ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

Alper BURGAÇ

CONTROL TECHNIQUES FOR OSCILLATING WAVE ENERGY CONVERTER

DEPARTMENT OF MECHANICAL ENGINEERING

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ABSTRACT

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CONTROL TECHNIQUES FOR OSCILLATING WAVE ENERGY CONVERTER

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This study aims at achieving increase in the power capture performance of heaving type oscillating wave energy converters with the proposed control techniques. It has been shown that the power capture performance of a heaving wave energy converter depends on meeting the resonance condition with the incident wave frequency. In regular sea wave conditions, the task of setting the control parameters is a well-known task where the wave frequency is clearly defined. However, in irregular sea conditions, the wave frequency needed for control settings is not clearly defined and there does not exist a widely accepted procedure for identification of wave frequency. In the first part of the study, an investigation on how the power capture performance of a heaving wave energy converter varies with the varying the ratio of power take off unit damping to radiation damping is performed. This study has proven to have considerable benefits. In second part of the study, a control algorithm including Fuzzy Logic controller which controls the added mass is proposed. The results of the study show that the power capture performance of the heaving wave energy conversion system is increased. Also, as the last part of this study, an approach is proposed that combine renewable energy production system with the reverse osmosis desalination plant. The power captured by the wave energy conversion system is utilized to produce fresh water from the reverse osmosis-based desalination system model. The simulation results indicates that the operation of the combined system is a feasible solution to the fresh water issue and it is also much environmentally friendly.

Keywords: Wave Energy, Fuzzy Logic, Renewable Energy, Control Application, Power Capture Performance

ÖZ

DOKTORA TEZİ

SALINIMLI DALGA ENERJİSİ DÖNÜŞTÜRÜCÜSÜ İÇİN KONTROL UYGULAMALARI

Alper BURGAÇ

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Bu çalışma, önerilen kontrol teknikleri ile yükselen tip salınımlı dalga enerjisi dönüştürücülerinin güç yakalama performansında artış sağlamayı amaçlamaktadır.. Bir yükselen dalga enerji dönüştürücüsünün güç yakalama performansının, gelen dalga frekansı ile rezonans koşulunun karşılanmasına bağlı olduğu gösterilmiştir. Kontrol parametrelerinin ayarlanması dalga frekansının açıkça tanımlandığı düzenli deniz dalgası koşullarında, iyi bilinen bir durumdur.Ancak, düzensiz deniz koşullarında, kontrol ayarları için gereken dalga frekansı net olarak tanımlanmamıştır ve dalga frekansının tanımlanması için yaygın olarak kabul edilen bir prosedür mevcut değildir. Çalışmanın ilk bölümünde, bir yükselen dalga enerji dönüştürücüsünün güç yakalama performansının, PTO ünitesi sönümlemesinin radyasyon sönümleme oranına göre nasıl değiştiği üzerine bir araştırma yapılmıştır. Bu çalışmanın önemli faydaları olduğu kanıtlanmıştır. Çalışmanın ikinci bölümünde, ek kütleyi kontrol eden Bulanık Mantık denetleyicisini içeren bir kontrol algoritması önerilmiştir. Çalışmanın sonuçları, yükselen dalga enerji dönüşüm sisteminin güç yakalama performansının arttığını göstermektedir.Ayrıca, bu çalışmanın son kısmı olarak, yenilenebilir enerji üretim sistemini ters ozmoz tuzdan arındırma tesisi ile birleştiren bir yaklaşım önerilmiştir. Dalga enerjisi dönüşüm sistemi tarafından yakalanan güç, ters ozmoz tabanlı tuzdan arındırma sistemi modelinden tatlı su üretmek için kullanılır. Simülasyon sonuçları, birleşik sistemin işletilmesinin tatlı su sorununa uygulanabilir bir çözüm olduğunu ve aynı zamanda çevre dostu olduğunu göstermektedir.

Anahtar kelimeler: Wave Energy, Fuzzy Logic, Renewable Energy, Control Application, Power Capture Performance

EXTENDED ABSTRACT

The developing technologies provide convenience in people's daily lives at the expense of increasing energy use. It is getting harder to meet the increasing energy demand from fossil fuels due to limited stocks. The most likely and environmentally friendly solution to the energy crisis is the use of renewable energy systems. With this research direction, researchers focused their studies on renewable energy sources.

Renewable energy sources are basically classified as wind, solar and wave energy. The technology in solar and wind energy has reached a certain level. Although the current technology in solar and wind energy has reached a certain level in terms of usability, wave energy conversion systems still have not moved away from the research stage. It is widely known that wave energy is defined as a concentrated form of solar energy. This observation makes wave energy an important and very much vital source of renewable energy. The wave producing winds are actually generated by the differential heating open bodies of water of the earth, transferring some of their energy to form waves. Hence, the waves carry concentrated form of wind energy induced by solar energy. The worldwide potential of wave power is about 1-10 TW, which is equivalent to a usable energy source of 8000-80000 TWh per year.

However, in order to make this energy usable, there is a need for further research that consists of some technically difficult stages. Also, there is a need for a device that converts wave energy into useful energy form. The system that extracts wave energy is called wave energy converter (WEC) system. An important issue is the location where this system will be placed. It should be analysed and the characteristics of the waves occurring in this location should be determined. Mainly, the locations where the wave energy conversion systems will be placed are classified into three sections depending on the depth. These are named as onshore, near shore and off-shore types. The energy potential analysis of the waves reveals

that the most energetic ones are observed away from the shoreline. As the waves travel towards the shore, they lose their energy due to ground effect.

The energy carried by the waves simply defined as a function of significant wave height and wave frequency properties of the waves. After determination of the location, the appropriate wave energy conversion system geometry and working principle should be selected for that region taking into account the topological situation and sea state conditions. The WEC converts the motion of waves into mechanical energy by using some form of power take-off (PTO) mechanisms. After these stages, the WEC system must be controlled in order for the system to achieve high energy capture performance. The control application in WEC systems have been carried to a certain extend in regular waves and are well known. However, the real sea waves are far from being regular. In fact, the real waves are complex and naturally in irregular forms. Hence, there is a need to observe the irregular wave form in advance. The availability or achievability of the future wave climate information provides the time needed for tuning the WEC for the incident waves expected. Hence, estimation of the wave frequency from the wave elevation data becomes very much critical. For this purpose, there is a need for signal processing techniques such as sliding Discrete Fourier Transform.

The main challenge in implementation of a successful WEC system is to develop a control technique suitable for realistic irregular sea states. One of the main issues is to determine the wave properties well and to adjust the tuning parameters of the system in order to apply the right control settings at the right time. Although, it is accepted that the control techniques to improve the wave power extraction potential, understanding of the overall issue still remains to be very weak. The main objective of control strategies for oscillating types is to keep the WEC at resonance by adjusting the WEC's natural frequency (ω_n) to match the incident wave frequency. Adjusting the control parameters of the Power Take-Off (PTO) system properties, such as stiffness(k_{pto}), damping (b_{pto}) and the WEC mass (m), to the right value at right time is the main control approach adopted.

Mainly, the control applications reported in literature are based on adjusting PTO parameters and focus on the stiffness parameter adjustment. However, the damping coefficient is also another performance parameter of hydraulic PTO unit and it is related to energy absorbing ability of PTO unit. So, regulating the damping parameter of PTO may increase the energy extraction efficiency. In the first part of the thesis, the damping coefficient of the PTO unit is the main focus. Generally, it is accepted that to increase the power capture performance of the system with a control application, the damping of the power take off unit should be equal to the radiation damping coefficient. An investigation on how the captured power changes with the variation of b_{pto} parameter of the system with the varying ratios of radiation damping is performed. The results of analysis of the PTO damping issue for varying ratios of radiation damping, instead of equal to radiation damping, shows that the system power capture performance may be increased. In the literature, there are numerous studies that focus on control techniques for WEC systems. Most of the devices proposed for conversion of wave energy applications are oscillating type of systems with a frequency-dependent response based on the resonance phenomena. The way to keep the system in resonance is described as matching the natural frequency (ω_n) of the WEC to the incident wave frequency. Mainly, the fast-tuning technique is defined as adjusting the stiffness of the PTO unit to achieve resonance. However, adjusting the PTO's stiffness is quite hard to implement. On the other hand, a hybrid control technique is defined as a combination of fast and slow tuning applied together. In this technique, relatively simple compared to others, the mass of the WEC body is adjusted by adding or discharge the required amount of sea water. This in turn allows adjusting the system natural frequency to the desired frequency. In the second part of the thesis study, while the fast-tuning control adjusts the stiffness of the system in quantized form, the slow tuning controller adjusts the total mass of the system with the FL based rules. As for the case of wave energy application of the FL control, it is necessary to analyse the wave energy system with high level of uncertainty when the control problem becomes a really complicated one. This is where FL control systems become an important tool for the development of controllers for such complex systems. The results achieved show that the power capture performance of the WEC can be increased with the control implementation. The technique presented proves that using combined form of quantization effect and FL based slow tuning technique improves the overall performance of the WEC and increases the net captured power of the system.

Assuming that the energy is captured from the wave, if it cannot be stored then it needs to be used immediately. For on-shore region, the captured energy can be used on the location or can be transferred to grid with little effort. However, for the devices working on offshore region, there is an issue about it. For the third part of this thesis study, assuming that WEC operated at an offshore site and fresh water is a need, the simulation study is modelled to use the energy captured to produce fresh water by means of reverse osmosis desalination process. The main point here is to eliminate the weaknesses of both systems so that the combined system model can perform better than its subsystems operated separately. By achieving the synergistic solution, the combined system can be considered to be a far more feasible solution especially for future applications. The use of renewable energy does not only reduce the carbon footprint of the RO system but also reduces its energy dependency on fossil fuel sources.

Considering the results presented in the thesis, it is concluded that optimization of system parameters can increase system effectiveness. In addition, control implementations improve the power capture performance of WECs. In addition, the immediate use of power captured from WEC systems in combined systems, such as in combination with an RO-based desalination system, may be a more suitable solution, especially for remote locations such as offshore. It is clear that the use of renewable energy systems is important to reduce the carbon footprint of production systems.

GENİŞLETİLMİŞ ÖZET

Gelişen teknolojiler, artan enerji kullanımı pahasına insanların günlük yaşamlarında kolaylıklar sağlamaktadır. Artan enerji talebini sınırlı stokları nedeniyle fosil yakıtlardan karşılamak zorlaşmaktadır. Enerji krizine en olası ve çevre dostu çözüm ise yenilenebilir enerji sistemlerinin kullanılmasıdır. Bu araştırma yönelimi ile araştırmacılar çalışmalarını yenilenebilir enerji kaynakları üzerine yoğunlaştırmışlardır.

Yenilenebilir enerji kaynakları temel olarak rüzgar, güneş ve dalga enerjisi olarak sınıflandırılır. Güneş ve rüzgar enerjisinde teknoloji belli bir seviyeye ulaşmıştır. Güneş ve rüzgar enerjisinde mevcut teknoloji kullanılabilirlik açısından belirli bir düzeye ulaşmış olsa da dalga enerjisi dönüşüm sistemleri hala araştırma aşamasından uzaklaşmamıştır. Dalga enerjisinin, güneş enerjisinin konsantre bir formu olarak tanımlandığı yaygın olarak bilinmektedir. Bu gözlem, dalga enerjisini önemli ve çok hayati bir yenilenebilir enerji kaynağı yapmaktadır. Dalga üreten rüzgarlar, aslında dünyanın açık su kütlelerinin kademeli olarak ısınması ile meydana gelir ve enerjilerinin bir kısmını dalgalar oluşturmak üzere transfer eder. Bu nedenle, dalgalar güneş enerjisinin neden olduğu konsantre rüzgar enerjisi biçimini taşır. Dünya çapındaki dalga gücü potansiyeli yaklaşık 1-10 TW'dir ki bu da yıllık kullanılabilir bir enerji kaynağına eşdeğer olan 8000-80000 TWh'dir.

Ancak bu enerjiyi kullanılabilir hale getirmek için teknik olarak zor aşamalardan oluşan daha ileri araştırmalara ihtiyaç vardır. Ayrıca dalga enerjisini faydalı enerji formuna çeviren bir cihaza da ihtiyaç vardır. Dalga enerjisini çıkaran bu sisteme dalga enerjisi dönüştürücü (DED) sistemi denir. Önemli bir konu da bu sistemin yerleştirileceği konumdur. Lokasyon iyi analiz edilmeli ve bu lokasyonda meydana gelen dalgaların özellikleri belirlenmelidir. Temel olarak dalga enerjisi dönüşüm sistemlerinin yerleştirileceği lokasyonlar derinliğe göre üç bölüme ayrılmıştır. Bunlar kıyı, kıyıya yakın ve açık deniz türleri olarak adlandırılmaktadır. Dalgaların enerji potansiyeli analizi, en enerjik olan dalgaların kıyı şeridinden uzakta gözlendiğini ortaya koymaktadır. Dalgalar kıyıya doğru ilerledikçe yer etkisiyle enerjilerini kaybederler.

Dalgaların taşıdığı enerji, dalgaların önemli dalga yüksekliği ve dalga frekansı özelliklerinin bir fonksiyonu olarak tanımlanır. Konum belirlendikten sonra, topolojik durum ve deniz durumu koşulları dikkate alınarak o bölge için uygun dalga enerjisi dönüşüm sistemi geometrisi ve çalışma prensibi seçilmelidir. Dalga enerjisi dönüştürücüsü, güç çekme ünitesi (GÇÜ) mekanizması kullanarak dalgaların hareketini mekanik enerjiye dönüştürür. Bu aşamalardan sonra sistemin yüksek enerji yakalama performansına ulaşabilmesi için DED sisteminin kontrol edilmesi gerekmektedir. DED sistemlerinde kontrol uygulaması, düzenli dalgalar halinde belirli bir aşamaya taşınmıştır ve iyi bilinmektedir. Ancak gerçek deniz dalgaları düzenli formda olmaktan uzaktır. Aslında gerçek dalgalar karmaşık ve doğal olarak düzensiz biçimlerdedir. Bu nedenle, düzensiz dalga formunu önceden gözlemlemeye ihtiyaç vardır. Gelecekteki dalga iklim bilgisinin mevcudiyeti veya ulaşılabilirliği, dalga enerjisi dönüştürücüsünün oluşacak dalgalara göre ayarlanması için gereken süreyi sağlar. Bu nedenle, dalga yüksekliği verilerinden dalga frekansının tahmini çok kritik hale gelir. Bunun için kayan Ayrık Fourier Dönüşümü gibi sinyal işleme tekniklerine ihtiyaç duyulmaktadır.

Başarılı bir DED sisteminin uygulanmasındaki ana zorluk, gerçekçi düzensiz deniz durumları için uygun bir kontrol tekniği geliştirmektir. Esas konulardan biri, doğru zamanda doğru kontrol ayarlarını uygulamak için dalga özelliklerini iyi belirlemek ve sistemin ayar parametrelerini ayarlamaktır. Kontrol tekniklerinin dalga enerjisi çıkarma potansiyelini arttırdığı kabul edilmesine rağmen, genel konunun anlaşılması hala çok zayıftır. Salınımlı tipler için kontrol stratejilerinin temel amacı, DED'in doğal frekansını gelen dalga frekansına uyacak şekilde ayarlayarak dalga enerjisi dönüştürücüsünü rezonansta tutmaktır. GÇÜ sistem özelliklerinden sertliğin ve sönümlemenin ayrıca DED kütlesi gibi kontrol parametrelerinin doğru zamanda doğru değere ayarlanması benimsenen ana kontrol yaklaşımıdır.

Esas olarak, literatürde bildirilen kontrol uygulamaları, GÇÜ parametrelerinin ayarlanması esasına dayanmaktadır ve sertlik parametresinin ayarlanmasına odaklanmaktadır. Ancak sönümleme katsayısı da hidrolik GÇÜ ünitesinin bir diğer performans parametresidir ve GÇÜ ünitesinin enerji emme yeteneği ile ilgilidir. Bu nedenle, GÇÜ'nün sönümleme parametresinin düzenlenmesi, enerji çıkarma verimliliğini artırabilir. Bu tez çalışmasının ilk bölümünde, PTO ünitesinin sönüm katsayısı ana odak noktasıdır. Genel olarak bir kontrol uygulaması ile sistemin güç yakalama performansını artırmak için GÇÜ sönümlemesinin radyasyon sönümleme katsayısına eşit olması gerektiği kabul edilmektedir. Sistemin GÇÜ sönümleme parametresinin radyasyon sönümlemesinin değişen oranları ile ayarlandığında yakalanan gücün nasıl değiştiği üzerine bir araştırma yapılmıştır. Radyasyon sönümlemesine eşit olmak yerine radyasyon sönümlemesinin oranları olarak değişen GÇÜ sönümlemesi analizi sonuçları, sistemin güç yakalama performansının artırılabileceğini göstermektedir.

Literatürde, DED sistemleri için yapılmış kontrol tekniklerine odaklanan çok sayıda çalışma vardır. Dalga enerjisi dönüşüm uygulamaları için önerilen cihazların çoğu, rezonans olgusuna dayalı frekansa bağlı yanıta sahip salınımlı tipte sistemlerdir. Sistemi rezonansta tutmanın yolu, DED'in doğal frekansını gelen dalganın frekansıyla eşleştirmek olarak tanımlanır.Temel olarak, hızlı ayar tekniği, rezonans elde etmek için GÇÜ sertliğini ayarlamak olarak tanımlanır. Ancak, GÇÜ'nün sertliğini ayarlamak oldukça zordur. Öte yandan, hibrit kontrol tekniği, birlikte uygulanan hızlı ve yavaş ayarın bir kombinasyonu olarak tanımlanır. Diğerlerine göre nispeten basit olan bu teknikte, WEC gövdesinin kütlesi, gerekli miktarda deniz suyu eklenerek veya boşaltılarak ayarlanır. Bu da sistemin doğal frekansının istenen frekansa ayarlanmasını sağlar. Tez çalışmasının ikinci kısmı olarak, hızlı ayar tekniği sistemin sertlik parametresini kademeli biçimde ayarlarken, yavaş ayarlı kontrol tekniği sistemin toplam kütlesini bulanık mantık (BM) tabanlı kurallarla ayarlar. BM kontrolünün dalga enerjisi uygulamasında, kontrol problemi gerçekten karmaşık hale geldiğinde yüksek düzeyde belirsizlikteki dalga enerjisi sistemini analiz etmek gerekir. BM kontrol sistemlerinin, bu tür karmaşık sistemler için kontrolörlerin geliştirilmesinde önemli bir araç haline geldiği yer burasıdır. Elde edilen sonuçlar, kontrol uygulaması ile DED'in güç yakalama performansının artırılabileceğini göstermektedir. Sunulan teknik, kademelendirme etkisinin ve BM tabanlı yavaş ayarlama tekniğinin bir arada kullanılmasının DED'in genel performansını iyileştirdiğini ve sistemin net yakalanan gücünü arttırdığını kanıtlamaktadır.

Enerjinin dalgadan yakalandığını varsayarsak, bu enerji eğer depolanamıyorsa hemen kullanılması gerekir. Kıyı bölgesi için, yakalanan enerji olduğu yerde kullanılabilir veya çok az çabayla şebekeye aktarılabilir. Ancak açık deniz bölgesinde çalışan cihazlar için bu konuda bir problemler mevcuttur. Bu tez çalışmasının üçüncü bölümü için, DED'in bir açık deniz sahasında çalıştırıldığı ve tatlı su ihtiyacı olduğu varsayılarak, simülasyon çalışması, ters ozmoz tuzdan arındırma işlemi yoluyla tatlı su üretmek için yakalanan enerjiyi kullanmak üzere modellenmiştir. Buradaki temel konu, kombine sistem modelinin ayrı ayrı çalıştırılan alt sistemlerinden daha iyi performans gösterebilmesi için her iki sistemin zayıf yönlerini ortadan kaldırmaktır. Bu sinerjik çözüme ulaşıldığında, kombine sistem özellikle gelecekteki uygulamalar için çok daha uygun bir çözüm olarak düşünülebilir. Yenilenebilir enerji kullanımı sadece ters ozmoz sisteminin karbon ayak izini azaltmakla kalmaz, aynı zamanda fosil yakıt kaynaklarına olan enerji bağımlılığını da azaltır.

Tezde sunulan sonuçlar göz önüne alındığında, sistem parametrelerinin optimizasyonunun sistem etkinliğini artırabileceği sonucuna varılmaktadır. Ayrıca, kontrol uyguları DED'lerin güç yakalama performansını iyileştirmektedir. Ayrıca, DED sistemlerinden yakalanan gücün RO tabanlı tuzdan arındırma sistemi ile birlikte kullanılması gibi entegre sistemlerde anında kullanılması, özellikle açık deniz gibi uzak konumlar için daha uygun bir çözüm olabilir. Üretim sistemlerinin karbon ayak izini azaltmak için yenilenebilir enerji sistemlerinin kullanımının önemli olduğu açıktır.

