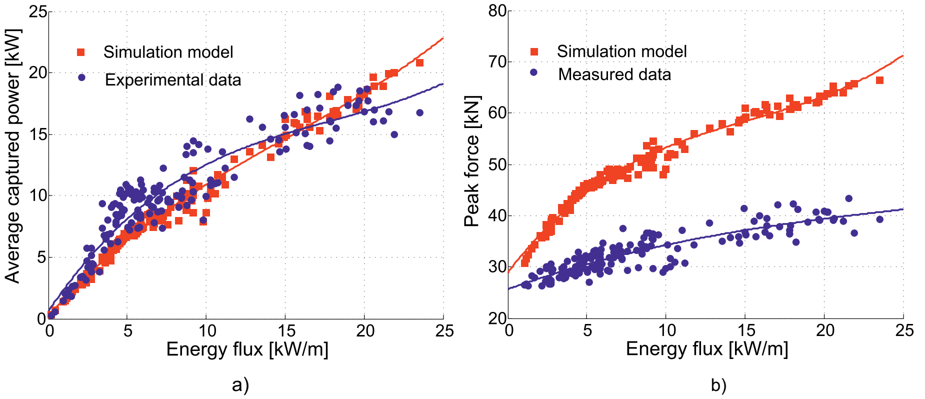

Figure 5.4. Comparison between the experimental results and the simulation results from the linear circuit model. (a) Captured electric power. (b) Peak line force. Adapted from Paper I. [60]

The experimental results have been checked further with the non-linear circuit model. The average power shows a slightly better fit, while the peak force shows a much better fit, compared with the linear circuit model simulation results. The results are summarised in Fig. 5.5.

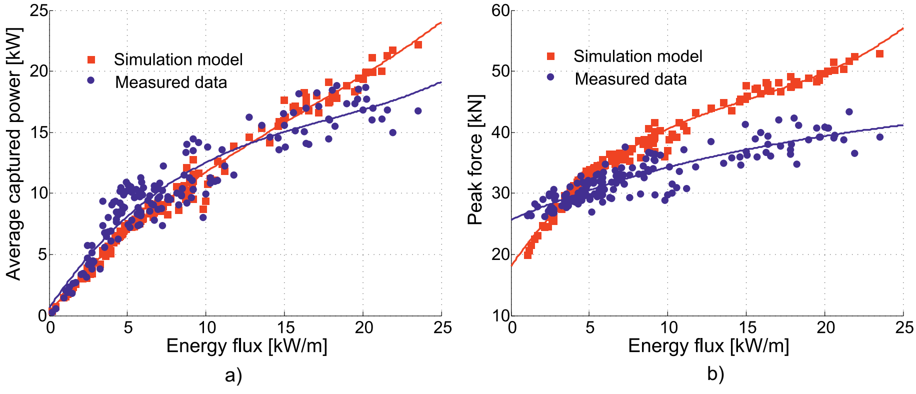

Figure 5.5. Comparison between the experimental results and the simulation results from the non-linear circuit model. (a) Captured electric power. (b) Peak line force. Unpublished results.

5.4 A fast estimation of absorbed electric energy

The main purpose of this study is to develop a quick assessment tool for WEC system modelling. After validation, studies have been carried out to use the circuit modelling method for planning a WEC system. The variables to be tested here include the material, the shape, the size and mass of the buoy, the mass of the translator, and the damping coefficients. Since the power absorption for a given WEC configuration can be computed fast, a comparison of the absorbed electric energy over a certain time period can be calculated to help the decision making.

The simulation is done using the circuit form shown in Fig. 5.2 for a more accurate prediction. Fig. 5.6 is to give an idea of how the first step of the computation is done. The absorbed power is computed for a range of wave climates, in a matrix form.

The second step is to use Eq. (3.11), together with the measured wave data statistics of a chosen location, to calculate the annual absorbed energy. The results of 10 different configurations of WEC units are presented in Fig. 5.7.

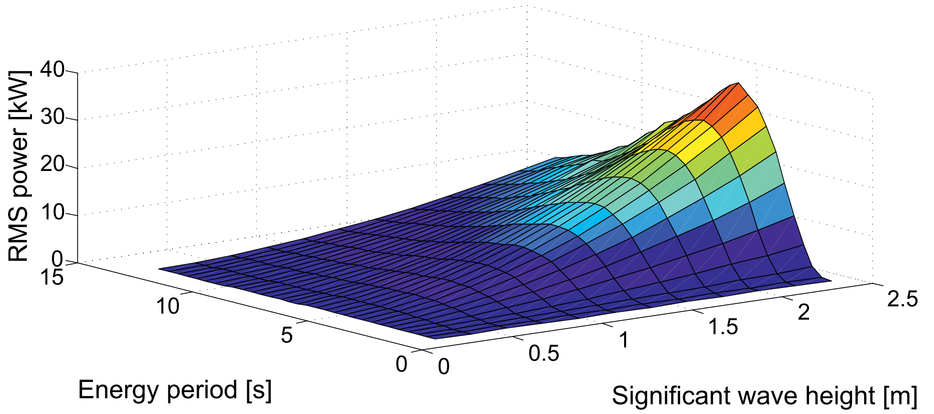

Figure 5.6. Example of the simulated average power for a range of the wave climate. Adapted from Paper III.

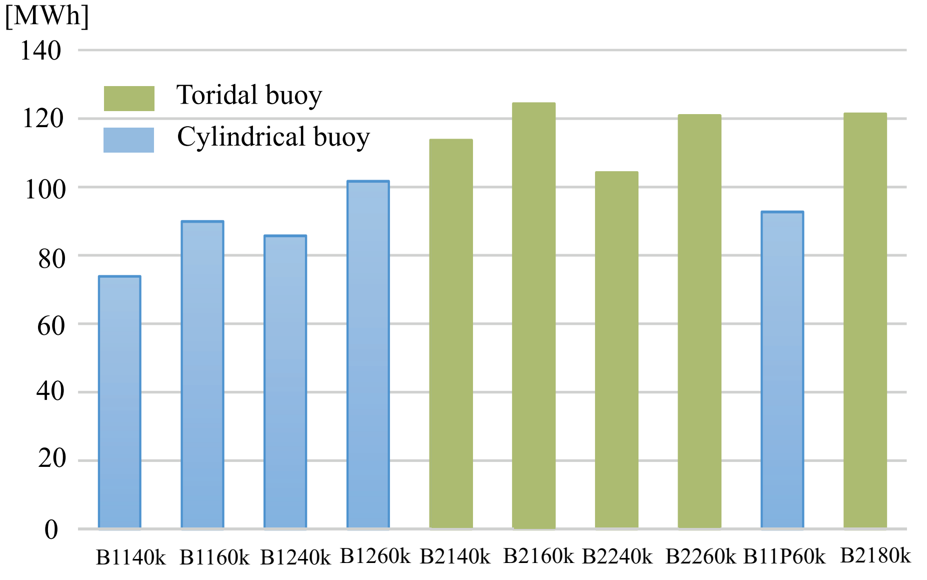

Figure 5.7. Example of simulated annual electric energy absorption for different WEC configurations. Adapted from Paper III.

6. Discussions

During the development of equivalent circuit models, thorough consideration has been given to general aspects like how to make the model useful in practice, as well as to small technical details like how many electrical references are needed in one circuit network. This chapter summarizes the most interesting findings of this research. The discussion parts in Paper I, II, III contain more detailed explanations and are recommended for further reading if interested.

6.1 New perspectives

The equivalent circuit models provide another perspective to the understanding of the physical WEC system. The conversion at element level reveals that, mass which includes moving parts and associated added mass, is inductive: the higher the mass, the more inertia it will bring to the system. The kinetic energy that mass possesses due to motion can be analogous to the temporary energy stored in a magnetic field in the inductor.

The hydrostatic stiffness and all springs are capacitive. They represent the ability to store potential energy in the oscillation process. A bigger buoy cross-sectional area and spring constant will result in larger capacitive impedance in the circuit, therefore more potential energy will be stored if the displacement is the same.

The hydrodynamic radiation damping and the electromagnetic damping coefficients were converted into resistors. They are the components that reduce the velocity of the buoy and translator, in other words, they dampen the motion.

From the electric circuit theory we know that only resistors consume active power. Inductors and capacitors do not consume any active power, only reactive power. In the energy conversion process, it means that only the hydrodynamic radiation damping and the electromagnetic damping consume energy in a WEC system. The other components just introduce phase shifts between force and velocity.

One may notice that the line force in the horizontal direction was converted into a varying resistor. This is because the horizontal force in the connection line would cause a frictional force between the buoy line and the funnel. Energy is consumed in the form of dissipated heat from this friction. Therefore, understanding the logic behind the conversion may help us to double check if the components were converted into the right form.

6.2 Level of model complexity

From the presentation of the results, one may notice that the circuit model was introduced from the simplest to the most sophisticated. To some extent, the equivalent circuit model can be seen as a Lego model, its core is the simplified linear circuit shown in Fig. 5.1 (b). It can be extended to adapt to different circumstances. This could be in one specific region, e.g., introducing retracting springs to the PTO part, or the whole circuit can be changed, e.g., from a linear to a non-linear circuit model.