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AI	: Artificial Intelligence
DFT	: Discrete Fourier Transform
DOF	: Degree Of Freedom
D_{wec}	: Diameter
F	: Force
$F_E(t)$	: Wave Excitation Force
$F_R(t)$	: Radiation Force
FL	: Fuzzy Logic
H(t)	: Power Take-Off (PTO) Force
H_{m0}	: The Significant Wave Height
HP	: The Required Power for Desalination
$K_E(t)$	: Wave Excitation İmpulse Response Function
$K_R(t)$	: Radiation Impulse Response Function
M_d	: Distillate Mass Flow Rate
M_f	: Mass Flow Rate
MOWC	: Multiple Oscillating Water Column
OWC	: Oscillating Water Column
P	: Wave Energy Flux Per Unit Wave Crest Length
PAWEC	: Point-Absorbing Wave Energy Converter
P_{total}^{max}	: Maximum Total Power
P_{elec}	: Required Electrical Power
P_h	: Hydraulic Pressure
P_{hyd}	: Hydraulic Power
P_{ins}	: Instantaneous Power
P_{ma}	: Moving Average Power
$P_{nominal}(t)$	: Average Capture Power at Time t

P_{req} : The Stiffness Adjustment System Required Power
PTO : Power Take-Off
Q_h : Hydraulic Flow Rate
RO : Reverse Osmosis
RR : Recovery Ratio
SR : Salt Rejection Percentage
TCF : The Temperature Correction Factor
T_e : Energy Period
SPC : Specific Power Consumption
TW : Terawatt
WEC : Wave Energy Converter
X_{av} : The Average Salt Concentration
X_b : The Rejected Salt Concentration
X_d : Distillate Product Salt Concentration
X_f : Feed Flow Rate Salt Concentration
a : Frequency Dependent Additional Mass
$a(\omega)$: Frequency-Dependent Added Mass Coefficient
b_{net} : Damping Coefficient
b_{loss} : Radiation Damping Loss
b_{pto} : PTO Damping
b_{rad} : Radiation Damping
b_{rad_nom} : The Radiation Damping Coefficient at The Nominal Wave Frequency
$b(\omega)$: Radiation Velocity Damping Coefficient
g : Gravitational Acceleration
h_{wec} : Height
k_{net} : Net Stiffness
k_{pto} : Stiffness Of PTO Unit

k_{pto}^{ins}	: Instantaneously Varied Stiffness
k_{pto}^{q}	: Quantized Stiffness
k_s	: The Salt Permeability
k_w	: The Membrane Water Permeability
m	: Total Mass
m_{dry}	: Dry Mass
m_o	: Zeroth Order Moment, Energy
m_{st}	: Additional Mass for The Water Tank
m_{tnk}	: Fixed Additional Mass of The Tank
q_s	: Quantization Steps
t_m	: End Time.
t_n	: Start Time
t_{sea}	: The Sea Temperature
v	: Velocity
x(t)	: The Position Of The Body At Time t
ρ	: Density
$()^{stab}$	: Stable Parts
$()^{unst}$	: Unstable Parts
ΔT	: Time Shift
$\zeta(t)$	: Wave Elevation
ΔP	: The Net Osmotic Pressure Across the Membrane
ρ_f	: The Feed Flow Rate Density
η_p	: The Driving Pump Efficiency
ω_{est}	: Estimated Wave Frequency
ω_n	: Natural Frequency of WEC
α	: Gain Alpha
ω_e	: Energy Frequency
δm_{st}^{req}	: Control Input of Required Mass of Water

1. INTRODUCTION

The developing technologies provide convenience in people's daily life at a cost of increasing amount of energy use. The related industrial activities as well as their energy demand are also increasing. A major part of the energy demand is met by fossil fuels. As widely known, the emissions and waste generated during energy production from fossil fuels harms the environment. Also, the limited reserve of fossil fuels has led to search for more clean, environmentally friendly and renewable based energy sources. The clean and environmentally friendly renewable energy sources are listed as solar energy, wind energy, bio energy and wave energy. It is important to note that some of these renewable energy related research and related engineering systems are mostly utilized. Besides such systems and related technology have reached to a certain capacity and technological development level. This statement is valid for wind and solar type renewable energy systems. It is seen that the reported developments for wave energy-based power systems seem to be slower in development relative to the other two renewable energy sources discussed. Hence, the developments related to wave energy systems appear to be relatively behind the technological readiness level compared to wind and solar energy systems.

Mainly motivated by the oil crisis, extensive research studies were conducted during the 1970s to investigate the feasibility of extracting energy from ocean waves (Boyle, 2004). The early studies noted that the wave energy systems and related research issues are complex interdisciplinary studies including non-linear effects between the wave energy converter and the sea waves as well as issues related to uncertainties about the sea states and wave climate. In the early studies, one of the main reasons for the slow progress is the irregular and the complex nature of the waves.

The importance of the wave energy itself is related to its source that is defined as a concentrated form of solar energy. The wave producing winds are actually generated by the differential heating of the earth pass over open bodies of water, transferring some of their energy to form waves. Hence, the waves carry concentrated form of wind and solar energy.

The energy of waves characterised by some critical parameters such as significant wave height and wave period. The energetic waves are generally occurring at the regions where the depth of the sea is higher, like oceans. The oceans have been reported to have great wave energy potential (Falcao, 2010). However, the complex and irregular composition of the ocean waves and also the non-linear nature of wave-WEC interaction makes the issue a challenging one (Yavuz et al, 2007).

Another important issue is extraction of energy from waves by using a wave energy converter. It is also reported that control application of wave energy converters improves the power capture performance of the wave energy converter systems (Yavuz et al, 2007) The main role of the control systems in such applications is to widen the effective working range frequencies of the system. Hence with the added control application to the WEC system, it is aimed at expanding the optimum operation conditions beyond fixed resonant frequency-based performances.

Although, control techniques appear to improve the wave power extraction potential, understanding of the overall issue still remains to be very weak. The main challenge in implementation of a successful WEC system is to develop a control technique suitable for realistic irregular sea states. The main objective of control strategies for oscillating types is to keep the WEC at resonance by adjusting the WEC's natural frequency (ω_n) to match the incident wave frequency. There are numerous studies that focus on control techniques for WEC systems. Most of the devices proposed for conversion of wave energy applications are oscillating type of systems with a frequency-dependent response based on the resonance phenomena (Falnes, 2002a). It can be seen from the related literature that there are mainly two types of control techniques named as phase control and latching control. Both techniques aim at keeping the system in resonance at all working condition. The phase control operates based on the principle of adjusting the tuning parameters of the power take off system. On the other hand, latching control is based on temporarily locking the motion of the WEC by adjusting the damping parameter of the power take off system at specific positions (Babarit et al 2010).

It is observed that there are not many practical WEC systems in operation. Hence, it appears that the technological readiness level of wave energy conversion is generally still in research and development stage. So far, there are not many working devices used in practical energy generation purposes. Also, in our country, the wave energy conversion is not a popular topic to study. Some rapid developments can be achieved if more comprehensive international cooperation is established on the aspects of R&D of wave energy devices. One of the main subjects that inspired the creation of this study is to examine ways of performance improvements for wave energy converters based on control applications. The results of the present study may be the solution for the energy requirements of our country for meeting the increasing energy demand.

The work present in this thesis focuses on investigation of the wave energy conversion device modelling and control techniques for oscillating type WEC systems. The control approach preferred is based on hybrid phase control application including the AI based slow tuning and also fast tuning on the developed oscillating type WEC model. In addition, the damping coefficient-based control approach is also studied to investigate its effect on the wave energy extraction performance. Also, the existing wave theory has been examined in detail for modelling of WEC systems.

1.1. Contribution of the Thesis

In this study, the control techniques on a heaving type wave energy converter to improve the energy extraction performance are studied. Contribution of the thesis can be summarized as follows;

1. In order to perform the study in realistic conditions irregular sea states are chosen as sea states.
2. A heaving type wave energy converter device is modelled in MATLAB/SIMULINK environment.
3. The control approach preferred is based on hybrid phase control application on the developed oscillating type WEC model includes;
    a. AI based slow tuning
    b. Fast tuning.
4. A Fuzzy Logic controller is constructed to improve the performance of slow tuning control application.
5. The damping coefficient-based control approach is studied to investigate its effect on the wave energy extraction performance. The relation between radiation damping and the power take-off unit damping is investigated. The effect of the variation of the power take-off damping on power capture performance of WEC is examined.
6. An integrated WEC-Desalination system model is developed to investigate the performance of the desalination process using the WEC PTO generated power.

1.2. Organization of the Thesis

The rest of this thesis is organized as follows. In Section 2, the previous studies on wave energy, wave energy conversion and the control techniques are presented. In this section, the classification of wave energy converters by structures, operational principles and related PTO unit types are provided in detail. In addition, control approaches used for performance optimization of WEC devices are also presented.

In Section 3, the material and methods and related issues are discussed. The modelling of the wave energy converter is discussed. The developed MATLAB/Simulink model details are presented. The details provided includes the approach adopted in controlling the WEC system based on the identified wave frequency settings. After generating the energy from WEC system, it is used the reverse osmosis (RO) based desalination process. In this section, the details of the RO based desalination system are also presented.

In Section 4, the simulation model related results are presented. The modelled system examined at realistic irregular sea states. The simulation results for hybrid control application including both slow and fast tuning are presented in detail. Also, the investigation on performance of a heaving type wave energy converter for variation of radiation damping over power take-off damping ratio is performed. In addition, the simulation results for the renewable energy-based desalination process model are also presented.

In Section 5, conclusions of the thesis and the related future works are presented.

2. PREVIOUS STUDIES

In this section, issues related to concept of WEC system topics are introduced. These topics include wave energy, classifications of WEC systems and control techniques applied on the WEC devices.

The energy crisis in the 1970s accelerated the trend towards alternative energy sources rather than crude oil-based energy sources in the world. In these periods, especially solar energy and wind energy-based energy conversion systems found their place in energy research studies. Due to the constantly increasing energy need and the fact that the solar and wind-based systems alone are not sufficient to provide this energy demand, there is surely a need for other alternative environmentally friendly energy sources. The wave energy is among the candidate energy sources with highly environmentally friendly feature. Studies on wave energy have been carried out all over the world where countries with or without a coast to the sea or the ocean. Especially with the influence of the studies in the field of fluid mechanics (Olgivie, 1963; Longuet-Higgins, 1963; Pierson and Moskowitz, 1964; Black, 1975;), the popularity of this field increased even more when an infrastructure was established for the studies in this field. As a result of these, especially towards the end of the 1970s, publications on the structures of these systems began to be made, especially under the leadership of Evans (Evans, 1979), Fry (Fry and Jeffery, 1979) and Newman (Newman, 1979). In the studies carried out in the following years, the research topic has shifted to the development of wave energy converter systems. Among the systems developed, examples of oscillating types are Edinburgh University's Duck (Salter et al., 1976; Edinburgh University, 1979; Anderson, 1985; Salter, 1993), Bristol University's Bristol Cylinder (Leijon et al., 2006; Bjarte et al., 2006), Lancaster University's Lancaster cylinder (French, MJ, and Bracewell, R., 1985; Shwater, 1992), Flounder (French and Hurdle, 1982; Folley, 1991) and PS Frog (French and Hurdle, 1982; Lancaster University, 1988; Bracewell, 1990), Coventry University's Clam (Converty

University, 1986; Lockett, 1991; Peatfield, 1991). However, the investigations of the systems that are the subject of these studies have been limited to linear wave and linear system structure and behaviour. Budal and Falnes (Budal and Falnes, 1975) are the first researchers to introduce the definitions of resonance and point-absorbing wave energy converter (PAWEC) and explain the details of the operation of these systems, especially despite the linear system and environment limitations encountered. These studies of Budal and Falnes, in particular, shaped the studies in the following years and caused them to be the most important researchers of the period after Evans, Jeffery and Newman. In those years, the limited features of computer systems, their limited use in research and the fact that the software on fluid mechanics has not been developed yet, forced the studies to stay within the limits of linear theory, and the experimental studies were aimed at proving the linear structures of these theoretical studies. However, the researches that continued feverishly until the mid-1980s were interrupted by the decline in oil prices and the decrease in interest, but some further studies were carried out in this area (Spiegel, 1965; French, 1982; Lancaster University, 1988; Bracewell, 1990; Folley, 1991). This effect lasted until the mid-1990s, research groups shifted their work to different subjects in the interim period, and the experimental systems and related laboratories established in the previous years were closed or put on hold at the end of the financial support cut off. However, due to the increasing energy demand since the mid-1990s, the interest in renewable energy sources and the reaction to nuclear energy, investment and research studies for these systems have started to be given weight again. Country analyses for wave energy studies Sweden (Bergdahl, 1979; Bergdahl, 1992), England (ETSU, 1985; ETSU, 1994), Norway (White, 1989), Spain (Matas, 1992), Denmark (Thorpe, 1993), Japan (Miyazaki, 1995; Hotta, 1995) and India (Falnes, 1997) and related reports have been published. In these studies, the high energy potential of these regions and the importance of this energy source to be captured have been revealed.

The worldwide wave power resource is approximately 1-10 TW, which is equivalent to an annual available energy resource of 8000-80000 TWh per annum. In comparison to other renewable energy resources wave energy is concentrated, “15-20 times more available energy per square meter than either wind or solar” (Vining and Muetze, 2007). Briefly, the wave energy can be considered as a concentrated form of solar and wind energy transferred to waves. Once that energy is transferred to waves, it can be transported kilometres with little loss The world’s wave energy potential is given in the Figure 2.1.

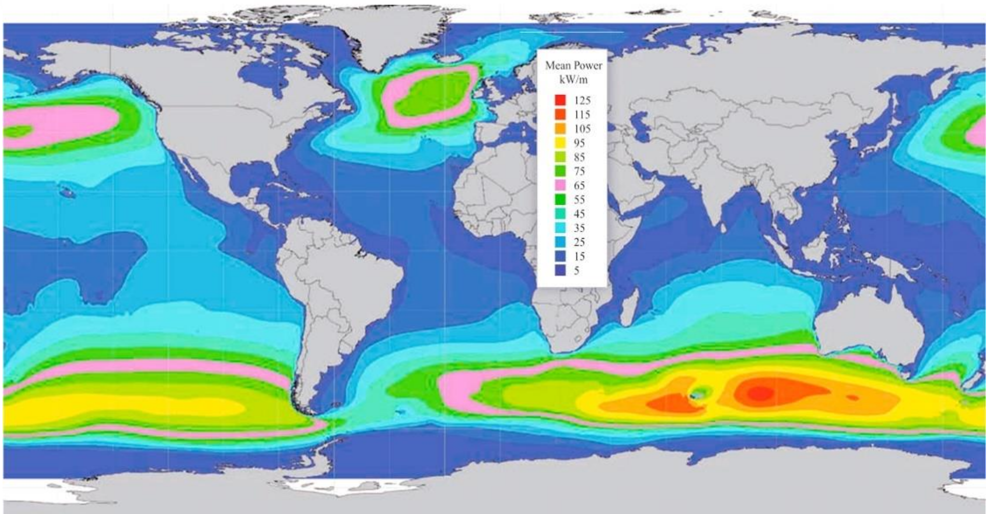


Figure 2.1. The global wave power density distribution (Lehmann et al, 2017)

The point with the best wave potential in the world is 1,400 km on the Kerguelen Island in the Southern Ocean. The annual wave energy potential recorded here is 140 kW/m. The highest recorded energy potential in the northern hemisphere is 400 km west of Rockall. The average annual wave energy potential recorded at this point is 90 kW/m. The monthly wave energy potential recorded in both hemispheres of the world is 200 kW/m in total. On the other hand, although these detected points have a wave climate carrying maximum energy, they are not suitable for the use of WEC systems. Preferred installation sites for WEC systems and WEC farms are mostly coastal areas with a depth not exceeding 50-60 meters (Cruz, 2008).

The effect of seasonal change is another criterion that cannot be ignored for WEC systems. The change in the wave climate of the region where the system operates during the year also determines how much of the year the system will spend efficiently.

Linear wave theory is the core theory of ocean surface waves used in ocean and coastal engineering and naval architecture. According to that theory, wave power could be determined by wave height, wave length, and water density. This relation is mathematically explained as;

$$P = \frac{\rho g}{64\pi} H_{m0}^2 T_e \tag{2.1}$$

Where P is the wave energy flux per unit wave crest length, ρ is the density of the water, g is the gravitational acceleration, h is the significant wave height and T is the wave energy period.

It has been reported that approximately 1-10 TW energy is transferred to oceans (Vining, 2005). The wave, which can move on the ocean surface with very little energy loss, mainly loses a large amount of energy due to the effect of friction as it approaches the shore (Cruz, 2008). Most of the energy contained in waves is close to the water surface and the energy decays exponentially with the depth below the surface. This is the reason why most wave energy conversion devices are designed to float and pierce the water surface in order to capture the maximum energy (Boyle, 2004).

Wave energy converter itself can be defined as the device that can extract the energy from the waves. It has been stated as it is necessary to displace water in an oscillatory manner and with correct phase, in other words, the energy has to be removed from the waves in energy conversion purpose (Falnes, 2002b). (

There are a wide variety of different types of wave energy converters. Although these types have diversity among themselves, the following three characteristics are seen as common to all of them (Bracewell, 1990).

1. They need a work surface that can withstand waves
2. It is necessary to provide a stable reference system that will react against wave forces.
3. The reference positions of their structures must be in a state resistant to some form of power mechanisms. Work surfaces must be capable of being moved by wave forces.

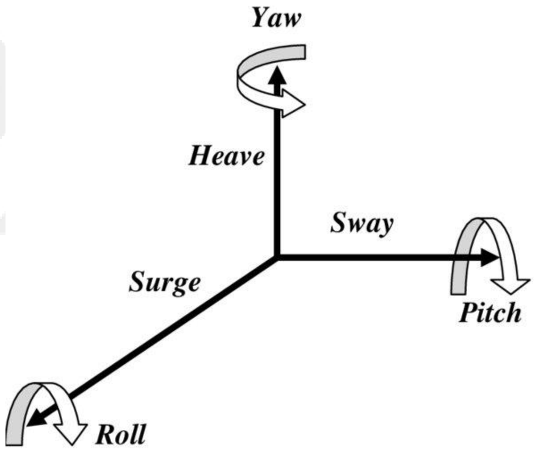


Figure 2.2. Six degree of freedom (Zeng, 2012)

A floating object can make six different axial movements with the effect of waves acting on the body on the sea surface. Therefore, any free-floating body on the sea surface can be defined as a dynamic system with six degrees of freedom. With a similar approach, WEC systems can be considered as dynamic systems with six degrees of freedom if there is no restriction in their movements (Sabuncu, 1983). In Figure 2.2, the schematic representation of 6 degree of freedom is given. They are sway, heave and surge are linear motions along the three perpendicular coordinate axes in the space; roll, pitch and yaw are rotational movements 3 with respect to the three perpendicular directions (Zeng, 2012). The main issue of the six fundamental solid body modes, only heave, surge, and pitch are directly coupled to the waves (French et al, 1987). For this reason, in the studies on the motion types and energy properties of wave energy converters, it has been seen that the three motion types have the most intense energy potential. This direct coupling effect that makes these modes so popular. The power, which can be extracted from a motion mode and is anti-symmetric with respect to the waves, is twice as great as that to be had from a symmetric mode, such as heaving. However, it is the coupling effects between these two modes that make the behaviour of a pitching and surging device a complicated one (Yavuz, 2011).

Studies on the development of WEC systems are grouped under three main headings. These can be listed as the system geometry, the energy conversion system and the development of control systems that will keep these systems in continuous oscillation (Guo and Ringwood, 2021).

In studies conducted only in the field of system geometry, there has been reached up to a hundred designs in terms of geometric diversity. Even if they work with similar logic, there are systems with different geometrical structures.

Although there are many types of WEC systems in terms of geometry, the large number of geometries in question, most of them are still in the design phase (Whittaker, 1965; Hotta et al., 1995; Salter and Lin, 1995; Thorpe, 1995, Pelc and Fujita, 2002, Henderson, 2006, Qiao et al. 2020).

2.1. Classification of WEC Systems

2.1.1. Classification of WEC Systems by Location

Among the types of wave energy converters encountered, three different groups emerge. These types are generally due to differences in the application area. When these systems are classified according to their application areas, 3 different types emerge. These groups can be listed as follows.

a) On-shore applications
b) Near shore applications
c) Off-shore applications

Therefore, in the examination of the systems in question, a geometric structural analysis should be made according to this class distinction. WEC systems in each region have their own characteristics. For example, while the energy obtained in on shore applications is low, the wave energy potential in off-shore location is much higher. On the other hand, while maintenance and intervention are easier in on shore applications, a lot of effort is required for operations such as maintenance in offshore applications.

2.1.1.1. On-Shore Applications

The sea waves move on the sea surface with very little energy loss, but lose more energy as they approach the shore. This is mainly due to the shallowing of the water level and the effect of increasing friction force. The common logic of coastal type WEC systems is that the wave coming towards the shore at certain speeds converts the energy of the wave down into electrical energy. This principle usually takes place in 3 stages. First, the buffer part is moved by the waves coming towards the shore. Then, the moving parts compress the air in a piston or cabinet. and finally, turbines rotate with the movement of air and electrical energy is produced with the magnetic field formed. The LIMPET, one the most common OWC is presented in Figure 2.3 (Falcao, 2016).

Figure 2.3. LIMPET OWC plant

The idea makes the LIMPET unique is its construction method. In order to avoid working on the actual shoreline, the LIMPET avoids wave action during the construction process. Once the devices completely constructed, the bund at front is removed and allows the sea access the device. Generally, the OWC devices work with the reversing air flow. This process requires special turbine called Wells' turbine. The schematic representation of Wells' turbine is given in Figure 2.4.