The comparison between the full-scale offshore experiment results with simulation results from the circuit models indicates that, for a rough estimation, the linear circuit model can be good enough to estimate the output power from a WEC unit. This enables researchers from different backgrounds to do simulations with this simple series connected RLC circuit model. The non-linear circuit model does show a better fit with both the power and the force comparison, which is consistent with the theory. Thus, people who know more about electric circuit theory and simulation, can use non-linear circuit modelling with logic control switches for a more accurate estimation.

Besides the complexity in the circuit layout, questions have been asked about whether the model can take irregular waves as input to obtain more accurate predictions. There is a trade-off relation between accuracy and computation time. A model including irregular waves would involve convolution operation and this would slow down the simulation. Apart from that, the original purpose of developing a circuit model is to make things easier, so in theory every researcher having basic knowledge of electric circuits and mathematics can employ the method. The requirements of adding a convolution block and reading irregular wave data will lead to a more complicated Simulink model and consequently less people will be able to use it. Therefore, it is suggested to keep this option selectable. For researchers who are good at Simulink and hydrodynamics, including irregular waves into the circuit model is possible with embedded blocks. While for others, the sinusoidal input waves would produce fairly good predictions for an approximation, and the computation time would be much shorter.

6.3 Consistency between force and electric circuit analysis

Electrical analogies are derived from equations of motion, which are based on force analysis under different scenarios. In most cases, electric circuit analysis techniques can be applied directly to analyse the WEC system. For example, when the translator has retracting springs attached, they will move with the same velocity. These two elements are represented by a series connected inductor and capacitor in the equivalent circuit. The same current will pass each component for a series connected circuit, hence the analysis in electric circuit field is consistent with the force analysis.

However, it is still necessary to think first if the electric circuit analysis result agrees with the force analysis result. Superposition technique, for instance, cannot be applied to the buoy moving in the heave and surge case, since it contradicts with the force analysis.

6.4 Accuracy and error analysis

To assess the accuracy of both the linear and the non-linear circuit models, the absolute differences of the average power and the peak force between the experimental and the simulated results have been analysed and plotted in Fig. 6.1. In general, the non-linear equivalent circuit's output deviates less than the linear circuit's output. Furthermore, there is a better accuracy for the average power prediction than for the peak force.

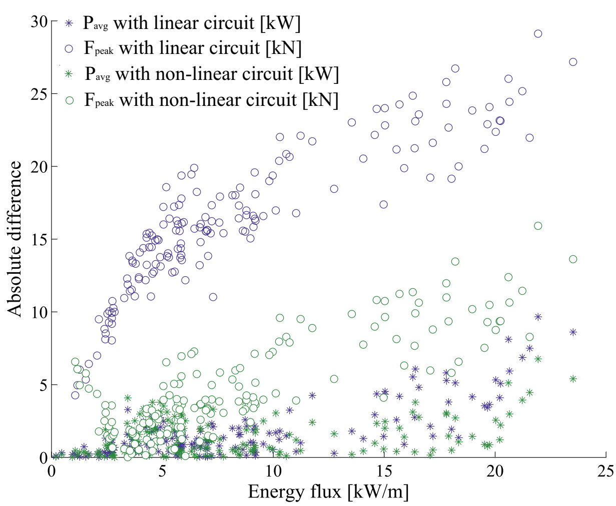

Figure 6.1. The absolute difference of the average power and peak line force from linear and non-linear circuit models. Adapted from Paper I. [60]

For the non-linear circuit model, the deviations can be caused by that for high waves, the buoy may have been totally submerged, so that the actual excitation force is smaller than the predicted one. This explains why the simulated line force and the absorbed power are lower in reality than in the simulation's output.

The linear circuit model has excluded the non-linear factors, such as the limited stroke length of the translator, the elasticity of the connection line, or the end-stop springs. Therefore, it is anticipated that the prediction will be less accurate than for the non-linear circuit model.

Moreover, the experimental measurement data are recorded with the limited sampling frequency. This causes distortions of the experimental data compared to the real value of the average power or the peak force. For each 10 minutes of power data, there are 8960 data points used for the average power estimation. For the peak force data, however, there are only about 100 data points representing the peak forces during these 10 minutes. The measurements for the peak force would therefore be less accurate than those for the average power.