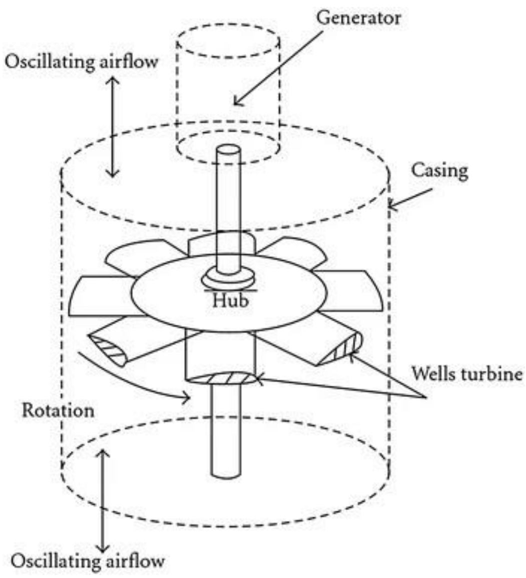


Figure 2.4. The Wells' turbine model

If a normal turbine is used in this type of system, since the turbine blade will move in different directions when water enters and leaves the room, the system will work intermittently, which reduces the efficiency of the system. In this case, the energy production of the system will also be low since continuity cannot be ensured. Therefore, it is appropriate to use a wells turbine for such systems. This turbine has a special property shown in Figure 2.5 that can rotate in the same direction while air passes through in both direction (bidirectional), forward or backward (Halder et al, 2017).

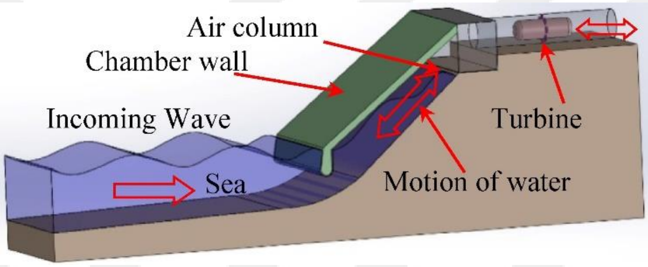


Figure 2.5. The operation of Wells' turbine for OWC WEC

On the other hand, due to the high capital cost and lack of suitable sites on coastline limits the use of OWC WEC systems, hence a new technology is conducted to address the problem. The OWC system is re-designed to work on a coastal structure such as a harbour breakwater or a coastal protection structure. It is reported that the use of the OWC system combined with breakwaters can increase the function of the both systems. The first breakwater OWC wave power plant, presented in Figure 2.6, is constructed with 16 air chambers on a 100 m breakwater section, which is referred to as the first MOWC (Multiple Oscillating Water Column). The operation starts in the year 2011 with a total capacity of 300 kW (Zhang et al, 2012).


Figure 2.6. Mutriku breakwater OWC

Another WEC used in on-shore is TAPCHAN (Tapered Channel Wave Energy). The schematic representation is given in Figure 2.7 (Fay et al, 2020). This device works with the overtopping wave energy conversion principle. It uses a tapered concrete channel to elevate part of the incoming waves above their natural height in order to fill a raised reservoir. These systems consist of a tapered concrete channel with a wall height of 3-5 meters above the water level, feeding the reservoir built on the edge of the cliff. The potential energy of this water body is first converted into mechanical energy and then into electrical energy with the help of the turbine and generator couple. The seawater is allowed to return to the sea by passing through low head turbines. Since it has very few moving parts, wear and tear events are less than other types, so it has low maintenance cost and high reliability. However, TAPCHAN requires a coastal environment where a large reservoir can be constructed. As one can see, finding the right location for TAPCHAN to work is very difficult since TAPCHAN's success is dependent on earth's geography and naturally occurring events.

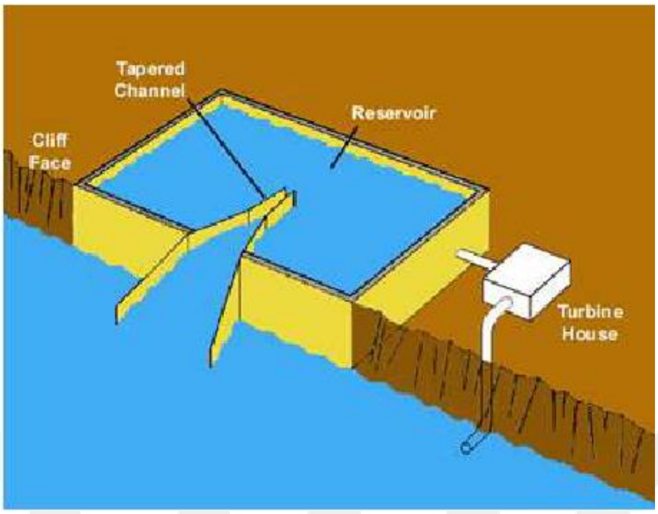


Figure 2.7. The schematic representation of TAPCHAN WEC (Tapered Channel Wave Energy)

Another on-shore WEC system is ECO Wave which is placed on land or on an existing structure like a harbour wall, as presented in Figure 2.8. The floating buoys are attached to the structure via flexible arms. The heaving motion of the buoys pumps the hydraulic fluid onshore to power a hydraulic generator.

Figure 2.8. The Implementation of Eco Wave WEC (Eco Wave Power)

The floaters draw energy from incoming waves by converting the rising and falling motion of the waves into a clean energy generation process. More precisely, the movement of the floaters compresses and decompresses hydraulic pistons which transmit bio-degradable hydraulic fluid into land located accumulators. In the accumulators, at a pressure is being built. This pressure rotates a hydraulic motor, which rotates the generator, and then the electricity is transferred into the grid, via an inverter. The fluid, after decompression, flows back into the hydraulic fluid tank, where it is then re-used by the pistons, thus creating a closed circular system. The system commences production of electricity from wave heights of 0.5 meters. The whole operation of the system is controlled and monitored by a smart automation system. Also, when the waves are too high for the system to handle the floaters automatically rise above the water level and stay in the upward position until the storm passes. Once the storm passes, the floaters return to operation mode (Eco Wave Power). The operation is presented in Figure 2.9.

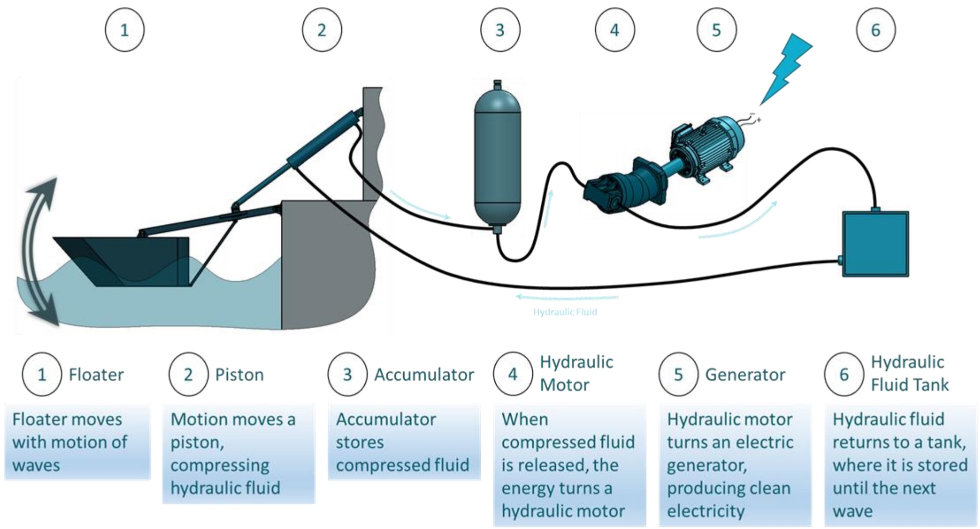


Figure 2.9. The Eco Wave heaving buoy (Eco Wave Power)

It is possible to roughly divide on-shore WEC systems into structural classes. Their common logic is to extract the energy of the wave coming towards the shore at a certain speed, by a moving part, and to immediately convert it into electrical energy by means of moving parts. For this, either a piston or compressed air pressure in a chamber is used.

One point that should be mentioned here is that regions with lower wave regimes are more applicable for WEC systems. The main reason for this is the difficulty of installing and operating the WEC system, which occurs due to ambient conditions in extreme wave climates.

2.1.1.2. Near-Shore Applications

The near shore type WEC systems in general operate at water depths of 10-25 meters. These types of systems always rank second when compared to on shore and off-shore type WEC systems in terms of ease of installation and energy conversion potential. The near-shore WEC systems can generate more energy than on-shore applications, but lower than offshore applications.

One of the near shore wave energy converters, working the same principle of OWC, is the OSPREY, as presented in Figure 2.10. Here, the incoming wave currents are concentrated and amplified by the inclined and rising side walls, similar to some models of onshore converters, and the air in the collector is compressed. With the outward movement of the compressed air, the turbines are rotated and again, as in many converter types, mechanical energy is obtained before this movement and then electrical energy. In 1995, The system is damaged by storm during installation and removed from site. Replacement planned but abandoned due to unforeseen problems with site. (Falcao and Henriques, 2016).

Figure 2.10. The near shore WEC system OSPREY (Hannon et al, 2018)

Another device developed by Aquamarine Power Limited and Queen's University Belfast for near shore applications is the Oyster. Oyster, represented in Figure 2.11, is a converter that converts oscillations made by the surging movement of waves into electrical energy as its basic operating principle. These types of surging devices are situated in shallower water close to shore because it is only in shallow water that the circular movement of water particles in deep water then becomes elongated into horizontal ellipses. The Oyster has reversible water pistons and was developed for near shore operation at depths of 10 to 15 metres. When waves get the Oyster up and running, it pumps high-pressure water to the shore through a straight pipeline located at the bottom of the sea. The most complex part of the system is the conventional standard hydroelectric generators used for generating electrical power (Renzi et al., 2014). The Oyster is manufactured and checked at the factory, before it is ready to be released at sea.

The Oyster, which is brought to the seaside by a suitable vehicle, is released into the sea with the crane used and becomes suitable for work.

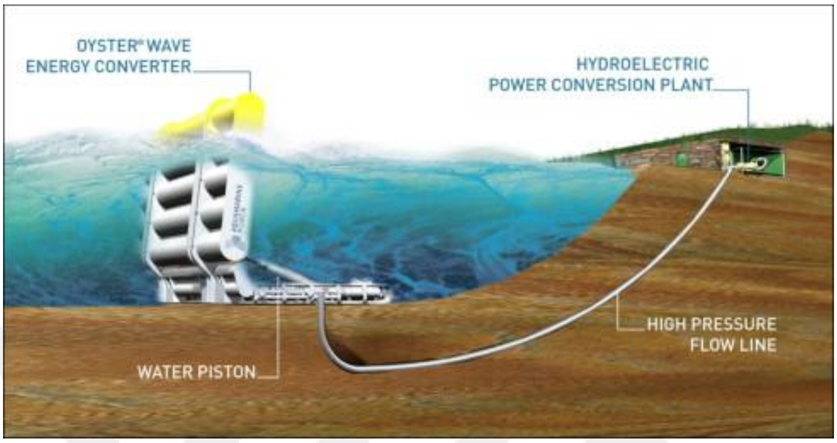


Figure 2.11. Oyster WEC system (Renzi et al. 2014)

Another nearshore surging device is the WaveRoller developed by AW Energy. WaveRoller, presented in Figure 2.12, is a device with several flaps mounted on a single seabed platform where the movements of each flap activate piston pumps that drive an on-board hydraulic motor and generator. The machine works in coastal areas about 0.3-2 km from the coast at depths of 8 to 20 meters, where the wave surge is most powerful. Depending on tidal conditions, it is mostly or completely submerged and anchored to the seafloor. A single WaveRoller unit (combination of a panel and PTO) is rated between 350kW and 1000kW with a 25-50% capacity factor, depending on wave conditions at the project site. Technology can be deployed in single units or on farms.

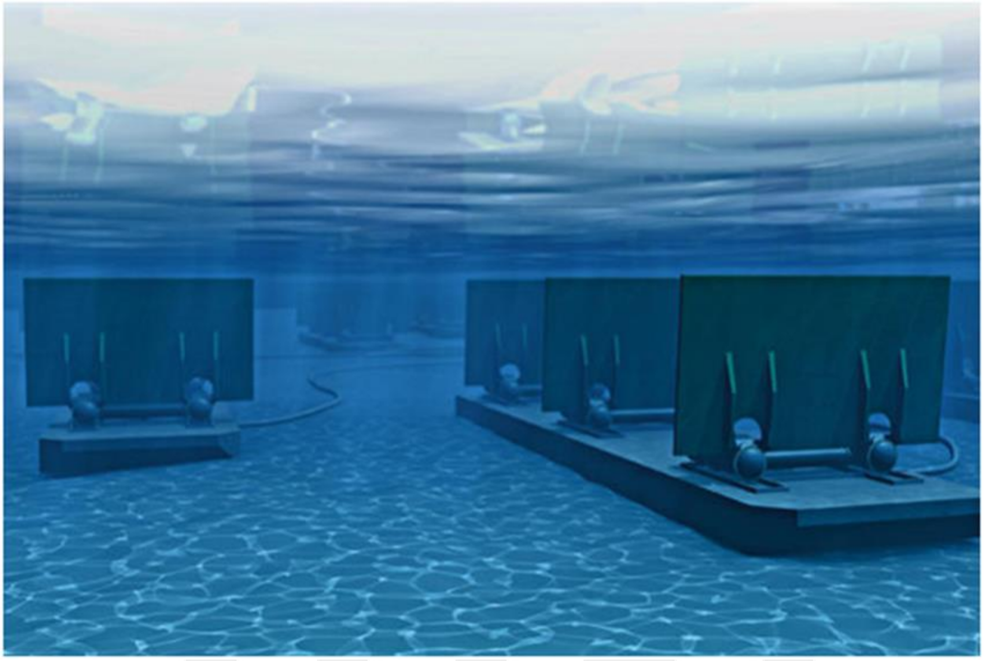


Figure 2.12. AW-Energy’s WaveRoller WEC device (AW Energy)

The McCabe wave pump, as presented in Figure 2.13, was originally developed in the 1980s as a floating device for moderate wave depths. It consists of three rectangular steel pontoons, which are hinged together across their beam. These pontoons are aligned so that their longitudinal direction heads into the incoming waves. The three pontoons move relative to each other in the waves. The essential aspect of the scheme is the damper plate attached to the central pontoon. This increases the inertia of the central pontoon ensuring that it stays relative still. Therefore, the fore and aft pontoons move relative to the central pontoon by pitching about the hinges. Energy is extracted from the rotation about the hinge points by linear hydraulic rams mounted between the central and two outer pontoons near the hinges. A 40m long prototype was briefly deployed off the coast of Kilbaha, Ireland in 1996 (Thorpe, 1999).

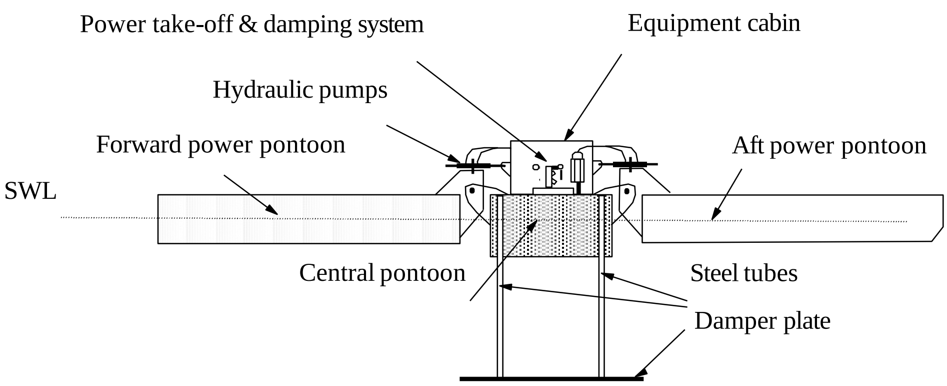


Figure 2.13. Outline of the McCabe Wave Pump (Thorpe, 1999)

The WaveStar is a near-shore device in which two rows of floating buoys move in relation to a central, bottom standing platform. Waves run the along length of the machine, lifting the floats in turn and the movement generates hydraulic pressure to power a central motor and generator. The line of floats should enable continuous energy production and a smooth output. A test section of the 600kW machine has been connected to the grid on 2010.

2.1.1.3. Off-Shore Applications

They are WEC types that operate in waters deeper than 40 meters. Stronger damping mechanisms are required in these systems so that they can operate with strong wave regimes in deep waters. These systems, which are generally floating or positioned close to the surface in order to benefit from the wave energy, usually contain a buoy assembly.

One of the biggest common problems in the production of offshore WEC systems is the cost of cables placed on the seabed. On many coasts, energetic wave climates can be obtained 5 – 15 km off the coast. In order to feed the produced energy to the grid, it is necessary to use the cables fixed (or buried) on the sea floor. In terms of service life, these cabling systems, which are exposed to external factors such as corrosion, impact and destruction, must be able to last for at least 30

– 35 years. The biggest impact on the total installation cost of offshore WEC systems is considered to be the cabling costs.

The main advantage of extracting wave energy at off-shore regions as the energetic waves generally occur at those regions. However, the construction and the maintenance at off-shore region are difficult and costly operations (Chen et al., 2013).

Pelamis differs significantly from coastal and near-shore types in terms of shape (Figure 2.14). In the simplest terms, Pelamis is a system consisting of long rod bodies connected to each other by rotating joints and pistons placed on these connection points. Due to this structure, Pelamis makes the same kind of ripple movement on the sea waves in harmony with the wave movement. This undulation movement is basically a bending movement that takes place from these points by the joints at the connection points of the rod bodies to each other. During this bending movement, the opening and closing of the pistons between the rod bodies is ensured. As a result, we initially capture the irregular, uncontrolled force carried by the sea wave and turn it into a regular mechanical movement. After this point has been reached, since it catches a regular mechanical movement, the mechanical energy of this movement can now be converted into electrical energy. In accordance with the structure of the system, this happens sometimes by pumping oil and sometimes by directly producing electrical energy with pistons that undertake the task of generating electricity and basically contain elements such as stator.

Figure 2.14. The Pelamis WEC

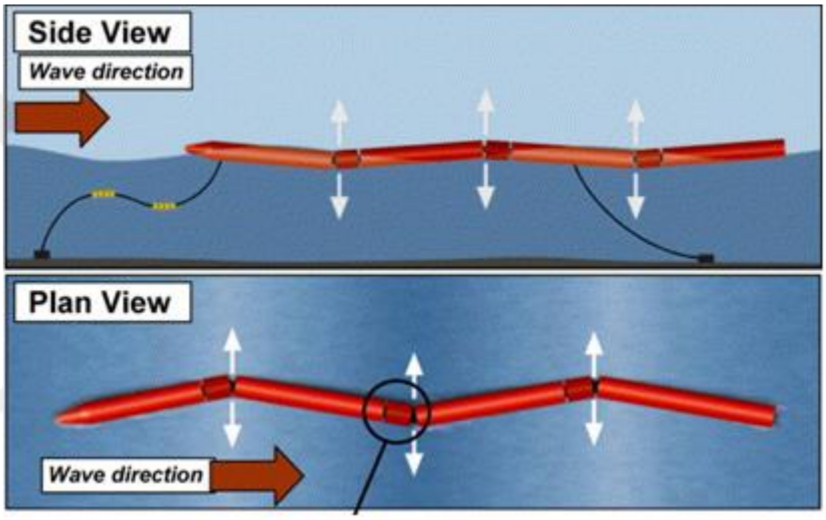


Figure 2.15. The Pelamis WEC

One of the most successive devices for off-shore region is the WEC named as Pelamis. In the simplest terms, Pelamis is a system consisting of long rod bodies connected to each other by rotating joints and pistons placed on these connection points (Figure 2.15). Due to this structure, Pelamis makes the same kind of undulation motion on sea waves in harmony with the wave motion. This ripple motion is basically a bending motion that occurs at these points through the joints at the connection points of the rod bodies. During this bending movement, the opening and closing of the pistons between the rod bodies is ensured. As a result, we initially capture the irregular, uncontrolled force carried by the sea wave and turn it into a regular mechanical movement. After this point has been reached, since it catches a regular mechanical movement, the mechanical energy of this movement can now be converted into electrical energy. In accordance with the structure of the system, this happens sometimes by pumping oil and sometimes by directly producing electrical energy with pistons that undertake the task of generating electricity and basically contain elements such as stator.

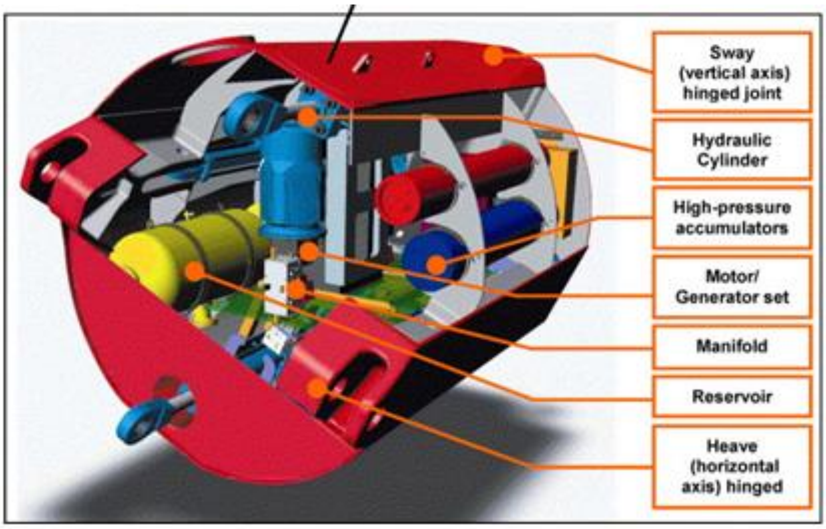


Figure 2.16. The schematic representation of the PTO of Pelamis

The intermediate modules of the Pelamis WEC also work as the power of the system. In Figure 2.16, one of the Pelamis intermediate modules is shown together with the PTO elements on the module. The PTO of the Pelamis WEC consists of hydraulic circuit, hydraulic cylinder, accumulator, control manifold, engine and generator elements. Due to the bidirectional operation of the pistons in the circuit, there is a bidirectional pressurized fluid entry into the system. The bidirectional flow, not suitable for starting the engine, is then converted to unidirectional flow in the control manifold, and then sent to the engine-generator assembly. The Pelamis system, which resembles a large snake on the ocean, is connected to the sea floor with a chain and weight mechanism. This chain mechanism used allows Pelamis to maintain its position, while reducing the movement flexibility of the model. In this way, the baiboi movement of the system can be prevented and the efficiency can be increased. With the help of its unique design, Thorpe 1999 reported that the Pelamis WEC system is one of the most efficient WEC system. The body, which is forced to bend at the joints by the rotational effect of the wave on the body, can respond to different axial bending forces due to its special hinged design.