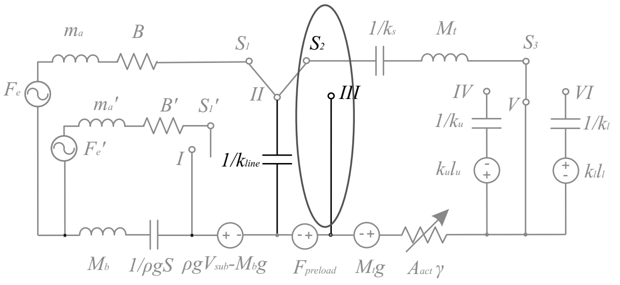

Figure 6.2. Possible reasons for the drift of the simulated peak force.

It can be observed that for the absolute difference of the peak force, there is an almost constant drift between the linear and non-linear circuit models. Through a series of testing in Simulink, it has been found that there are two major reasons caused this drift. First, by replacing the capacitor $1/k_{line}$ with a voltage meter, a bigger line force would occur. Second, the electric switch in Simulink has a very small but finite conductance when it is open. In our case, the branch with switch S_2 has been affected by this setting. This finding has been illustrated in Fig. 6.2.

The present validation of the peak force is unfortunately not completely satisfactory, especially for the linear circuit model. Further studies are needed to come to a solid conclusion on the causes of these deviations, and to try to improve the circuit model accordingly so as to improve the estimation. At the same time, a higher sampling frequency for future force measurement is need, in order to capture peak forces more accurately.

6.5 Highlights of the model

The equivalent circuit model exhibits all the important parameters that may influence power absorption in one electric circuit network; there are no hidden equations behind electrical components, nor sub-systems in Matlab Simulink model. This one-layer model could promote the understanding of the relations among each element in the WEC system.

Not many generator designers know what added mass is, while they are certain to know what an inductor is. The way of representing hydrodynamic coefficients by electrical components in this study opens a channel of communication for engineers from different disciplines.

Most importantly, the equivalent circuit modelling method is fast to assess a WEC's performance. The simplification of only considering regular waves greatly reduces the computation time, so the simulation can be conducted quickly in time domain. The quick assessment benefits the wave power system modelling in two ways. First, one can see the consequence of changing one parameter immediately and the impact of this change to other subsystems or to the entire WEC system. This is especially useful when examining the WEC performance in the dominate wave climate. Second, in the early design stage, it enables testing many different configurations of a WEC for a group of different sea states, which may help to choose the WEC system with the maximum electric energy production for a selected site.

6.6 Limitations of the model

The wave-buoy interaction model is based on the potential linear wave theory. This requires the point absorber to be much smaller in dimension than the wave length, and the incident waves to be non-steep with small amplitudes. Hence, big floating structures or a point absorber oscillating in storms cannot be simulated with this circuit model.

In addition, since the hydrodynamic parameters are set each time for a single harmonic wave, the analysis in this paper is valid for regular waves only.

The proposed method still relies on the numerical software WAMIT to compute hydrodynamic coefficients, and FEM software to simulate a synchronous linear generator. This limits the circuit model to testing different buoys, or certain configurations of the generator. Applying the analytical solutions of the wave-body interaction can be one way to eliminate the dependence on commercial hydrodynamic software, if only a simple geometry of the buoy is taken into consideration. However, a detailed generator design that would affect the electromagnetic damping coefficient γ, such as the coil winding plan, the choice of magnets or the air gap, cannot be modelled or simulated by the circuit model.

7. Conclusions

This thesis has focused on modelling the point absorbing wave energy conversion system with the equivalent circuit method. Based on this study, the following conclusions can be made.

Feasibility and performance

It is feasible to establish a linear, or non-linear equivalent circuit model to model the dynamic behaviour of a wave energy conversion system.

The average absorbed power can be predicted satisfactorily, while the peak force in the connection line could not be anticipated to a reasonable accuracy, from the linear circuit model.

The non-linear circuit model can simulate the wave energy conversion system more accurately than the linear circuit model.

Capability of the model

The equivalent circuit model is capable of simulating the velocity and the displacement of the buoy and the translator, the force in the connection line, the absorbed electric power, and the Power Take-off damping force.

The model can only be used when the potential linear wave theory is valid, i.e., for small-sized buoys oscillating in small-amplitude waves. Only regular waves have been taken as incident waves for the current equivalent circuit modelling method.

General aspects

The force analysis precedes the electric circuit analysis techniques. Since the equivalent circuit model simulates the dynamic behaviour of a WEC system, it is essential to make sure that the circuit analysis techniques are conducted when the equivalent analysis can be carried out by the force analysis for the real WEC system.

The suggested equivalent circuit modelling method can accelerate the decision making process on the choice of a single point absorbing wave energy conversion system configuration.

8. Future Work

There is still a lot of work to be done on the road of improving equivalent circuit models for wave energy conversion system modelling:

- The current circuit model uses the hydrodynamic coefficients computed by the commercial code WAMIT. For simply shaped buoys, it is possible to compute the hydrodynamic coefficients analytically. This will eliminate the prerequisite of learning and using WAMIT, and can therefore make the circuit simulation faster and easier.

- Validating the proposed equivalent circuit models for the rubber damper case and the buoy moving in heave and surge case, to examine the accuracy of the circuit model. This will be helpful for the design of the rubber damper, or the selection of the buoy.

- The current equivalent circuit has only been validated for resistive loads. A further verification study can be done considering different electrical loading systems.

- Some interesting research topics such as the tidal compensation, or two body system in wave energy area, may be studied via the equivalent circuit modelling method.

9. Summary of Papers

Paper I

Modelling a point absorbing wave energy converter by the equivalent electric circuit theory: A feasibility study

This paper studies the feasibility of using an equivalent circuit model to assess the wave energy converter. A complete circuit model is introduced at the beginning. To make a preliminary assessment on the circuit model performance, a simplified model has been used to estimate the captured power and force in the connection line. Simulation results have been compared with the offshore full scale experimental data. Results indicate that the power can be predicted quite well, while the peak force in the connection line could not be estimated accurately.

The author performed most of the work in this paper.

This paper is published in *Journal of Applied Physics*.

Paper II

A Methodology of Modelling a Wave Power System via an Equivalent RLC Circuit

This paper explains the general methodology of deriving an equivalent electric circuit model for a WEC system. Three increasingly complicated cases are taken as examples for the demonstration. The paper also includes how to apply the circuit model for WEC system analysis, and a detailed discussion on the equivalent circuit modelling method.

The author performed most of the work in this paper, except deriving the equations of motion for the coupled surge and heave motion.

This paper is submitted to *IEEE Transactions on Sustainable Energy*, revision requested.

Paper III

Planning a wave energy conversion system by equivalent circuit modelling method

This paper has elaborated how to use the equivalent circuit modelling method as a tool to facilitate the decision making when planning a WEC system. Different buoys, weights of translators and damping coefficients are selected to form different WECs. A power absorption matrix can be estimated rapidly from the equivalent circuit simulation, together with wave data statistics at a chosen site, the annual absorbed electric energy from different WEC systems can be conveniently predicted.

The author performed most of the work in this paper.

This paper is a manuscript.

Paper IV

Experimental results on power absorption from a wave energy converter at the Lysekil wave energy research site

A simple model has been brought out for determining power production limit in this paper. By examining the experimental data with the proposed model, it has been noticed that the buoy size and the weight of the translator influence the absorbed power the most. Optimization of these two parameters, is believed will make the WEC produce power more evenly over the upward and downward cycles.

The author participated in deriving equations and writing the introduction and discussion part of the paper.

This paper is published in *Renewable Energy*.

Paper V

Force in the connection line for a wave energy converter: simulation and experimental setup

The paper includes two parts, first it presents a theoretical study of the hydrodynamic characteristics of a torus buoy, which is going to be deployed in Lysekil. Then it gives an introduction on a 500 kN force measurement system, which is planned to measure the line force for the same WEC unit. The force measurement system has been tested on shore in Lysekil, the test proves that the communication system and the force transducer function well.

The author performed most of the work in this paper.

The paper is under review in *Journal of Offshore Mechanics and Arctic Engineering*. It is transformed from the peer-reviewed paper that was presented by the author at the *33rd International Conference on Ocean, Offshore and Artic Engineering*.

Paper VI

Measurement System for Evaluating Wanted and Unwanted Forces on a Point Absorbing Wave Energy Converter during Offshore Operation

The paper presents the principle, implementation and test results of a set of measurement system installed on a WEC unit. The force in the connection line as well as the vertical and horizontal strain in the generator hull will be measured. With these measurements the forces acting on the generator during offshore operation can be monitored and analysed. A brief discussion of error sources and possible improvements is also given.

The author wrote the connection line force and the buoy measurement system parts, and has contributed with Fig. 4 and Fig. 6.

The peer-reviewed paper was presented by Liselotte Ulvgård at the *25th International Ocean and Polar Engineering Conference*.

Paper VII

Wave Energy Research at Uppsala University and The Lysekil Research Site, Sweden: A Status Update

The paper gives the latest status update on Lysekil porject. Besides a background introduction, it includes the ongoing researches on the deployment of a new marine substation, tests of several concepts of heaving buoys, grid connection, measuring station, modelling of wave power farms, implementation of remote operated vehicles for underwater cable connection, and environmental studies.