The WaveStar WEC system is designed for nearshore locations. As wind turbines became attractive and the efficiency of hybrid system operations began to be understood, research began on how WaveStar WEC systems could work more efficiently with wind. The 60-float WaveStar configuration has an estimated rated impact of 18 MW and provides the ability to add a 9 MW wind turbine (Figure 2.17). WaveStar has formed an industrial consortium to produce the first full-scale 1 MW WaveStar WEC to be tested commercially. The concept of this integrated system is given in Figure 2.17 (Ghafari et al, 2021). While the wind power industry is mature, it is only suitable for certain locations and is limited to a relatively shallow depth range. Additionally, offshore wind turbines are becoming more attractive than onshore wind turbines because wind direction and speed are more consistent in deep water open areas than in land areas. In the future, combining WEC systems and a floating wind turbine could result in higher energy recovery and lower costs, making offshore energy cost competitive. (Ghafari et al, 2021)

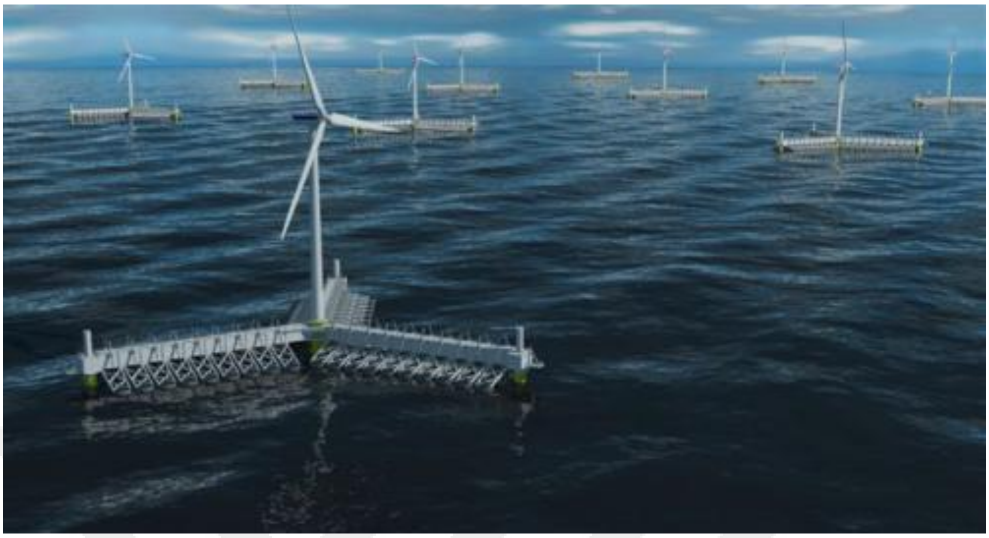


Figure 2.17. Artist impression of the farm of the WaveStar WEC with wind turbine

The basic idea of the Wave Dragon wave energy converter is the use on an offshore floating platform, which has well-known and well-developed principles of power projects derived from water using conventional methods. A ramp mechanism is placed in front of this system. It must be located above sea level in order to generate energy, which will allow overtopping wave movement (Vining, 2005). When the wave comes over the ramp, the water level rises above the body (Overtopping) through the inclined structure of the hull. The water rising above the ramp is transferred to a reservoir and from there it is passed through a turbine. Thus, energy production is provided. A prototype identified as The Wave Dragon (Figure 2.18) at Nissum Bredning was tested in Denmark for a period of 20 months from May 2003 to January 2005 for a power generation of 20 kW at a scale of 1:4.5. A picture of the system taken during trials is shown in Figure 2.18 (Thorp, 1999).

Figure 2.18. The Wave Dragon WEC prototype

The Wave Dragon provides electricity generation in three stages. It lifts the ocean waves above the reservoir and allows them to be stored there. The stored water is then passed through the turbines and the circular motion (rotation) of the turbines is converted into electrical energy by the power draw unit. The working principle of the Wave Dragon WEC can be seen at Figure 2.19 (Parmeggiani et al 2013).

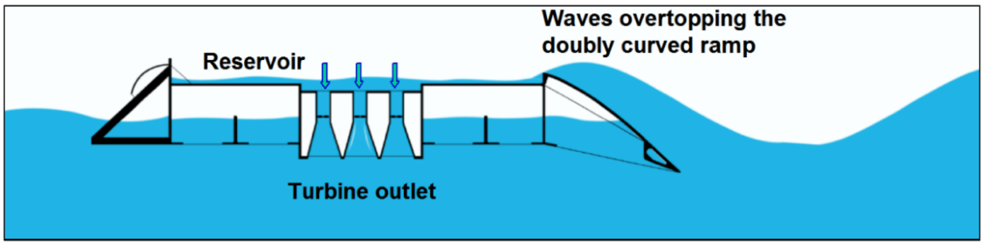


Figure 2.19. The working principle of Wave Dragon WEC

Wave Dragon is a DEK system anchored by tie rods and can be stand-alone or parked where water depth is greater than 20 meters with adequate wave climate.

It can be observed that power generation values increase with the increase in wave climate values. When the wave climate value doubles, the power value reaches a value close to three times. Following the positive results of prototype sea trials, Wave Dragon is currently being scaled up to commercial size. The structural design of a 1.5 MW pre-commercial demonstrator unit is to be deployed at the DanWEC test site in Hanstholm, Northern Denmark. The characteristics of the demonstrator are summarized in Table 2.1 (Parmeggiani et al, 2013).

Table 2.1. Features of Wave Dragon demonstrator

Property	Value
Weight	6500 t
Platform dimensions	76 m × 50 m
Reflector length	84 m
Wingspan of reflectors	170 m
Height	12 m
Max crest level above MWL	approx. 3 m
Reservoir volume approx.	1400 m3
Average wave power resource	6 kW/m
Water depth	30 m
Rated power	1.5 MW
Average Yearly Power Production	2 GWh

The system also includes a pneumatic mechanism to adjust the sinking amount of the floating system, a magnet fixed to the turbine to regulate the generator's speed, and an inventor assembly (Vining, 2005). As in other offshore applications, transmission cables are required to transfer the energy produced in Wave Dragon.

The Carnegie Wave Energy (CWE) is developing the CETO technology to harness wave energy into electricity generation and producing fresh water. The current and fifth generation of the technology, CETO 5, consists of a submerged buoy, known as the Buoyant Actuator (BA), driving a hydraulic cylinder which pressurises the working fluid in a pipeline back to shore. The pressurised fluid then drives a hydro-electric system, thereby producing power for the electricity network (Rafiee and Fievez, 2015). The schematic presentation and the working is shown in Figure 2.20.

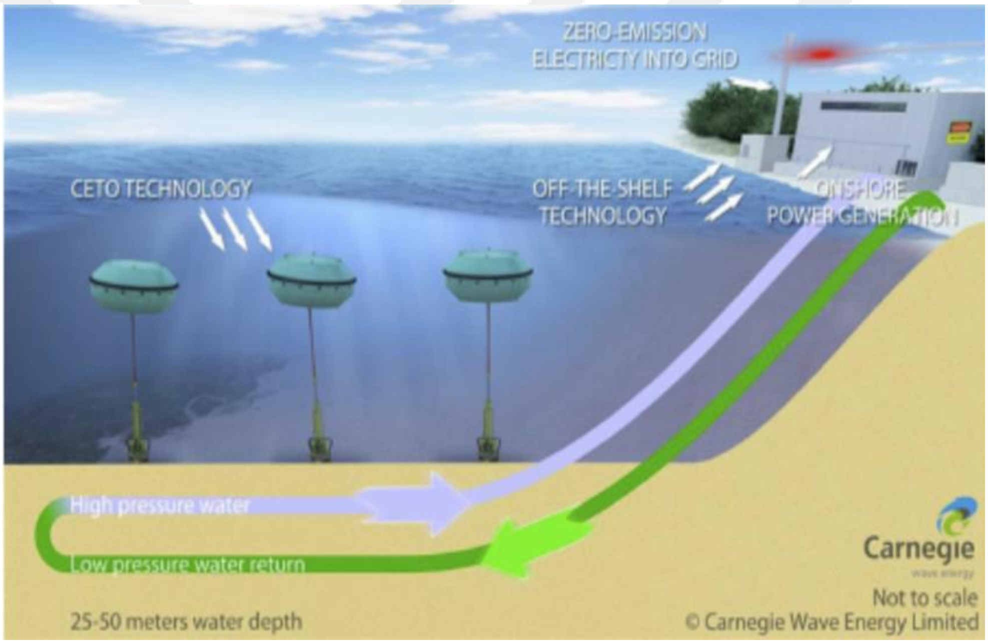


Figure 2.20. The CETO WEC System

The CETO WEC has some unique advantageous. It is fully submerged so it can protect itself from the chaotic sea states rather than the floating WEC devices on the sea level. The 6th generation CETO is developed well. It proves itself over 10 years with onshore, wave tank and tens of thousands of hours of in-ocean testing. Also, the modular array design makes the CETO a scalable device. The 6th generation of CETO can cooperate with a desalination system. The CETO is an underwater buoyant float that attached via a flexible mooring line to a simple pump which is fixed on the sea bed via a gravity anchor or steel pile. The movement of float wrt the pump is used to pressurize seawater and the output from an array of these devices is collected for onward transmission to the shore where it drives a Pelton turbine to produce electricity.

OPT's PowerBuoy extracts energy from ocean waves and is already patented where it is defined as a system with foundations such as hydrodynamics, electronics, energy conversion and computer systems. The PowerBuoy is a system that can be described as “intelligent” that can respond appropriately to different waveforms. The result is a pioneering, patented, ocean-tested system that reliably generates electricity in a clean and environmentally beneficial way. The OPT WEC device is presented in Figure 2.21.

The rising and falling of the waves cause the buoy to move up and down freely. The resulting mechanical stroke is transferred to an electric generator by means of a sophisticated power extraction unit. The power produced here is transferred to the shore via underwater cables.

Figure 2.21. The OPT WEC (Neill and Hashemi, 2018)

The sensors on the PowerBuoy continuously communicate the state of the ocean environment and the performance of various ancillary systems to the shore. The obtained data is transmitted to the shore in real time. In the event of a very large oncoming wave, the system is automatically locked and power generation is stopped. When the wavelengths return to normal, the system unlocks and its operation returns to its previous state.

The Archimedes Wave Swing, shown in Figure 2.22(AWS Ocean, 2021), design consists of a solid chamber seated on the seafloor and a cylinder assembly with an open top closed by a floating cylinder. The air trapped in the watertight compartment between the two cylinders is kept. With the effect of the incoming wave, the pressure increase or pressure decrease occurs on the floating body. As a result of this effect, the floating cylinder moves up or down, causing the air between the two cylinders to be compressed or causing a vacuum effect in the intermediate chamber. As the sea wave energy levels vary, the pressure on the system changes. The system is mainly suitable for deployment in water depths in excess of 25 m and can be configured for ratings between 25kW and 250kW by selecting the appropriate scale (AWS Ocean, 2021).

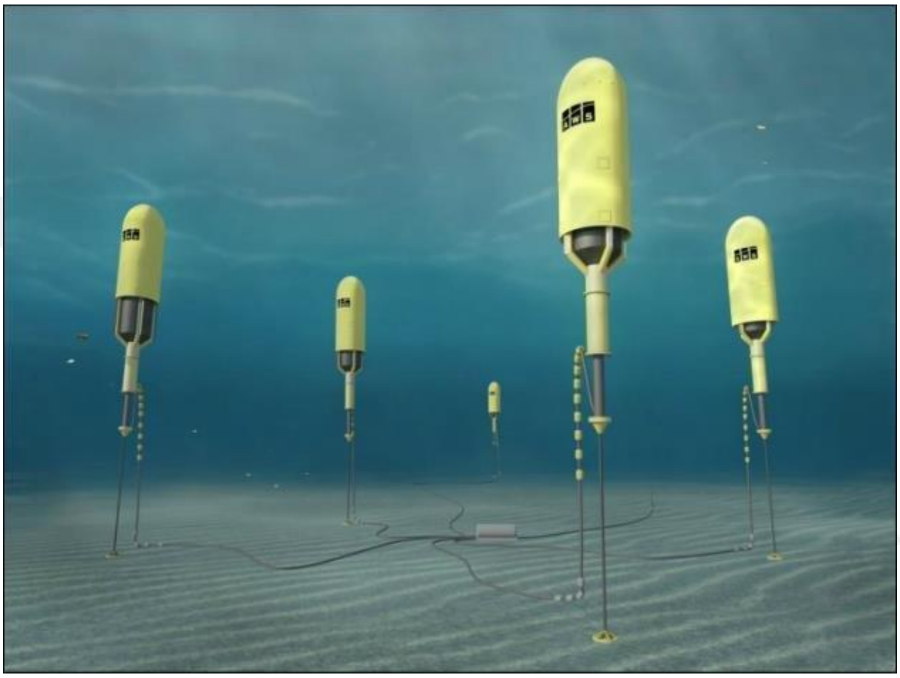


Figure 2.22. The Archiemedes Wave Swing WEC system

Therefore, it works by moving the piston up and down. In the system, a stopping point is designed to prevent the piston moving in the middle of the stator from rising further after a certain point. This is because the cause is too high, which requires the piston to stop after a certain point. It concerns both the sparsity of the waves and the design of the shape of the system. There is also a spring system connected to this system. By using this spring, some of the energy of the wave, which has more energy than needed to pull the piston up, is stored in the spring. In other words, after a certain point, some of the energy that the piston cannot store due to its capacity is stored together with the spring. In addition, the energy is stored in the spring. The piston that goes up is brought back to its original position, allowing the system to work in both directions (Leijon et al.,2006.).

The oscillation movement created by the roller assembly with the effect of the wave is converted into electricity with the help of a power drawing unit included in the system. A permanent magnet linear generator is used for the electrical conversion process in the AWS design. By matching the frequency of the system to the frequency of the wave, the total stroke length made by the system can be greater than the wave height. The weight of the floating part alone is 400 tons. With 5000 tons of water taken into the pontoons and balance tanks, the mass of the system reaches approximately 7000 tons. Most of the weight is in the balance tanks used to submerge or float the system. The air volume required for the system to stay at a medium level is around 3000 m3. This value can be changed by pumping the water in or out (Cruz, 2008)

The AquaBuOY unit is a point absorber developed by Finavera Renewable Energy (Astariz and Iglesias 2015). In Figure 2.23, the schematic representation of the Aquabouy is shown. The AquaBuoy wave energy converter is a system that converts ocean wave energy into electrical energy and uses a low-cost and innovative component (part) known as the Hose-Pump. The Hose-Pump is a thin, hollow, elastic cylinder that can work in harmony with the pumping of the fluid. When the Hose-Pump is attached to a float, periodic extensions (extensions) occur under the pressure of the fluid produced and forced by the wave action. The solution to the conversion of wave energy to electrical energy is to complete the conversion via two multi-device types, consisting of a standard hydro-power turbine and a generator.

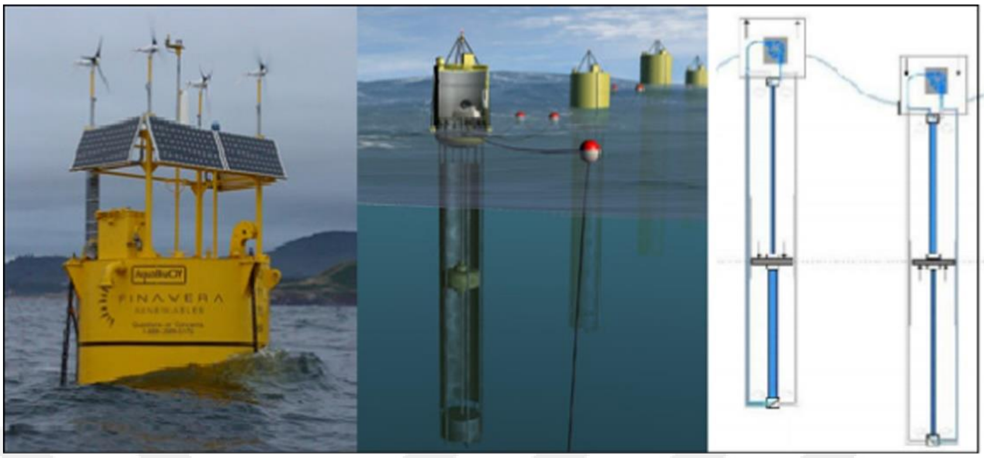


Figure 2.23. The AquaBuOY WEC

The potential and kinetic energy approaching the shore is converted into another and more regular movement by the mechanical elements of the WEC. This movement is usually a piston motion, the air flow advancing in a certain channel, or sometimes a spring movement that relaxes and stretches. At this stage, whole potential or kinetic energy of the wave extracted is transformed into mechanical energy. Afterwards, it is converted the mechanical energy into electrical energy. By converting this energy into electrical energy, the main goal is achieved and electrical energy is obtained from wave energy. For direct use, it needs to be converted AC electrical energy and to be delivered to the plants and the devices that require electrical energy (Weinstein et al, 2004).

The AquaBuOY is synchronized with the grid by using a variable speed AC-DC-AC converter and the voltage is increased with a step-up transformer. Flexible riser cables connect the devices to a junction box on the ocean floor. This aspect is standard and does not raise any significant concerns.

2.1.2. Classification of WEC Systems by PTO Type

The power generation process in WEC systems is an important issue in itself. Intermediate systems used in converting the wave energy that the system draws from the environment into electrical energy are called power extraction units (or Power Take-Off units, PTOs). When the developed WEC systems are examined, it is seen that the power draw method used varies for different types of WECs.

Although the selected methods differ from each other, the basic working logic of the power draw unit has not changed much. The PTO units basically consist of three main parts. The first part includes the wave interacting part, the second part includes the carrier part and the third part includes the generator assembly. The first part is the part that interacts with the wave force and converts it to mechanical energy. Basically, the second part, which provides the energy transfer between the first part and the third part, undertakes tasks such as rectifying the energy it receives during this transfer process and rearranging it so that it can be transferred to the generator.

The high efficiency of the WEC system is directly related to the PTO. For this reason, it is very important to use the most accurate PTO design for a WEC system to be operated at high efficiency.

There are three main methods used in the design of the PTO for WEC systems. The method used in the system also determines the type of PTO. The Power Take-Off unit types can be classified under some main topics. The main types are Pneumatic, hydraulic and the linear generator.

2.1.2.1. Pneumatic Systems

In this type of electrical conversion, the concept of turbine type transmission is used to mean that a turbine directly connected to the generator is driven by the effect of flow. The turbine type PTO applications in DEK systems are mostly oscillating water column and overtopping type of WEC systems. The most important advantage of turbine type applications is that the system does not pose a problem for the environment as there is no risk of leakage. On the other hand, the disadvantage of these turbines is that problems are encountered at the design stage where suitable for sea water is an issue to ve solved. An example of a pneumatic PTO is given in Figure 2.24 (Falcao, 2010).

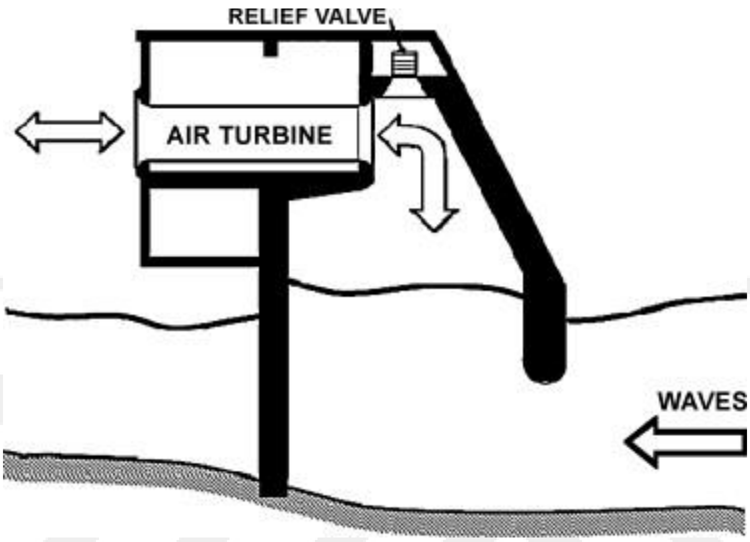


Figure 2.24. The schematic demonstration of Pneumatic system in OWC

The main reason for this is that sea water is a complex fluid, since it contains various components, whose characteristics cannot be determined. In addition, in near shore applications, abrasive particles can cause damage to valves and seals.

2.1.2.2. Hydraulic Systems

They are typically used in devices where the energy conversion system is based on exploiting the linear motion produced by the interaction of the body with energetic waves. Therefore, a suitable conversion interface is required between the linear energy capture and the electric generator. This system should be able to operate with high forces at low frequencies. Essentially, hydraulic systems can operate in reverse to their conventional counterparts. The movement of the body feeds the energy of the hydraulic motor, which in turn feeds an electric generator. (Maria-Arenas et al, 2019).