The author is included in the paper as having been involved the Lysekil project and written a small part of the paper.

The peer-reviewed paper was presented by Arvind Parwal at the *11th European Wave and Tidal Energy Conference*.

Paper VIII

Lysekil Research Site, Sweden: A Status Update

The paper gives a status update for Lysekil project. Starting from an introduction of Lysekil research site, the paper summarises the key parameters of generators and buoys that have been used in Lysekil project. Besides, the second marine substation, observation tower and environmental study have also been briefly introduced. In the end, experimental results of absorbed power from different generators connected with different buoys have been presented.

The author is included in the paper as having been involved in the Lysekil project.

The peer-reviewed paper was presented by Erik Lejerskog at the *9th European Wave and Tidal Energy Conference*.

10. Svensk Sammanfattning

Världens energikonsumtion har ökat dramatiskt sedan industrialiseringen. Statistik från IEA (International Energy Agency) visar att världens energiförsörjning har fördubblats mellan 1971 och 2012. Denna våldsamma ökning har i till en stor del bestått av fossila bränslen som kol, olja och gas. Beroendet av fossila bränslen som energikälla kan ses som en påtaglig fara för nationell energisäkerhet, och miljö- och klimatskadorna från exploatering, raffinering, förbränning och avfallshantering av fossila bränslen är ett globalt problem.

Alla tre delar av energisystemet – energikällan, transmission och konsumtion – behöver vara miljövänliga och effektiva, och dessutom kompatibla med varandra. I omvandlingssteget gäller det att byta ut fossila bränslen mot förnybara energikällor som vind, sol eller geotermisk energi. I transmissionssteget kan förlusterna minskas genom att elektricitet produceras nära användarna. Konsumtionssteget kan minska det totala behovet av energi genom energieffektivisering och användning av ny teknik som LED-lampor eller förbättrad isolering. Förändrade livsstilar, som minskad bilism, kan också vara viktigt för att minska energikonsumtionen i världen. Genom smarta elnät, elmätare och anpassad infrastruktur mellan elproducenter och konsumenter kan energisystemet bli välbalanserat.

Vågenergi är liksom sol- och vindkraft en förnybar energikälla, som finns över hela jordklotet i stora resurser. I dagsläget är vind- och solkraft relativt mogna teknologier som byggs ut i stor skala, medan vågenergi inte utnyttjas i samma grad. Jämfört med andra förnybara energikällor har vågenergi en fördel genom att energidensiteten är högre i vågor än i sol och vind, och dessutom är tillgängligheten högre och följer konsumtionsmönstret bättre. För länder som har kustlinjer eller öar är vågkraft därför en attraktiv förnybar och miljövänlig energikälla.

Hittills har utvecklingen av vågkraftsteknologi främst skett i liten skala i laboratorium; storskalig kommersiell effektproduktion har ännu inte uppnåtts. Den huvudsakliga tekniska utmaningen är den hårda marina miljön: metall rostar i havsvatten, och höga vågor under stormar kan orsaka stora skador. För att vågkraft ska kunna vara en pålitlig energikälla krävs inte endast en stabil elproduktion under normala förhållanden, utan även att vågkraftverken överlever höga vågor och andra utmaningar till havs.

Vågkraftgruppen vid Uppsala universitet har studerat elproduktion från havsvågor sedan 2002. Det utvecklade vågkraftskonceptet består av en flytande boj vid vattenytan kopplad genom en vajer till en linjärmotor på havsbotten, en så kallad punktabsorbator. Inuti generatorn är permanentmagneter monterade på en vertikal translator, som rör sig inuti en stator där spolar är lindade. När bojen lyfts av vågrörelsen så dras translatorn genom statorn, och det förändrade elektromagnetiska fältet genererar en elektrisk ström i spolarna. Systemet är okomplicerat och kräver inga mellanliggande mekaniska omvandlingssteg, vilket ökar tillförlitligheten och effektiviteten.

Punktabsorbatorer är fördelaktiga ur fyra perspektiv: först och främst är den okänslig för vågriktningen, vilket innebär en högre energiabsorption. För det andra kommer effektfluktuationerna i en park av punktabsorbatorer vara mycket mindre än jämfört med ett enskilt stort vågkraftverk, eftersom bojarna inte kommer oscillera i takt. För det tredje kan tillverkning, transport och sjösättning ske mer kostnadseffektivt när vågkraftsparkerna består av många mindre enheter, än ett fåtal stora. För det fjärde är det lätt att skala upp effektproduktionen genom att öka antal vågkraftverk, utan att några designparametrar måste ändras.

Det kompletta punktabsorberande vågkraftsystemet består av flera delsystem: boj, vajer, generator (som inkluderar en translator och en stator), elektriskt omvandlingssystem och last. Den gängse metoden att modellera systemet är oftast att kombinera resultaten från separata modeller av de olika delsystemen, som den hydrodynamiska interaktionen mellan våg och boj, FEM-simulering av generatorn, och simulering av det elektriska systemet. De enskilda delsystemen involverar forskare från olika discipliner och kräver olika mjukvara, vilket kan vara komplext och tidskrävande.

Att snabbt kunna bedöma prestandan för ett helt vågkraftsystem är motivationen till att ta fram en övergripande plattform för modelleringen. Den här avhandlingen beskriver processen att använda ekvivalenta kopplingsscheman som verktyg för att simulera hela vågkraftsystem. De fysikaliska parametrarna i systemet översätts till elektriska komponenter, så att hela systemet kan studeras genom att simulera en elektrisk krets.

Genom att starta från kraftanalysen för systemet, så kan rörelseekvationen, som härleds från Newtons andra lag, jämföras med Kirchhoffs spänningslag. Kraften motsvaras av spänningen, dämpningskoefficienten av resistansen och massan av induktansen. Vidare motsvaras faktorer som kan lagra potentiell energi av kondensatorer, hastigheten av strömmen, och en förändring i kraftekvationen motsvaras av en förändring av kopplingsschemat, som kan implementeras genom en strömbrytare.

Genom denna översättning kan våg-bojinteraktionen och energiomvandlingen modelleras i samma visuella gränssnitt. Efter att dimensionerna på systemet och de hydrodynamiska koefficienterna har bestämts, så kan elektrisk effekt och kraften i vajern beräknas i kopplingsschemat, där harmoniska vågor används som input. Vidare kan den årliga elproduktionen uppskattas om statistik över vågklimatet finns tillgängligt.

Modellen med ekvivalenta kretsscheman innefattar endast harmoniska vågor. Denna förenkling reducerar simuleringstiden kraftigt, så att simuleringen kan genomföras för ett stort intervall av vågklimat. Den snabba modelleringen är fördelaktig eftersom man snabbt kan studera hur olika parametrar påverkar prestandan, och justera designparametrar för att optimera systemet.

Grunden i metoden är ett förenklat elektriskt kopplingsschema som motsvarar ett vågkraftsystem som verkar under ideala linjära förhållanden. Utifrån denna grund kan kopplingsschemat utökas eller justeras för mer komplexa vågkraftsystem och studier. Den enklaste modellen kan användas för att få en grov uppskattning av elproduktionen, och forskare som är mer insatta i elektricitetslära och kraftteknik kan använda icke-linjära kretsar med logiska brytare för en mer realistisk beräkning av elproduktion och kraft i vajern.

11. 中文概要

伴随着工业化进程的推进和人们对于生活品质要求的提升，人类社会对能源的需求日益增加。国际能源署的统计结果显示，从 1971 年到 2012 年之间，世界的初级能源供给量增加了一倍还要多。这巨大的增长主要是由煤炭、石油及天然气这三种化石能源支撑。对于化石能源的重度依赖不但会威胁到一个国家或地区的能源安全，化石能源在开采、提炼、燃烧和废料处理过程中所引起的环境破坏和污染也十分令人担忧。

如何在不破坏环境的前提下满足能源需求，提前做好应对化石能源迟早会枯竭的准备，这就需要对已有的能源系统进行升级改造。如果简单的按能源供给 - 传输 - 使用三个环节来划分，假设每个环节都足够的清洁，各环节之间又相互匹配兼容，理论上这个能源系统就会更加安全环保且高效。

具体来说，在供给环节，如果将化石能源在能源供给端的比重降低甚至消除，转而采用可再生能源如风能、太阳能、地热能等来发电产热，那可以预见到由供给端所产生的环境污染会大幅减少。在输送环节，如果能够采用分布式电（热）网，就近生产就近使用，那么由远距离传输所造成的能源损耗也会减少。在使用环节，如果通过技术改造提高能源使用效率，那么实际的净耗能就会降低，比如使用 LED 灯泡，推广使用建筑保温材料等。此外，宣传节能知识使人们有意识的节约能源，也是减少消耗的重要手段，如乘坐公共交通工具，夏天不要把空调的温度调太低等等。最后，如果这三个环节能够及时沟通反馈，生产者可以根据需求调节产量，使用者能够根据能源供给量选择使用时间，那么整个能源系统就会形成一个吐纳平衡的健康循环, 减少能源浪费或在储能环节的能量耗损。智能电网，智能电表等理念和技术就是建立在这个愿景之上。