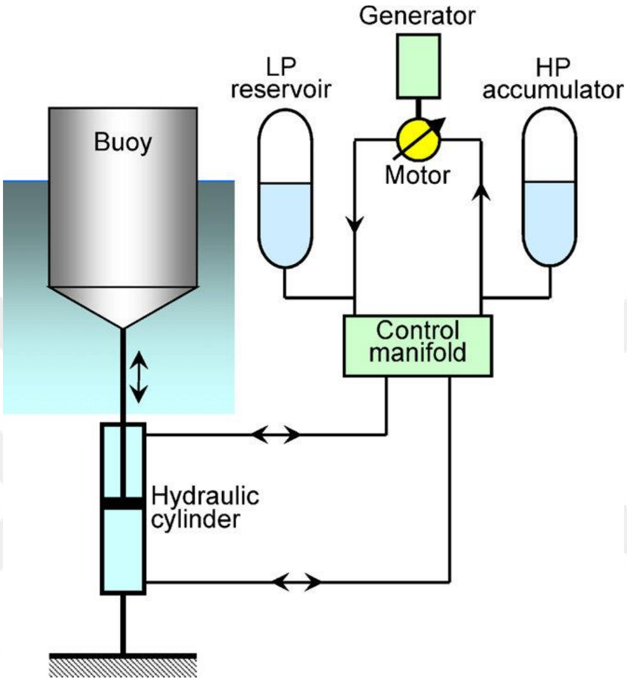


Figure 2.25. The hydraulic PTO circuit for WEC system.

In hydraulic PTO systems, as shown in Figure 2.25 (Falcao, 2010), the generator generally used in the application can be operated at fixed speed. On the other hand, the hydraulic motor must have variable capacity in order to drive the generator at close speeds. In controlling and calculating the capacity of the hydraulic motor to be used in the circuit, it should be decided according to the wave climate in which the system operates. In addition, the addition of a safety valve to the system increases the safety of the system. Adding an accumulator to the system is a very common method in the development of hydraulic type power take-offs to increase the flow quality of the fluid. With the inclusion of accumulators in the system, the excess energy accumulated in the system can be stored, and in the opposite case, such as a decrease in the circuit pressure, the circuit pressure can be balanced by the pressure relief of the accumulator to the system. In this way, the risk of cavitation caused by irregular flow rate is reduced.

In hydraulic PTO applications, the wave coming into the system is generally in an irregular form. In cases where this form is irregular, the fluid in the ports of the hydraulic cylinder must be rectified by passing through the check valves. If an accumulator is used in the system, the fluctuating fluid flow seen in the diagram can be regulated, and the rotational torque required for the generator can be obtained by transferring this fluid to a variable capacity hydraulic motor.

2.1.2.3. Direct Drive Systems

The linear generators, as shown in Figure 2.26 (Farrok et al, 2018), are similar to conventional generators that convert mechanical rotational energy into electrical energy. However, in such applications, instead of the rotor element, an element usually defined as a translator is used. The movement of the translator element is up and down, unlike the rotational movement of conventional generator rotors. The advantage of linear generators is that they convert the wave motion directly into electrical energy without the need for hydraulic systems or gearboxes (Lejerskog, 2016). Having fewer moving parts causes the system to work more efficiently than hydraulic systems. Another advantage of using a linear generator in PTO is that with this method, the system can be lighter and the cost can be reduced to lower levels.

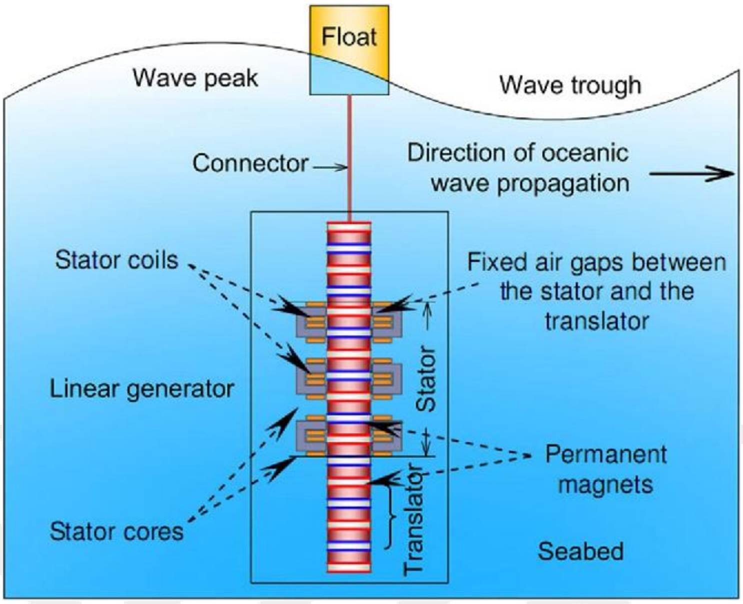


Figure 2.26. Existing linear generator for WEC systems

The disadvantage of linear generators is that the linear generator used must be specially designed. In this method, as in hydraulic systems, system elements cannot be taken from the shelf and used directly. For this reason, the linear generator idea is quite expensive. Another important disadvantage of these systems is that the linear generator is directly faced with this serious wave force in case of any huge wave, since the generator directly interacts with the wave. In many applications, this problem has been tried to be solved by adding an additional braking or locking system to the system.

2.2. Control Approaches for WEC Systems

The main task of the control system of the wave energy converter is to ensure the continuity of energy production by keeping the converter in continuous oscillation. The continuous oscillation of the system also means that the system remains constantly in resonance. In order for a system to remain in resonance, the natural frequency of the converter and the frequency of the force on the geometric surface of the wave must be equal or almost equal to each other. The closer these two values are to each other, the better the performance gets. Active control of the PTO is equivalent to the control of the response of a WEC. An appropriate and well-designed PTO control not only improves the power output of a WEC, but also impacts the WEC's survivability under severe conditions and the life span of the mechanical hardware.

In general, the natural frequency of the system is one of the important design parameters that should be considered in the developed mechanical systems. So much so that the studies on the natural frequency of the system in the standard design process are based on the difference between the natural frequency value of the system and the frequency value of the environment in which the system will operate. Thus, the system can be protected from resonance effects and the operating life of the system can be increased. In WEC systems, on the other hand, studies on the natural frequency of the system are the opposite of general engineering practices. In WEC systems, it is essential that the system remains in resonance with the wave effect. The primary task of the control system in WEC systems is to analyse the wave conditions of the converter and to find the frequency of the force of the wave on the main body. In other words, it is to adjust the parameters that it will control under certain conditions (Nunes et al., 2011). After determining these parameters, it is to adjust the frequency of the converter according to the values obtained. It is widely accepted that wave energy conversion systems must remain in resonance in order to continuously produce energy.

Considering the working principles of PAWEC type WEC systems, it is seen that these systems should be in a state of continuous oscillation. The energy conversion system can produce electrical energy by absorbing energy from this continuous oscillation of the WEC system. Therefore, it is necessary for the converter to oscillate continuously. In this respect, the wave situation in the environment where the WEC system is located should be constantly examined. In addition, it should be ensured that the WEC is kept in resonance by adjusting the spring effect and/or damping effect from the mass of the system or the energy conversion system parameters.

In order to keep the WEC system to remain in resonance, the state of the waves and the system should be examined by the control system, adjustments should be made according to the data obtained, and it should be ensured that the natural frequency of the converter is equal to or almost equal to the frequency of the wave force. Since these adjustments require changing the natural frequency of the system, the adjustments can be made on the following three main features of the system.

1. By changing the mass, which is one of the physical properties of the converter.
2. By adjusting the spring effect created by the energy conversion system.
3. By changing the damping parameter of the energy conversion system.

2.2.1. Phase Control

In phase control, the main objective is to provide resonance conditions by adjusting the WEC's frequency to the incoming wave frequency in order to maximize energy extraction (Falnes, 2002a). Mainly the resonance condition is provided by adjusting stiffness of PTO unit (k_{pto}) (Korde et al, 2016) and/or added mass of the overall system (Burgaç and Yavuz, 2019). The PTO parameters must be tuned to the right values at calculated times. This is the key point of a successful implementation of the control application. The PTO parameters must be tuned to the right values at calculated times. This is the key point of a successful implementation of the control application. In the studies on the control of WEC systems, the process of adjusting the natural frequency by changing the mass of the system is called slow tuning. As the name suggests, the adjustment process with this method takes a lot of time. In this adjustment method, which is relatively simple compared to other methods, the mass of the WEC body is increased by taking the required amount of water to adjust the system to the desired natural frequency, or the mass of the water in the body is reduced by evacuating as much as necessary. In the control applications made with this method, the WEC system can adjust the natural frequency of the system according to a wave situation that will be encountered for large regime changes in the environment.

2.2.2. Latching Control

One of the control methods that can be used in regular wave studies is the latching control type. Studies in this type of control are based on PTO harmonics and the regular wave ratios. The locking control method defined with certain hydrodynamic ratios was used by Budal and Falnes (Budal and Falnes, 1980) in a PAWEC type system. In the study, a single-degree-of-freedom float type WEC moving up and down was used. The latching control method principle is based on temporarily locking the motion of the WEC at specific positions. This type of operation leads to intermittent motion. (Babarit et al, 2010). The latching control can only be applicable if the natural frequency of WEC is greater than the wave excitation frequency (Budal and Falnes, 1980).

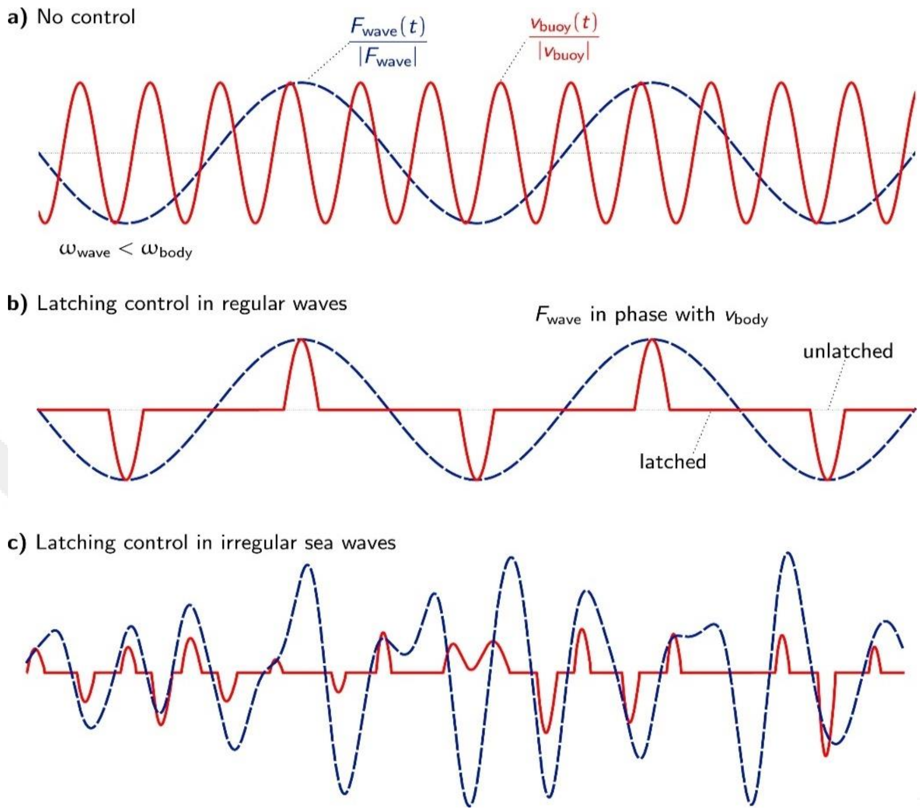


Figure 2.27. a) Typical velocity for heaving buoy with a natural frequency higher than the frequency of excitation force. b) Latching control to tune the phases of the heaving velocity and the excitation force. c) Latching control for a system subject to irregular sea waves

For a typical big offshore WEC systems, generally the natural frequency of oscillation substantially exceeds the range of frequencies of the ocean waves (Figure 2.27.a, Henriques et al, 2016). To overcome this problem, Budal and Falnes proposed latching control for oscillating buoys. Latching control for a oscillating buoy WEC in heave consists of stopping the device during appropriated time intervals in such a manner that the oscillating velocity is in phase with the excitation force (Figure 2.27.b). At irregular sea waves, the optimal or sub-optimal control strategies require the prediction of the excitation force acting on the WEC to compute in real-time the release and stop instants (Figure 2.27.c) (Henriques et al, 2016).

3. MATERIAL AND METHOD

3.1. The physical System

In this section, the properties of the WEC such as the structural features, modelling and control problem definition for the single degree of freedom systems are generally determined and discussed. The studies presented aims at solving the control problem, developing the control system models and providing a solution of the control problem. Then, the control system models are developed. The simulations of the control system include modelling and pre-processing for simulation stages, including the WEC model. In the simulation examinations, the performance of the system is examined for different sea states and the performance of the control system is determined.

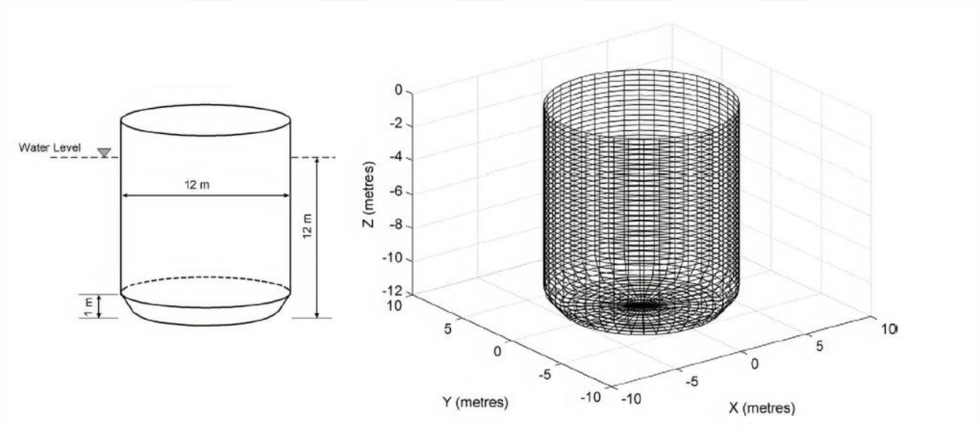


Figure 3.1. Geometric presentation of WEC

The Figure 3.1 shows the fragmented state with the panel method based on hydrodynamic modelling (Yavuz et al, 2006). In modelling, especially the symmetry of the system with respect to the x, y and z axes facilitates the analysis, as well as provides convenience in the application of the system. These conveniences make the calculations that need to be made especially according to the wave direction unnecessary. In other words, the symmetrical feature of the structure allows it to operate independently of the direction of the wave.

Table 3.1. Physical properties of modelled heaving WEC

Definition		Value
ρ	Density [tonne/m3]	1
m_{dry}	dry mass [tonne]	1369
D_{wec} h_{wec}	Diameter [m] Height [m]	12 12
m	total mass [tonne]	m_{dry} + a
k_{net}	Stiffness [kN/m]	1134
b_{net}	damping coefficient [kNs/m]	b_{inf}+KR(s)
k_{pto}	PTO stiffness [kN/m]	k_{pto}= f(w)
b_{pto}	PTO damping [kNs/m]	b_{pto}= b_{rad}(ω)

The physical properties of the wave energy converter are given in Table 3.1 (Yavuz et al, 2006). In addition to the dimensions of the shape of the system, the physical properties based on the modelling are also given. The dry mass of the wave energy converter represents the basic construction mass. The added mass is the additional fluid mass determined by hydrodynamic analysis. The total mass is obtained by adding the fluid mass value to dry mass.

3.2. Mathematical Model of the WEC System

Mathematical models of a floating body are often expressed in the frequency domain. However, these models are only valid when the input excitation signal is a regular wave. The motion of the free surface in real or realistic circumstances rarely reaches the steady state conditions, so it should be presented in time-domain (McCabe et al. 2005).

In this section, a time-domain model developed by McCabe et al (2005) is presented. The model uses transfer functions directly driven from frequency dependant hydrodynamic data as a solution to the problem of convolution integrals and related transformations. This approach requires the time-scaling of the input, and so it is necessary to pre-process the entire input signal before the evaluation of the output (Yavuz et al 2006).

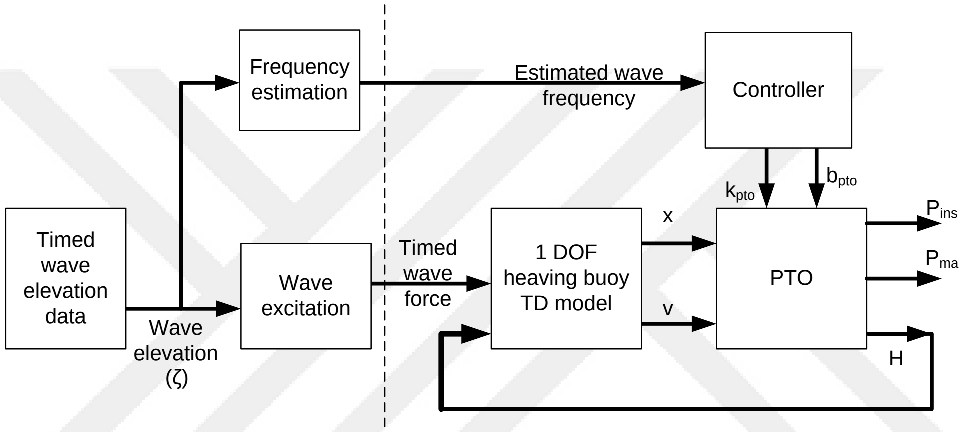


Figure 3.2. Structure of the simulation model of point-absorber WEC system

Due to the above-described process, as illustrated in Figure 3.2 (Yavuz et al, 2006), the adopted time-domain model of point-absorber WEC system consists of two parts that run in consecutive steps. In Part 1, the timed wave elevation data is processed to yield the timed wave force signal and the timed wave frequency signal is estimated. In Part 2, on the other hand, Simulink model is presented where the wave force is used to excite the WEC model and the displacement (x) and velocity (v) signals are calculated.

The equation of motion in the time domain for a single translational mode, or degree of freedom, subject to wave effects can be expressed in the form (Yavuz et al, 2006).

$$m_{dry}\ddot{x}(t) = F(t) \tag{3.1}$$

in which $x(t)$ is the position of the body at time t, m_{dry} represents the inertial mass of the body, and $F(t)$ is the total force on the body.

The total force, in the simplest case, consists of three components, radiation force, $F_R(t)$, Power Take-Off (PTO) force $H(t)$ and wave excitation force, $F_E(t)$, Thus

$$F(t) = F_E(t) - F_R(t) - H(t) \tag{3.2}$$

The wave excitation force, $F_E(t)$, is defined as

$$F_E(t) = \int_{-\infty}^{+\infty} K_E(t-\tau)\zeta(\tau)d\tau \tag{3.3}$$

in which the $\zeta(t)$ is the wave elevation at time t. The wave excitation impulse response function IRF $K_E(t)$, defines the component of the response when the wave elevation at the origin of the coordinate system is a unit impulse function (Korsmeyer et al 1999).

The radiation force, FR(t), is given by (McCabe et al 2005)

$$F_R(t) = a\ddot{x}(t) + b\dot{x}(t) + cx(t) + \int_{-\infty}^{t} K_R(t-\tau)\dot{x}(t)d\tau \tag{3.4}$$

where a, b, c and $K_R(t)$ are the frequency-independent added mass, radiation velocity damping, hydrostatic restoring stiffness coefficients and radiation (IRF), respectively.

Equation (1) can, therefore, be expressed as

$$(m_{dry} + a)\ddot{x}(t) + b\dot{x}(t) + cx(t) + \int_{-\infty}^{t} K_R + (t-\tau)\dot{x}(\tau)d\tau =$$
$$\int_{-\infty}^{+\infty} K_E(t-\tau)\zeta(\tau)d\tau - H(t) \quad (3.5)$$

The radiation IRF, $K_R(t)$, defines the component of the response when the motion of the body, in otherwise undisturbed water, is a unit impulse.

It can be shown (Kristiansen and Egeland, 2003) that $K_R(t)$ is related to the frequency-dependent added mass coefficient, $a(\omega)$, and radiation velocity damping coefficient, $b(\omega)$ by the unilateral Fourier transform

$$\int_{0}^{+\infty} K_R(t)e^{-iwt}dt = [b(\omega) - b] + i\omega[a(\omega) - a] \quad (3.6)$$

For a real system of finite energy, the magnitude of the Fourier transform tends to zero as the frequency tends towards infinity, which implies that

$$a = a(\infty) \text{and } b = b(\infty) \quad (3.7)$$

The frequency independent added mass and radiation velocity damping coefficients are the values to which the respective frequency-dependent hydrodynamic parameters are asymptotic as the frequency is increased to infinity. The infinite-frequency added-mass parameter, $a(\infty)$, is usually non-zero. If the body is not in motion through the fluid, $b(\omega) \to 0$ as $\omega \to \infty$. It has been shown (Lee and Newman, 2005) that the wave excitation force IRF, $K_E(t)$, is related to the frequency-dependent wave excitation coefficient by the bilateral Fourier transform

$$\int_{-\infty}^{+\infty} K_E(t)e^{-i\omega t}dt = F(\omega) \quad (3.8)$$

in which F(ω) is the complex excitation force or moment amplitude produced by an incident wave of 1 metre amplitude and ω radians per second frequency.