目前利用风能和太阳能的技术已经比较成熟，而另一种不为大多数人所知的波浪能，同样有着清洁无污染、储量巨大的特性，却常常在能源利用计划里难觅其踪。与其他可再生能源相比，波浪能还有能量密度高、可用性接近 90%（常年有浪）、季节性强度变化与用电量变化相符合等优势。对于拥有海岸线的国家或是小岛，采用波浪能发电作为一种永不枯竭且环境友好的能源解决方案，有着广阔的发展前景。

迄今为止，对波浪能的开发利用大多还处于实验室研发，或是小规模测试阶段，大规模商业发电还未实现。限制波浪能发电装置发展的主要技术原因在于严酷的海洋环境: 海水对金属有较强的腐蚀性，而暴风雨时的大浪会产生极大的破坏力。这意味着波浪发电装置不仅要在常规海浪下持续稳定发电，还要能耐腐蚀，并在大浪下存活下来。

瑞典的乌普萨拉大学电力系波浪能研究小组自 2002 年起开始研究一种点吸收式波能发电置。该装置由一个浮在水面的浮漂通过上下浮动，

驱动沉在海底的直线式发电机发电。直线发电机的动子表面装有永磁铁，环在四周的定子里是线圈，浮漂随海浪浮动时通过一根结实的线缆带动动子上下运动，产生变换的电磁场，从而在定子的线圈里感应出电压。由于该装置直接将波浪能转换成了电能，在能量转换过程种省去了机械能这一环节，这大大降低了系统的复杂性，相应的提高了系统的可靠性和能量转换效率。

采用点吸收式波能发电装置的优点有四个：一是点吸收式原理使得浮漂对来波的方向不敏感，利于对波能吸收；二是在波能发电场里，当有多个点吸收式波能发电装置并联，由于每个浮漂振荡不同步，叠加起来产生的总电压波动会比较小。相对于安装一套大型波能发电装置，这种多个装置并联的设计对变电站里电力电子设备的要求会降低；三是由于体量相对较小，其制造、运输和安装投放较为容易；四是规模易调节，可以根据不同项目装机容量的需求不同，只需调节装置个数即可满足项目需求，无需为每个项目重新设计装置本身。

单个波能发电系统的主要组成部分是浮漂，连接线，发电机（包括定子和动子），电力转换系统和负载。对整个系统的建模通常是由对浮漂和波浪相互作用的水动力模拟、系统的受力分析、发电机的有限元建模、电力系统及负载的仿真等一系列子系统建模的叠加组成，这一过程往往需要由不同领域的研究人员用多种软件协同合作才能完成，复杂且耗时。因此，我们希望能有一个相对统一的平台来进行系统建模，以期能够实现快速方便的预测波能发电装置的输出功率等主要参数。这篇论文介绍了采用电路作为建模平台，将各个子系统对整体系统运行的影响统一用电路元件表现出来，实现利用电路分析模拟系统运行情形的研究进展。

从系统的运动方程出发，将每个由牛顿第二定律导出的受力平衡方程视为一个由基尔霍夫电压定律导出的压降方程，我们就可以将波能发电系统等效为一个由电压、电阻、电感、电容和开关组成的电路。其中，力对应电压、阻尼对应电阻、质量对应电感、能储存势能的部件对应电容、速度对应电流、受力状态的改变对应电路形式的改变，由逻辑开关控制。通过这种转换，浮漂与波浪间的互相作用就能与能量提取装置有机的结合起来，在确定波能发电系统的参数后，可以快速的仿真出在规则海浪下，发电系统提取的功率，和连接线承受的力。如果结合选定波浪场的历年波浪统计数据，还能估算出一台波能发电装置的年发电量。这对系统的建模优化产生了两个积极的影响：一是在子系统优化改进过程中，可以快速预估其调整变动对其他子系统或是总系统产生的影响；二是在前期设计时能够充分尝试多种组合，有助于选择出最优方案。

针对波能发电装置建立的等效电路模型像积木一样，是可以无限扩展的。它的内核是由系统在理想线性情况下的受力方程推出的一个简化版电路，向外可以根据研究侧重点的不同或是系统设计的更换而进行相应的调整变换。如果对计算精度不过分苛求，不同领域的研究人员可用基本的电路知识，通过最简的电路模型便可预估波能系统的平均输出功率。如果对电路理论和模拟较为熟悉，则可以采用含有逻辑控制开关的非线性电路对系统进行更为精确的模拟分析。

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