If $A_R(s)$, $B_R(s)$, $A_E(s)$ and $B_E(s)$ are polynomials in the complex Laplace variable $s = \sigma + i\omega$ and the Laplace transforms of the IRFs, $K_R(t)$ and $K_E(t)$, can be expressed as ratios of these polynomials thus

$$K_R(s) = \frac{B_R(s)}{A_R(s)} \tag{3.9}$$

and

$$K_E(s) = \frac{B_E(s)}{A_E(s)} \tag{3.10}$$

then, with initial rest conditions, the Laplace transform of equation (5) is

$$[(m_{dry} + a)s^2 + bs + c]X(s) + \frac{B_R(s)}{A_R(s)} sX(s) = \frac{B_E(s)}{A_E(s)} Z(s) - H(s). \tag{3.11}$$

where $X(s)$, $Z(s)$ and $H(s)$ are the Laplace transforms of $x(t)$, $\zeta(t)$ and $H(t)$ respectively. The Fourier transforms of the IRFs will also be polynomial ratios, with the same coefficients as (9) and (10), but in terms of the imaginary part of the Laplace variable, $i\omega$, so it follows from equations (6) and (9) that

$$Re\left[\frac{B_R(i\omega)}{A_R(i\omega)}\right] = [b(\omega) - b(\infty)] = b(\omega) \tag{3.12}$$

and

$$Im\left[\frac{B_R(i\omega)}{A_R(i\omega)}\right] = \omega[a(\omega) - \omega(\infty)] \tag{3.13}$$

From equations (8) and (10)

$$Re\left[\frac{B_E(i\omega)}{A_E(i\omega)}\right] = Re[\,F(\omega)] \tag{3.14}$$

$$Im\left[\frac{B_E(i\omega)}{A_E(i\omega)}\right] = Im[\,F(v)] \tag{3.15}$$

Hence, the coefficients of the Laplace transfer functions (9) and (10) can be related directly to the frequency dependent added mass, radiation damping and excitation force data.

The wave excitation IRF, K (t) E, is non-causal (Falnes, 2002b), so the associated transfer function (10) will be unstable. Therefore, it is impractical to use the transfer function in this form. Instead, the transfer function is first expressed as the sum of stable and unstable parts (denoted by the superscripts “stab” and “unst” respectively)

$$\frac{B_E(s)}{A_E(s)} = \frac{B_E^{stab}(s)}{A_E^{stab}(s)} + \frac{B_E^{unst}(s)}{A_E^{unst}(s)} \tag{3.16}$$

The wave excitation force is then calculated as the sum of two component forces, as a result of the decomposition of the transfer function in (16).

$$F_E(t) = F_E^{stab}(t) + F_E^{unst}(t) \tag{3.17}$$

The first force component is evaluated in a straightforward manner, its Laplace transform being

$$F_E^{stab}(s) = \frac{B_E^{stab}(s)}{A_E^{stab}(s)} Z(s) \tag{3.18}$$

whereas, a similar transfer function product for the second component

$$F_E^{unst}(s) = \frac{B_E^{unst}(s)}{A_E^{unst}(s)} Z(s) \tag{3.19}$$

is impractical due to the instability of the transfer function. However, if time scaling (Spiegel, 1965) is applied to the force component $F_E^{unst}(t)$, with a scaling factor of –1, equation (19) becomes

$$-F_E^{unst}(-s) = \frac{B_E^{unst}(-s)}{A_E^{unst}(-s)} [-Z(-s)] \tag{3.20}$$

Scaling time by –1 is the same as reversing its direction through this part of the system, thereby changing the causality, and hence stability characteristics, of this part of the process. Both the input and output sequences may be subjected to the same arbitrary time-shift, ΔT, to give

$$[-F_E^{unst}(-s)]e^{s\Delta T} = \frac{B_E^{unst}(-s)}{A_E^{unst}(-s)} [-Z(-s)]e^{s\Delta T} \tag{3.21}$$

If the original wave elevation sequence, $\zeta(t)$, is then defined on the interval $[t_s \; t_f]$, so that

$$\zeta(t) = [\zeta(t_s), \dots, \zeta(t_f)] \tag{3.22}$$

then, denoting a time-scaled and shifted sequence by the superscript TS,

$$\zeta^{TS}(t) = [\zeta(t_s), \dots, \zeta(t_f)] \tag{3.23}$$

which, if$\Delta T = t_s + t_f$, has the Laplace transform

$$\zeta^{TS}(t) = [-Z(-s)]e^{s\Delta T} \tag{3.24}$$

which is the input sequence to (21). Likewise, the output sequence from (21) is also the Laplace transform of a time-scaled and shifted sequence

$$F_E^{unst,TS}(s) = [-F_E^{unst}(-s)]e^{s\Delta T} \tag{3.25}$$

so that

$$F_E^{unst,TS}(s) = [F_E^{unst}(t_f), \dots, F_E^{unst}(t_s)] \tag{3.26}$$

from which the required component force sequence is given by

$$F_E^{unst}(s) = [F_E^{unst,TS}(t_f), \dots, F_E^{unst,TS}(t_s)] \tag{3.27}$$

The need for time scaling means that, in a simulation of the model, the wave force, F (t) E must be evaluated separately from the rest of the model. Since computation of the convolution integral in equation (3) requires knowledge of the entire wave elevation history, due to the limits of integration, the wave force cannot be calculated simultaneously with the radiation force. Discretized versions of (3) and other approximations reduce the infinite limits to some finite time span, but still require some amount of temporal dislocation between the wave excitation and radiation calculations (Yavuz et al 2006).

3.3. MATLAB Model of the WEC System

The mathematical model of the WEC presented in this report shows similarities to the previously reported frequency domain models (McCabe et al, 2004), (Yavuz et al, 2006). The presented study adopts the approach reported by (Yavuz et al, 2005; Yavuz et al, 2006). where the blocks with frequency dependent parameters, a(ω), b(ω) and c(ω), are replaced with the frequency independent parameters, a, b and c, respectively.

In addition, as shown in Figure 3.2, the input to the system is a wave force computed using the transfer function K (s) (described in Section 2) as suggested by (Yavuz et al, 2005; McCabe et al, 2005) In Figure 3, the time domain model specific blocks are highlighted in yellow. The K (s) R transfer function, in parallel with the damping coefficient of the WEC model, contributes for the frequency dependent changes for the overall frequency dependency effect. The overall mass (m) of the is time-constant and the defined as the aggregate of the dry (inertial) mass (m_{dry}) and the frequency-independent added mass (a)

$$m = m_{dry} + a \tag{3.28}$$

The damping coefficient (b or b_{inf}) of the WEC system is constant, and using the K (s) $_R$ transfer function, the net damping coefficient (b_{net}) of the WEC model is then

$$b_{\text{net}}(s) = bR_{inf} \tag{3.29}$$

The net stiffness (k_{net}) of the WEC model is also constant, it is independent of the wave frequency, and given by

$$k_{net} = c \tag{3.30}$$

then the Equation (11) could be rewritten in the form;

$$ms^2X(s) + b_{\text{net}}sX(s) + k_{\text{net}}X(s) = \frac{B_E(s)}{A_E(s)}Z(s) - H(s) \tag{3.31}$$

Thus, the simulation of the time-domain WEC is achieved in two stages. As mentioned earlier, in the first stage of the simulation, the wave elevation data is used in calculation of the timed wave force $F_E(t)$ and also in estimation of the wave frequency. The time series wave force $F_E(t)$ is itself determined in two steps, owing to non-causality and resultant instability of the process (Yavuz et al, 2007).

The adaptive controller used in tuning the system is based on the dominant wave frequency. It uses this information for determination of the tuning parameters in order to keep the WEC in resonance. Therefore, the second set of calculations for the simulations is an estimation of the dominant wave frequency in the wave elevation data. For this purpose, the discrete Fourier transform (DFT) is used in estimating the dominant frequency as a time series as suggested by Yavuz et al. (Yavuz et al, 2007).

In the second stage of the simulation, the computed wave force and other necessary parameters are stored in the workspace, before subsequently being utilised to drive the SIMULINK™ model of the WEC.

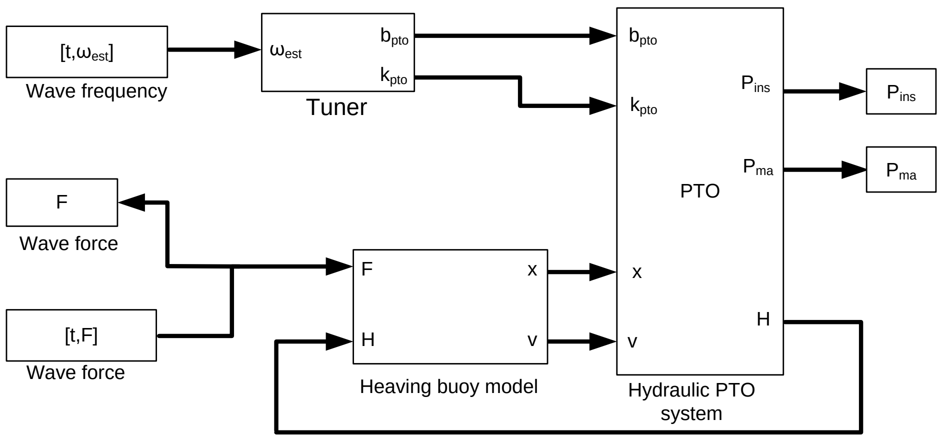


Figure 3.3. SIMULINK™ model of the point absorber WEC system

As illustrated in Figure 3.3, the SIMULINK™ Model includes a time-domain model of a 1– degree-of-freedom WEC block, a power take-off block and a tuner block. In the following description, the SIMULINK™ model variables are given in brackets. The inputs to the model are time series for the wave force F(F)and the associated frequency of the wave elevation ω_{est} (omega_info). The outputs are the time series for power take-off force, H (H), the heave displacement, x (x), the heave velocity, v (v), the instantaneous power, P_{ins} (P_{ins}), and a moving average power, P_{ma} (P_{ma}) (Yavuz et al, 2007).

The input to the tuner block is an estimate of the sea wave frequency ω_{est} (omega_info)., so that the optimum power take-off parameters k_{pto} (kpto) and b_{pto} (bpto) can be calculated using the equations (Yavuz et al, 2006; Yavuz et al, 2007):

$$k_{pto} = m\omega_{est}^2 - k_{net} \tag{3.32}$$

and

$$b_{pto} = b\omega_{est}^3 \tag{3.33}$$

where the coefficient b (b) is given by

$$b = \frac{b_{rad\_nom}}{\omega_{nom}^3} \tag{3.34}$$

and where $b_{rad_nom}$is the radiation damping coefficient at the nominal wave frequency as suggested by (Yavuz et al, 2006; Yavuz et al, 2007)

$$b_{pto} = \frac{b_{rad\_nom}}{\omega_{nom}^3}\omega_{est}^3 \tag{3.35}$$

It is clear that if the estimated wave frequency is close to the nominal frequency, then, it can be assumed that $\omega_{est} = \omega_{nom}$and hence b_{pto}will simply be equal to b_{rad} (assuming also that$b_{loss} = 0$) (Yavuz et al 2006). Therefore, equation 33 can be rewritten as follows,

$$b_{pto} = (b_{rad\_nom} + b_{loss}) \tag{3.36a}$$

Alternatively, if $b_{loss} \neq 0$then,

$$b_{pto} = b_{rad\_nom} \tag{3.36b}$$

The inputs to the PTO block are the heave displacement, x (x), and heave velocity, v (v), fed back from the 1-degree-of-freedom WEC block, and the power take-off stiffness, k_{pto} (kpto), and damping coefficient, b_{pto} (bpto), from the PTO tuner block. The outputs are the PTO force, H (H), the instantaneous power, P_{ins} (Pins), and a second-order moving-average power, P_{ma} (Pma).

The PTO force, or control force, is defined as

$$H = k_{pto}x + b_{pto}v \tag{3.37}$$

and the instantaneous power converted is defined as

$$P_{ins} = b_{pto}v^2 \tag{3.38}$$

A moving average value of the PTO power is also computed in the “moving average power blocks”. The moving average (P_{ma}) is defined as follows,

$$P_{ma} = \frac{1}{\int_{t_n}^{t_m} dt}\left(\int_{t_n}^{t_m} P_{ins}(t)dt\right) = \frac{1}{T_d}\int_{t_n}^{t_m} P_{ins}(t)dt \tag{3.39}$$

where $P_{ins}(t)$ and $T_d = t_m - t_n$, are the instantaneous power at time $t$and the moving average window length, where the latter is defined as the difference between the window start time (t_n) and end time (t_m). This function averages the input signal ($P_{ins}(t)$) over a time period T_d (typically 20 seconds) and yields a fast-acting smooth estimate of the moving-average mean power as suggested by (Yavuz et al, 2006; Yavuz et al, 2007).

Another parameter computed for analysis is the nominal power, which is computed for each time data sampling point, i.e.

$$P_{nominal}(t_n) = \frac{1}{t_n}\int_0^{t_n} P_{inst}(t)dt \tag{3.40}$$

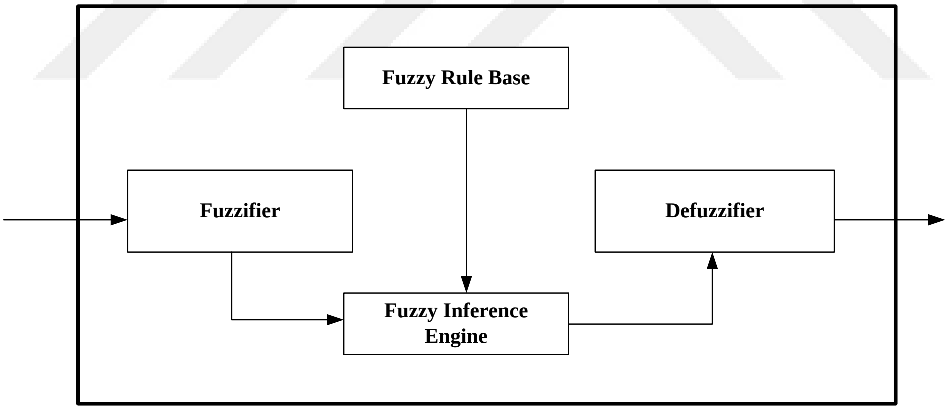
where $P_{ins}(t)$ and t_n are the instantaneous power and the time for which average power capture is calculated, respectively. Therefore, the average power $P_{nominal}(t)$ parameter indicates the average captured power at time *t*, as suggested by (Yavuz et al, 2006; Yavuz et al, 2007)

3.4. Fuzzy Logic based Control Applications

The term “Fuzzy Logic” was first introduced in 1965 by Lotfi Zadeh (Zadeh, 1965). FL controllers have been used to handle complex systems where system parameters have an inherit uncertainty. As Lotfi Zadeh, considered to be the father of FL, once remarked (Fuzzy Logic, 2021): "In almost every case you can build the same product without FL, but fuzzy is faster and cheaper."

Fuzzy logic is considered as a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. From human skills and reasoning it is possible to implement an inference system, through a set of *if-then* rules and membership functions (Guillaume, 2001). Fuzzy logic is a convenient way to map an input space to an output space. Mapping input to output is the starting point for everything. A basic Fuzzy Logic system configuration is shown in Figure 3.4. Fuzzy inference process comprises of five parts:

- Fuzzification of the input variables (Fuzzifier)
- Application of the fuzzy operator (AND or OR) in the antecedent(?)
- Implication from the antecedent to the consequent
- Aggregation of the consequents across the rules
- Defuzzification



.Figure 3.4 The basic configuration of Fuzzy Logic System

As it mentioned earlier, in irregular sea states, the optimum operation of the WEC cannot be achieved ideally at optimal condition. However, operating conditions of the system can be shifted towards near the optimal condition. Combining FL algorithm to the current controller would provide flexibility and robustness to the control structure assuming the FL algorithm is properly set. Hence, it is very much important to understand the underlying mechanism of the system and all its sub-systems before writing the FL controller code.

The FL control has been introduced to energy systems research for energy in many topics such as system management (Olatomiwa et al., 2016), industrial applications (van der Wal, 1995), solar systems (Bouchafaa et al, 2011), wind systems (Dambrosio, 2017) and so on. These studies mainly serve the purpose of optimizing the system operation. A comprehensive review study (Suganthi et al, 2015) on use of artificial intelligence (AI) in renewable energy systems shows us the use of AI in wave energy conversion is limited. As for the case of wave energy application of the FL control, it is necessary to analyse the wave energy system where system parameters contain high level of uncertainty. For such control applications, the control problem is a really complicated one mainly due to high level of uncertainty. This is where FL control systems become an important tool for the development of controllers for such complex systems. The main issue in the development of FL controller is to design the controller with the ability to handle the complexity of the system. The only way to achieve such ability is to define the FL rule base accordingly. In this study, the FL controller is used in adjustment of the additional mass for the water tank (m_{st}) of the WEC for slow tuning. In this approach, the m_{st} parameter is varied by using pumps to fill or discharge the water in the tank. This leads to variation of the m_{st} and provides a means to control the behaviour of the WEC system through variation of total mass of the system.

Determination of control parameters for WEC working in irregular wave conditions is a highly difficult issue due to the dynamic nature of all the system components including the sea conditions. As it can be shown in Figure 3.5, the information received from frequency estimation block is to be evaluated in membership functions by Fuzzy Logic controller. To combine the information sets received from these sources, a FL based decision-making mechanism is proposed. The decision-making uses a set of rules through which the input space is analyzed and fuzzified. Then, by using the FL control technique, the necessary PTO settings-based control commands are generated. The captured energy by PTO is then expected to be increased.

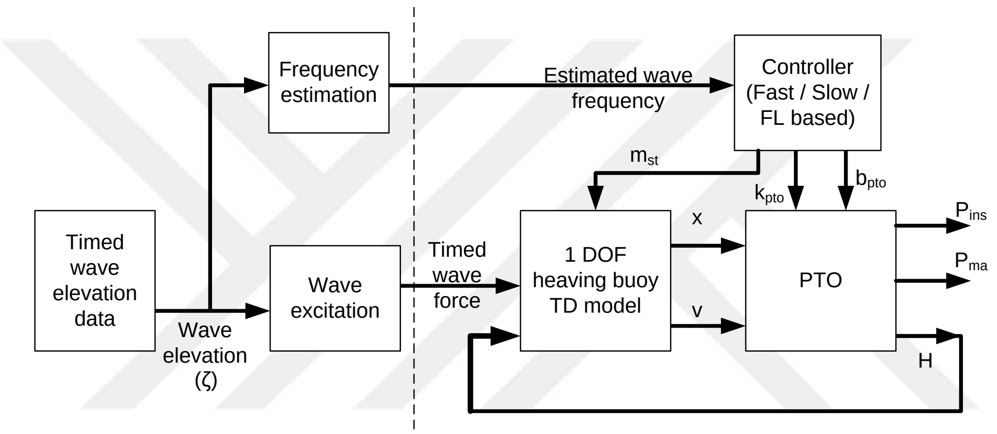


Figure 3.5. The structure of WEC model used in hybrid control algorithm

The Equation 28 represents the mass of the WEC system, which is phase controlled by fast tuning only. In this part of the study, the phase control is applied on a heaving WEC system in hybrid case (both fast and slow tuning applied.)

For this part the Equation 28 then becomes

$$m = m_{dry} + a + m_{tnk} + m_{st} \tag{3.41}$$

the overall mass of the system is varied with adjusted setting, m_{st}, provided from the controller. The fixed additional mass of the tank (m_{tnk}) is also added to the overall mass of the WEC.

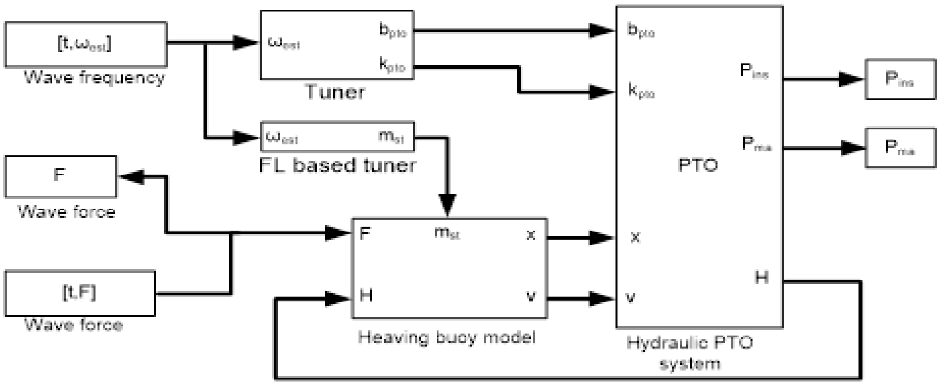


Figure 3.6. Simulink model of WEC system

As illustrated in Figure 3.6, the Simulink™ model includes a time-domain model of a one degree of freedom (DOF) WEC block, a PTO block, Tuner Block and FL based slow tuning block. In the following description the Simulink™ model variables are given in brackets. The stiffness of the system is used in quantized form. The k_{pto} settings are implemented in quantized form in a similar way reported by Mistikoglu and Yavuz (Mistikoglu and Yavuz, 2016). The schematic representation of this adjustment process is given in Figure 3.6. +

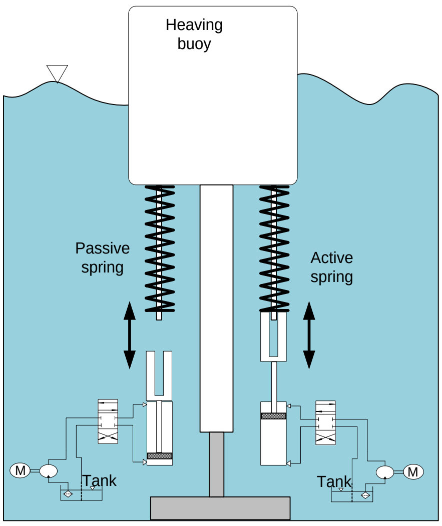


Figure 3.7. Schematic representation of quantization of PTO unit

The FL based slow tuner controls the mass of the system. For this purpose, the stiffness parameter has some limits and intervals. Eight couples of springs having the same specifications are used adjusts the stiffness interval, although the quantized stiffness systems trying to adjust the stiffness of the PTO system, mostly the system cannot match the exact system frequency. This leads to lack of matching the resonance condition causing the decrease in the power capture performance. In order to compensate for the mismatched frequency related power losses, the FL controller activates the pumps filling or discharging the water tank. The main operational principle of the system is presented in the Figure 3.8. The lack of quasi-resonance conditions is then provided with the help of the slow tuning adjustment. The m_{st} is used for slow tuning thereby improving the system's power capture performance.

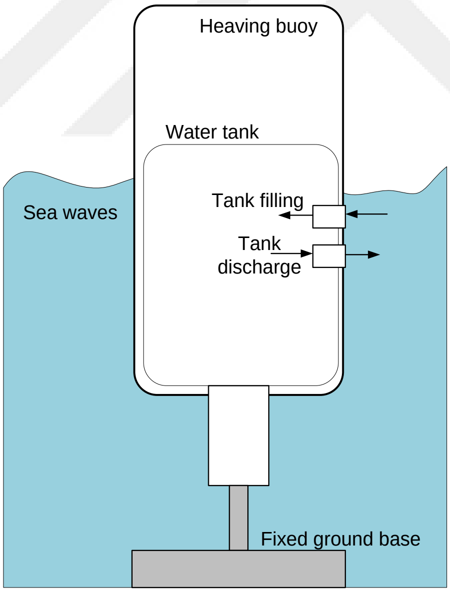


Figure 3.8. Tank filling and discharging representation of WEC

To provide the system with additional capability of compensation of quantization effect, FL based slow tuning is used to vary the total mass of the system. The technique is based on having a water tank on board with tank filling and discharging facility as shown Figure 3.7. In this case, FL based slow tuning technique is used in adjustment of m_{st} to meet the resonance condition. Four symmetric pumps are placed to pump water in to a tank to control mst of WEC to meet the resonance conditions. These pumps are driven by FL controller depending on the forecast-based incident wave frequencies and required m_{st} in the water tank.

3.5. Renewable Based Desalination Process Development as a WEC Application

The fresh water is a critical and vital resource that humanity needs as much as energy (Clemente et al, 2021). Energy and the fresh water are considered to be independent sources, but their interdependence is globally accepted for the human life cycle (Wakeel et al 2016). Integration of renewable energy systems with RO desalination systems is used for sustainable fresh water production (Ghenai and Bettayeb, 2021). The use of renewable energy does not reduce specific energy consumption but reduces the energy dependency on fossil fuel sources (Amy et al, 2017).

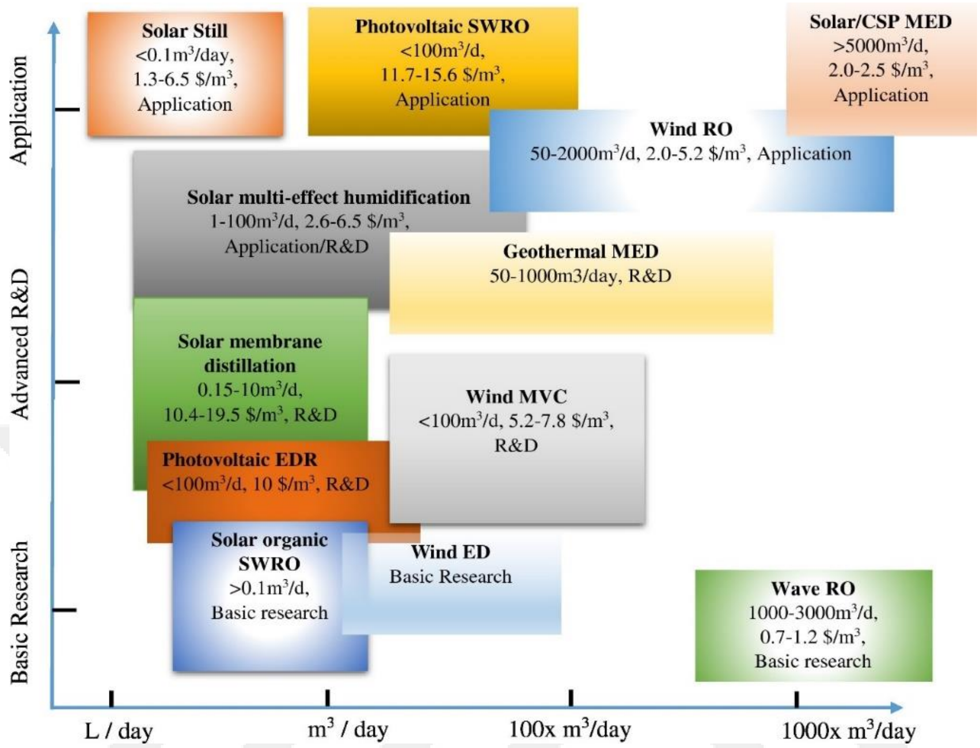


Figure 3.9. Status of the renewable energy-based desalination methods (Shahzad et al, 2017)

Figure 3.9 illustrates the classification of the renewable energy-based desalination methods by the stage of development, capacity and the cost. It can be clearly seen that the wave energy based Reverse osmosis desalination is a basic research level. Also, it is reported that using the WEC systems as integrated in desalination plant can be a good solution in terms of the reasonable and practical solution to generation, transport and consumption of WEC generated energy (Sadri and Rahmani, 2019).

In this part of the thesis, a wave energy based reverse osmosis desalination plant is modelled. This hybrid model provides a combined simulation model for the wave energy system and desalination plant for capturing and using of the energy captured from waves for use in the desalination process. Hence, the energy needed for the RO desalination system irregularly varying sea-wave based clean energy is been used Instead of sending it to the shoreline, if the electrical energy generated by WEC is used for desalination process, then a very long power cable is not needed to connect the wave energy system to the main grid. This advantage simply eliminates the need for the connection to main power grid. The weaknesses of both systems can be compensated so that the combined system model can work far more efficiently. By achieving a synergistic solution, the combined system can be a far more feasible solution especially for future applications. Also, the system can work with less carbon footprint and the high energy requirement for the hydraulic pressure subsystem can be supplied from the renewable energy source.

The overall system is modelled in such a way that the model input is the wave elevation data in meters while the output is the clean water flow rate (Burgaç and Yavuz, 2021). In this overall system, there are two main sub-systems. The overall system model layout is presented in Figure 3.10. It consists of the WEC and the RO desalination plant models. Both subsystems are modelled by using MATLAB/SIMULINK simulation software (Matlab, 2009).

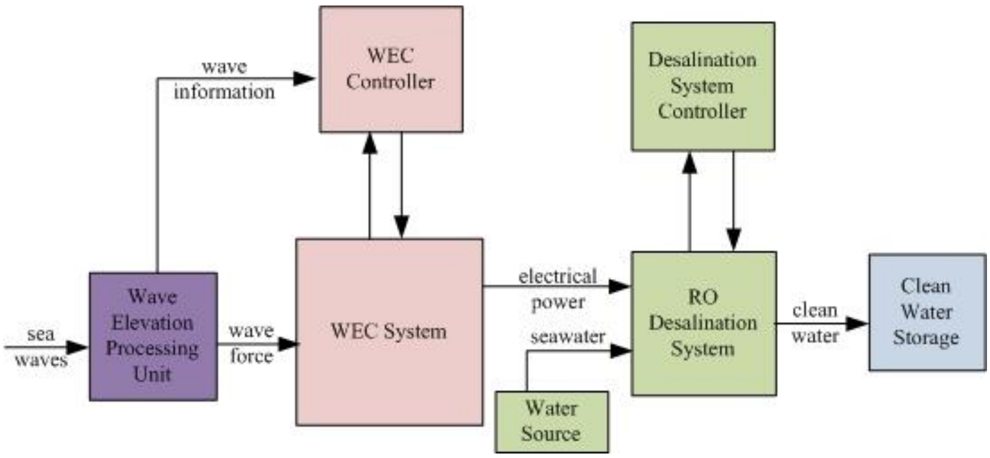


Figure 3.10. The overall WEC-RO hybrid system model

The modelled hybrid system mainly consists of 2 parts. In first part the WEC system generates mechanical energy from waves which runs the RO desalination part. The WEC model converts mechanical energy form of the wave energy into electrical energy. The electrical energy generated by WEC is then used in order to produce clean water by using the RO desalination model. The pre-processing of the feedwater before RO desalination process is a well-known issue. The WEC system model is previously well described in sections 3.1, 3.2 and 3.3. In the second part of the hybrid system model, the generated electrical energy both run the pumps to feed water to the system and operates the RO desalination system. The schematic representation is presented in Figure 3.11.

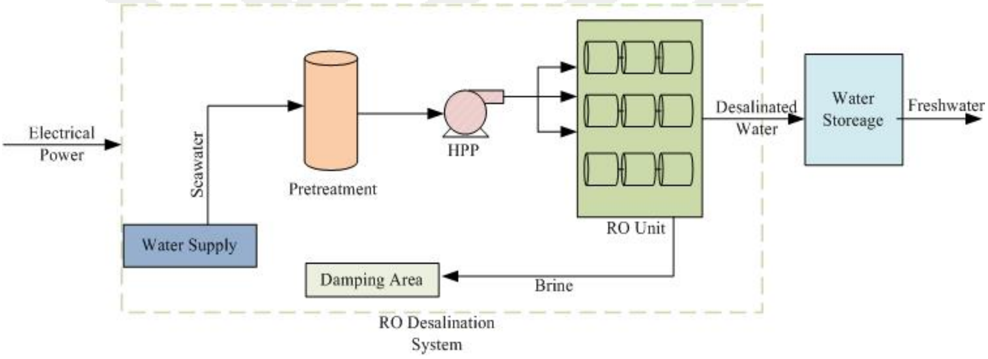


Figure 3.11. Simplified scheme of RO Desalination System

The RO process is used in wide range of applications such as water purification, food processing or production of drinkable water from salty water. The energy requirement for the RO desalination process is mainly caused from pressure requirement of pumps. Also, the salt concentration is directly related to the required power. In this model, the salinity of the seawater is taken as 1037 kg/m^3 including 37000 ppm of salt.

The basics of the mathematical model for the proposed RO desalination system are developed as presented below (Nafey and Sharaf, 2010). The permeate mass flow rate (M_f) based on recovery ratio (RR) and distillate mass flow rate (M_d) is:

$$M_f = M_d/RR \tag{3.42}$$

The distillate product salt concentration $X_{d:}$

$$X_d = X_f(1 - SR) \tag{3.43}$$

where X_f is the feed flow rate salt concentration, and SR is the salt rejection percentage and the rejected brine is found from:

$$M_b = M_f - M_d \tag{3.44}$$

the rejected salt concentration X_b (ppm) is estimated by:

$$X_b = \left((M_f X_f) - (M_d X_d)\right)/M_b \tag{3.45}$$

the average salt concentration X_{av} (ppm) is estimated as

$$X_{av} = \left((M_f X_f) + (M_b X_b)\right)/(M_f + M_b) \tag{3.46}$$

the temperature correction factor TCF is found by the relation below, where t_{sea} is the sea temperature

$$TCF = exp\ \ (2700((1/(273 + t_{sea})) - (1/298))) \tag{3.47}$$

the membrane water permeability k_w:

$$k_w = \frac{(6.84(10^{-8}))((18.6865-(0.177X_b))}{(t_{sea}+273))} \quad (3.48)$$

the salt permeability k_s is

$$k_s = (FF)(TCF)(4.72(10^{-7}))(0.06201-(5.31(10^{-5})(t_{sea}+273))) \quad (3.49)$$

where FF is membrane fouling factor. The required power (*HP*) for operation is:

$$HP = (1000M_f\Delta P)/(3600\rho_f\eta_p) \quad (3.50)$$

where ΔP is the net osmotic pressure across the membrane, ρ_f is the feed flow rate density and η_p is the driving pump efficiency. The specific power consumption (*SPC*) is calculated as

$$SPC = HP/M_d \quad (3.51)$$

The validation of the base desalination plant is indicated in the study by Sharaf (Nafey and Sharaf, 2010). In this part of the study, FTSW30HR-380 membrane element is used. The pump efficiency is 85%, the seawater temperature is 20^{o}C, and recovery ratio is 30%. While the regulated power capture rate increases with the high energy density waves, the desalination plant regulates its own operation based on the irregular power input from the WEC system. Hence, the main key input for the controller is the power capture rate of the WEC system.

The scalability is one of the main problems for the dynamically operating simulation models. In general, one of the most important conditions to be considered while designing the system is the scale at which the system is operated. According to the target application conditions, the system design is performed and the system parameters are adjusted as necessary. As the system scale changes, there are also changes in the power consumption, generation capacity and specific power consumption of the system. While designing the system, the RO desalination system adjusts itself depending on the power produced by the wave energy conversion system. The power produced in the WEC system basically varies depending on incident wave conditions, mainly the wave height and wave period. The wave height and wave period properties in a region where the wave energy conversion system operates are generally within a certain range. Although the power range that the system can produce changes instantaneously, its limits can be determined or predicted ahead. This information is also taken into consideration during the operation of the RO system. The RO system adjusts itself according to the estimated power range to be received from the WEC system. Also, the overall system works with different specific power consumption levels in different produced power instances.

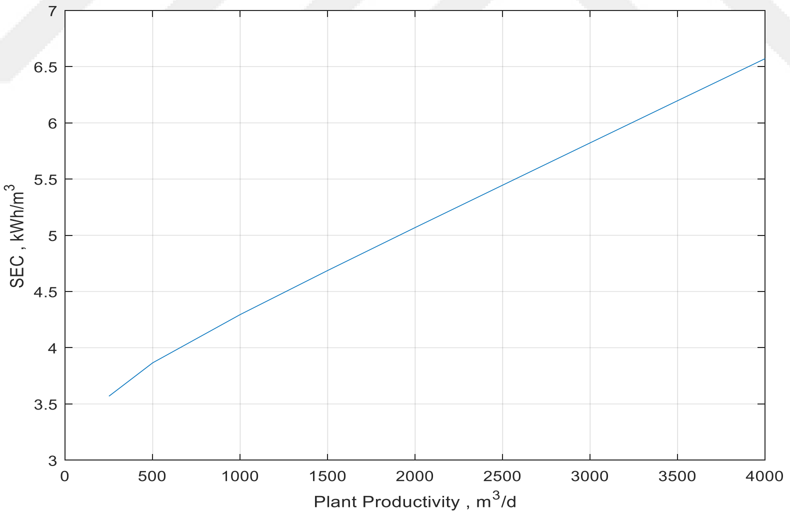


Figure 3.12. Specific energy consumption variation with productivity rate

In Figure 3.12, the specific energy consumption (SEC) variation to the plant productivity is presented for the proposed model. It is observed that the SEC increases while the production rate continues to increase. The main reason for the

SEC increase is the rise in feed pressure and feed mass flow rate of the water fed to the system in rising power generation. In the literature, it is reported that the SEC value varies in the range of 2-6.5 kWh/m^3 for different RO plants. These studies also cover the range of various RO plant sizes (Kim et al, 2019, Stillwell and Webber, 2016; Wang et al, 2021). The presented results from literature validate the achieved SEC range shown in Figure 3.11.

4. RESULTS AND DISCUSSIONS

This section presents the results and the related discussion for the heaving type WEC. The details presented in this section focus on the optimization of damping parameter of the PTO unit and the control application of the chosen heaving type one DOF WEC in order to increase the power capture performance. Also, the details for an integrated WEC and RO desalination system are provided.

In the first part of the study, the investigation results of the power capture performance variation within the variation of PTO damping over radiation damping. In literature, generally the PTO damping parameter is accepted as equal to the radiation damping. The radiation damping is a parameter changes with the estimated wave frequency as presented in the Equation 36b. In this part of the study, it is proposed that b_{pto} is defined as a function of hydrodynamic b_{rad} coefficient. Then, the Equation (36b) can be written as (Burgaç and Yavuz, 2020);

$$b_{pto} = \alpha b_{rad} \tag{4.1}$$

In our simulation studies, b_{pto} related calculations will use the definition given in Equation (36b) and Equation (52) to compare the performance difference. The main parameters used in the simulation study of the TD model are summarized in Table 4.1.

Table 4.1. Properties of WEC model

Parameters		Definition	Value
Inputs	ρ	density	1 [tonne/m3]
	dt	time step	0.2 [s]
	m_{dry}	dry mass	1369 [tonne]
	D_{wec}	diameter	12 [m]
	h_{wec}	height	12 [m]
Computed Parameters	m	total mass	1746 [tonne]
	k_{net}	stiffness	1134 [kN/m]
	b_{net}	damping coefficient	b_{inf}+KR(s) [kNs/m]
PTO Parameters	k_{pto}	PTO stiffness	k_{pto}= f(w) [kN/m]
	b_{pto}	PTO damping	b_{pto}= $b_{rad}(\omega)*\alpha$ [kNs/m]
	α	gain alpha	0.0…3.0

The simulations are performed by using the irregular wave elevation data obtained from the real sea state data (DS). Eight different wave elevation data sets derived from real states are used as the input wave elevation data for simulations.

The wave elevation data for each data set can be shown in Figure 4.1. The wave height increases with the increasing energy density of the waves. Each wave elevation dataset shown in Figure 4.1 is converted into wave force. The local dominant wave frequencies of each dataset are also estimated by processing the wave elevation data.

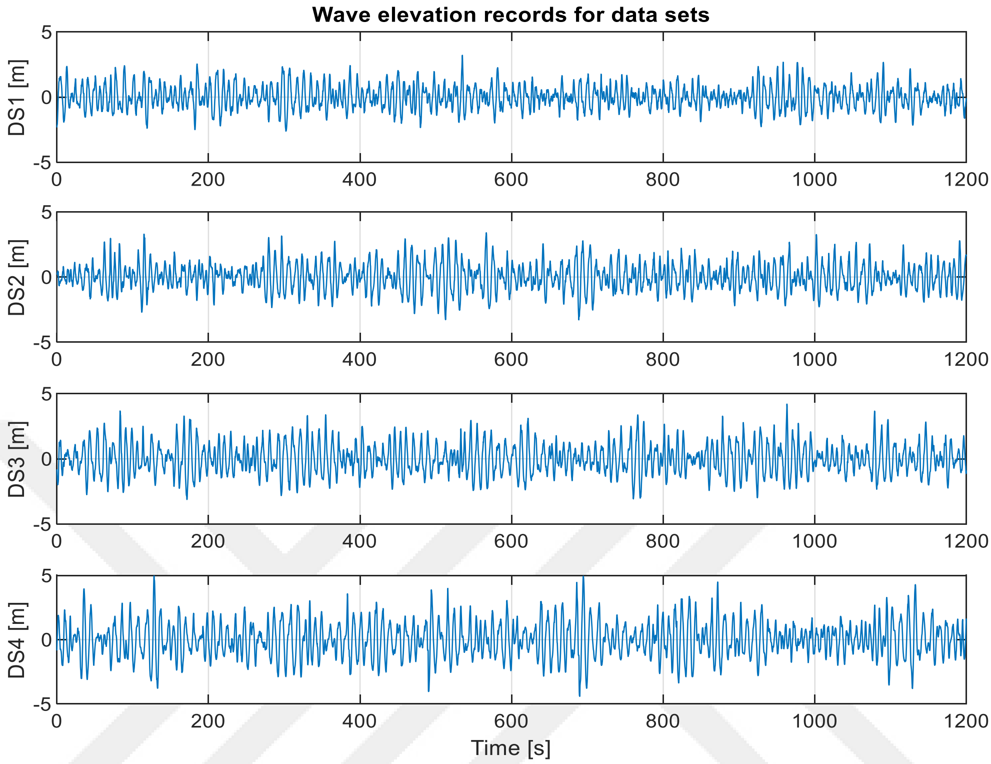


Figure 4.1. Wave elevation data of four different sea states

For wave frequency estimation, a Sliding DFT algorithm is used (Yavuz et al, 2007) The Sliding DFT algorithm is programmed to consider a chunk of data for analysis and it used to weigh coefficients that enabled dominancy of local data whereas reduced the effectiveness of the old data. In Table 4.2, the energy density information of each dataset along with some other sea state related properties are listed. In Table 2, 1-4 indices mean the wave heights are increasing from 1 to 4. The subscription of *a* and *b* corresponds to sea site measurements performed at two different locations at a reasonable distance. The measurements are taken at almost simultaneously at a nearby location.

Table 4.2. Results of TD model for irregular sea state dataset

			Datasets			
Parameters	Definition	Units	$DS1_{a,b}$	$DS2_{a,b}$	$DS3_{a,b}$	$DS4_{a,b}$
ω_p	peak frequency	rad/s	0.74	0.70	0.70	0.65
H_{mo}	significant wave height	m	3.55	4.13	4.65	5.53
$m_o=S(f)\Delta f$	zeroth order moment, energy	m^2s	0.79	1.06	1.35	1.91
T_e	energy period	sec	8.29	8.22	8.44	8.95
ω_e	energy frequency	rad/s	0.76	0.76	0.74	0.70

Typically, the b_{pto} value is predetermined and kept constant in passive control applications. However, in active control applications, b_{pto} parameter is defined as a function of b_{rad} parameter as given in Equation (3). In Fig. 4 variation of frequency dependent b_{rad} with respect to wave frequency is shown clearly. In this study, the b_{pto} parameter is set to be equal to b_{rad} parameter in the first case (Case1). As the second case (Case2), the b_{pto} parameter is varied with the gain α as a function of b_{rad} as defined by Equation (4).

The radiation damping parameter, presented in Figure 4.2, is determined by the estimated wave frequency (in the range of 0.0 to 1.8 rad/s). As illustrated in the figure, a small variation of wave frequency leads to large differences in b_{rad} values.

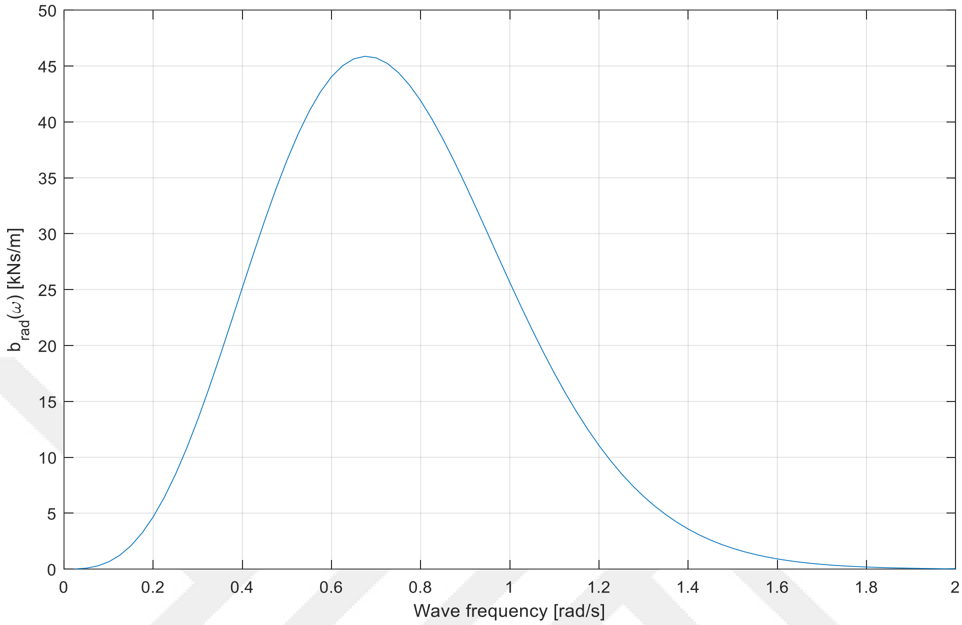


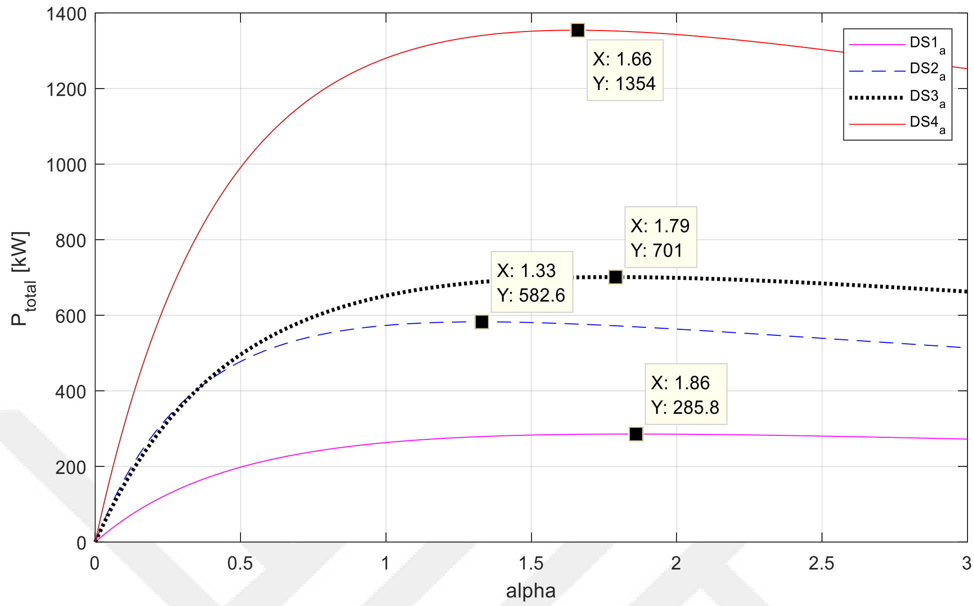
Figure 4.2. b_{rad} as a function of wave frequency

Hence, estimation of the wave frequency from the wave elevation data becomes very much critical. If the wave frequency estimation is made incorrectly, the system will not be able to select the appropriate b_{rad} and the power capture performance of the system may degrade. In the next part of the study, the results taken from the model is presented and discussed.

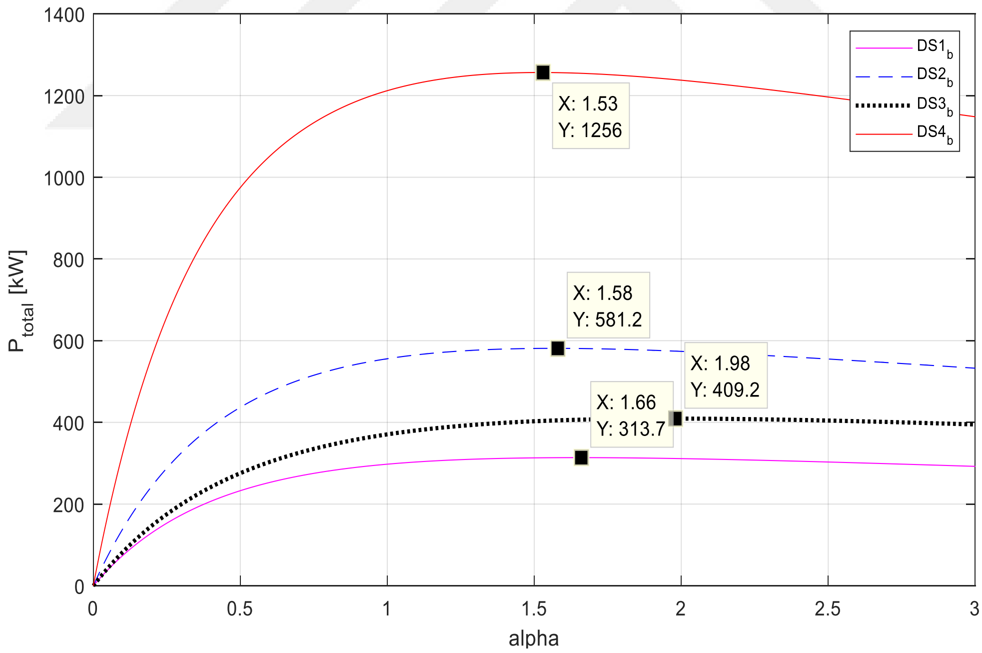
The investigation how the captured power changes with the variation of b_{pto} parameter of the system with the varying ratios of radiation damping is performed. In this part of the study, the results of the simulations are presented. The system is modelled and simulated in MATLAB/Simulink^{TM} software (Matlab, 2009). The wave frequency is estimated by using Sliding DFT technique. The results obtained from Sliding DFT method is used in order to determine both stiffness and frequency dependent radiation damping. In Case1, b_{pto} used to tune the WEC system is chosen being equal to the radiation damping parameter as shown in

Figure 4.2. In Case2, b_{pto} is calculated from Equation 52. Using the range for the gain alpha all b_{pto} values are pre-determined. These results are then used for evaluation of the simulation results thereby optimizing the system performance for eight different sea state datasets. In Figure 4.3.a and 4.3.b, the power capture performance results of the simulation study for different datasets with varying alpha values are presented. The variation of alpha and the captured power levels for different sea states are seen in the figure. It appears that $\alpha > 3$ does not seem to be providing any meaningful results.

In Figure 4.3.a, the power results for top four datasets are shown. The maximum captured powers at proper gain alpha values are also marked in the plot. It is seen that the best performing alpha gain for $DS1_a$, $DS2_a$, $DS3_a$ and $DS4_a$ are observed at 1.86, 1.33, 1.79 and 1.66, respectively.



(a)



(b)

Figure 4.3. Power outputs (P_{total}) for datasets with variation of α (a) For datasets [$D1_a$-$D4_a$] (b) For datasets [$D1_b$-$D4_b$]

In Figure 4.3.b, the power results for second four datasets are shown. The maximum captured powers at high performing alpha gain values are marked in the graph. It is seen that the best settings for $DS1_b$, $DS2_b$, $DS3_b$ and $DS4_b$ are gain alpha value of 1.66, 1.58, 1.98 and 1.53, respectively.

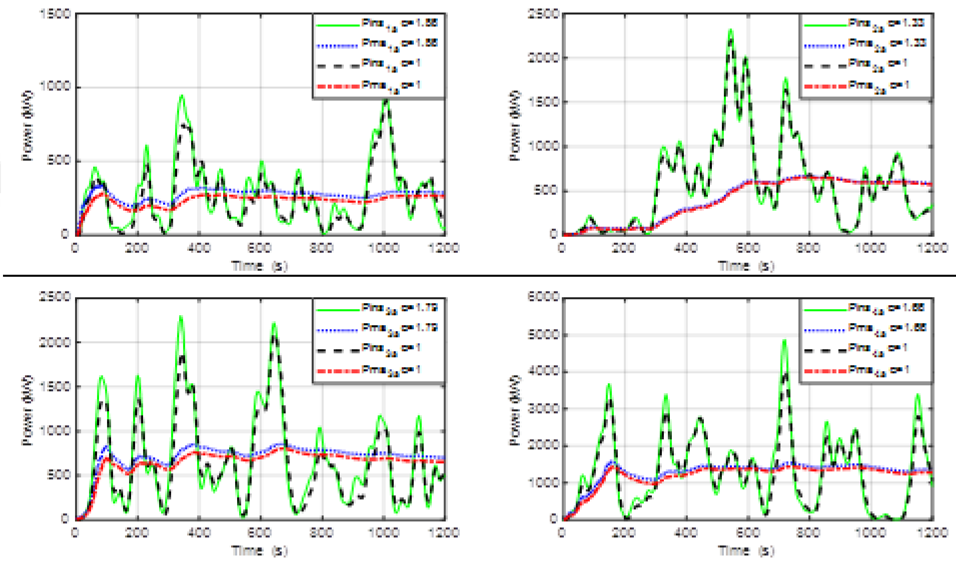


Figure 4.4. Instantaneous and moving average power results of $[DS1\text{-}4]_a$

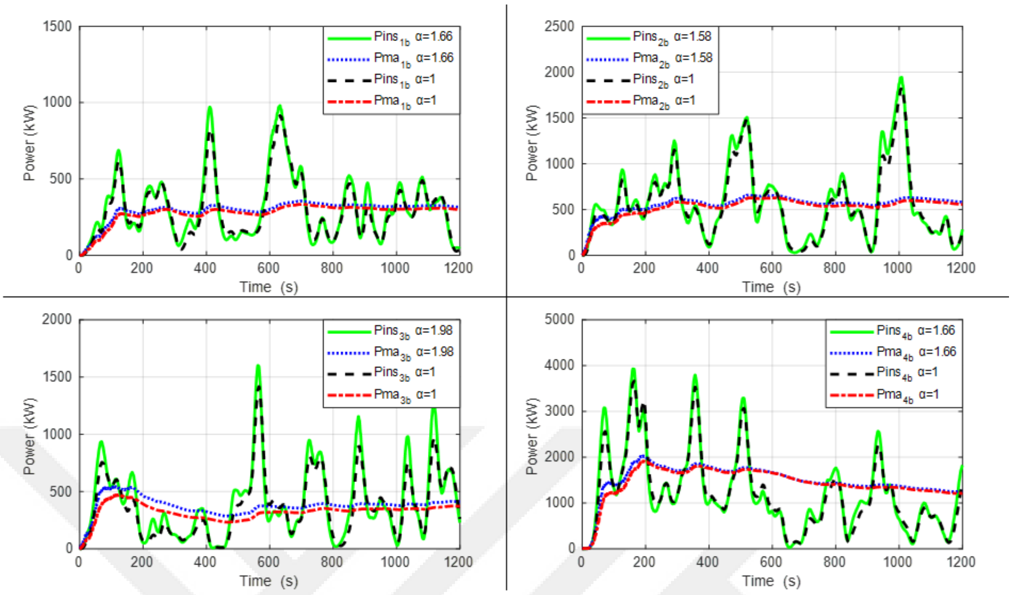


Figure 4.5. Instantaneous and moving average power results of $[DS1\text{-}4]_b$

The detailed instantaneous and moving average power results for all datasets in time scale are given in Figure 4.4. and 4.5. In both figures, all cases are shown for 1200 seconds time period. The α=1 terms show the results of first case of the study. The lines coloured as green and blue in the graphs are the power captured of the system where the power take off damping is adjusted as gain alpha times the radiation damping. This also means the system captures the maximum wave power.

Table 4.3. Total captured power results for variation of α for $DS1_{a,b}$-$DS4_{a,b}$.

#	Case1	Case2		
	P_{total} (kW)	P_{total}^{max} (kW)	α at P_{total}^{max}	% Power increase
$DS1_a$	263.2	285.8	1.86	8.58
$DS2_a$	573.2	582.6	1.33	1.64
$DS3_a$	651.9	701.0	1.79	7.53
$DS4_a$	1280.0	1354.0	1.66	5.78
$DS1_b$	297.7	313.7	1.66	5.37
$DS2_b$	555.8	582.2	1.58	4.74
$DS3_b$	370.7	409.2	1.98	10.38
$DS4_b$	1212.0	1256.0	1.53	3.63
		Average	1.67	5,95

The overall captured power results, covering all datasets, are also presented in Table 4.3. Table 4.3 provides overall averages of captured powers for all datasets for both cases along with rated power levels for each set. It is clearly seen that, as the result of the b_{pto} optimization, the captured power is clearly increased. The achieved performance increases in captured power results are observed between 1.64% and 10.38% while gain factor (α) takes the values between 1.33 and 1.98. The average of alpha value (1.67) and related power capture increase (5.95%) along with dataset specific power captures and alpha values are also provided in the table.

In the second part of this section, a slow tuning application which is based on adjusting the mass of the system while adjusting the stiffness is applied. The system controls not only the PTO parameters, but also controls the total mass of the system in hybrid form. In the study of Yavuz et al (Yavuz et al, 2006), the PTO parameters are adjusted instantaneously. The stiffness parameter is adjusted with the help of double acting hydraulic cylinder mechanism (Figure 4.6.). Later, Mistikoglu and Yavuz (Mistikoglu and Yavuz, 2016) showed that adjusting the stiffness of the PTO unit in quantized form will reduce the system load. The approach is based on adjusting the PTO stiffness quantized rather than instantaneously. However, the main problem with this approach was the mismatch resonance situation in these quantization intervals of the system. With this mismatch situation, the performance of the system and the captured power decrease. In order to fill this gap, it was necessary to eliminate this mismatch resonance condition. As a solution to the problem, the system mass is also adjusted with a hybrid control application. The system capture performance is improved and the resonance condition is achieved where the power capture performance is increased. The results of the evolution of this hybrid approach are given below.

This hybrid approach is evaluated in 3 cases. In the Case 1, all of the control parameters are varied instantly, in Case 2 the stiffness setting is used in quantized form. In Case 3, in addition to the settings for Case 2, m_{st} is used for slow tuning thereby improving the system's power capture performance. The main issue in Case 1 is that the energy requirement to achieve such instantaneous control settings is not only technically difficult but also very much costly. Therefore, in practice, the application of Case 1 may not be feasible. On the other hand, Case 2 appears to be more practical with less energy consumption at a far less cost due to the quantization effect. However, this approach suffers from drop in captured power levels due to mismatched resonance conditions caused by quantization effect. In order to bring the system back to resonance condition, there is a need for compensation of mismatched frequencies. Hence, the total mass parameter of the system is varied by adjusting m_{st}. This allows slight modification of the natural frequency of the system thereby meeting the resonance condition. Estimated future wave climate information is used for calculation of the needed total mass and related m_{st} as well as its timing. For this purpose, a tank on the WEC is filled up with seawater to increase the total mass to decrease the ω_n or the sea water in tank is discharged necessary amount to increase the ω_n. Hence, in this case, the tuning of the WEC is achieved by both slow and fast tuning. This approach makes the control technique more realistic, more practical and also most energy efficient. The details of simulation study are summarised in Table 4.4 with simulation related cases as well as control settings details.

Table 4.4. The simulation cases and the relevant control parameters

Cases	**PTO settings**		**Slow tuning settings**	**Energy requirement for instantaneous achievement of:**	**Expected energy consumption**
	k_{pto}	**b_{pto}**	**m_{st}**		
Case 1	Instantaneously varied	Instantaneously varied	N/A	1) k_{pto}	High
				2) b_{pto}	-
Case 2	Quantized	Instantaneously varied	N/A	1) k_{pto}	Moderate
				2) b_{pto}	-
Case 3	Quantized	Instantaneously varied	FL based inst. varied	1) k_{pto}	Moderate
				2) b_{pto}	-
				3) m_{st}	Moderate

In the Case 1, the control approach is based on instantaneous adjustment of the stiffness parameter of PTO system. There are some practical problems for varying the k_{pto} parameter instantly.

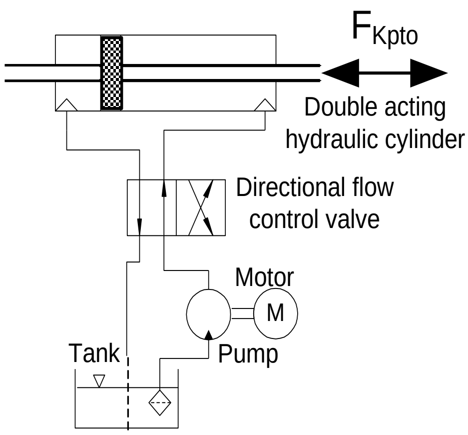


Figure 4.6. The outline of the instantaneous k_{pto} setting achievement using a hydraulic system

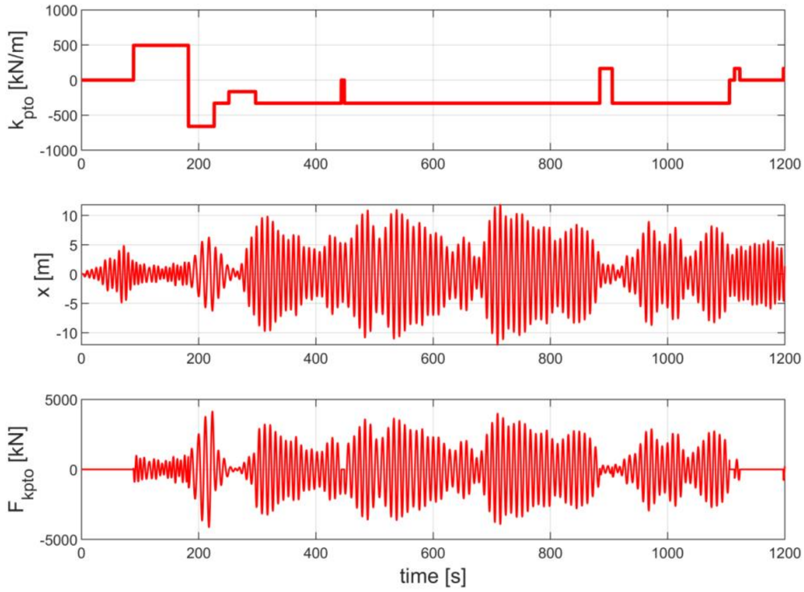


Figure 4.7. k_{pto} settings, x and related F_{kpto} for Case 1

In Figure 4.7, settings for k_{pto} are provided for a realistic sea state. In this figure also the x and the F_{kpto} force required for achievement of k_{pto} is presented. In Figure 4.9, hydraulic pressure (P_h), hydraulic flow rate (Q_h) and hydraulic power (P_{hyd}) required for instantaneous achievement of k_{pto} and required electrical power (P_{elec}) for Case 1.

It is shown in Figure 4.8 that the estimated wave frequency (ω_{est}) and ω_n are matched. This is the ideal resonance condition required for maximum power capture performance of a WEC. This approach proves that the instantaneous adjustment of k_{pto} unit satisfies the resonance condition only if the wave and WEC natural frequencies are perfectly matched.

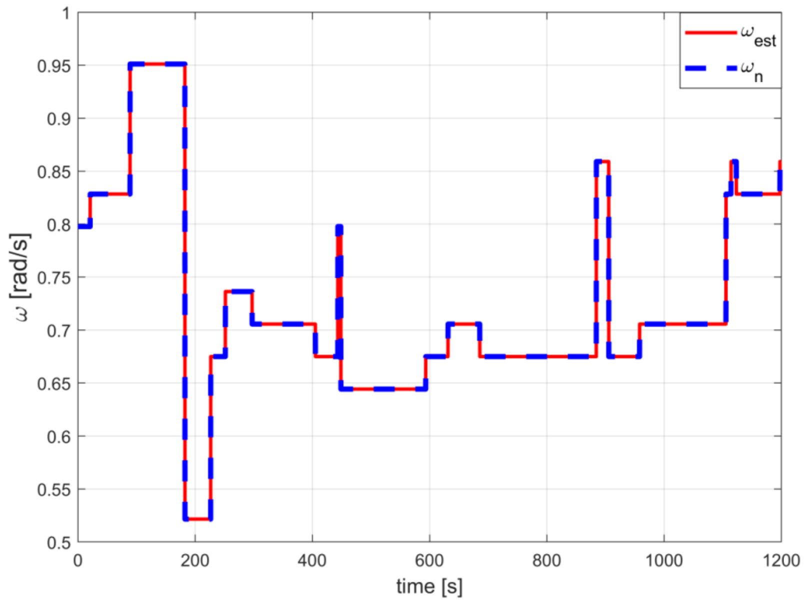


Figure 4.8. ω variations for Case 1

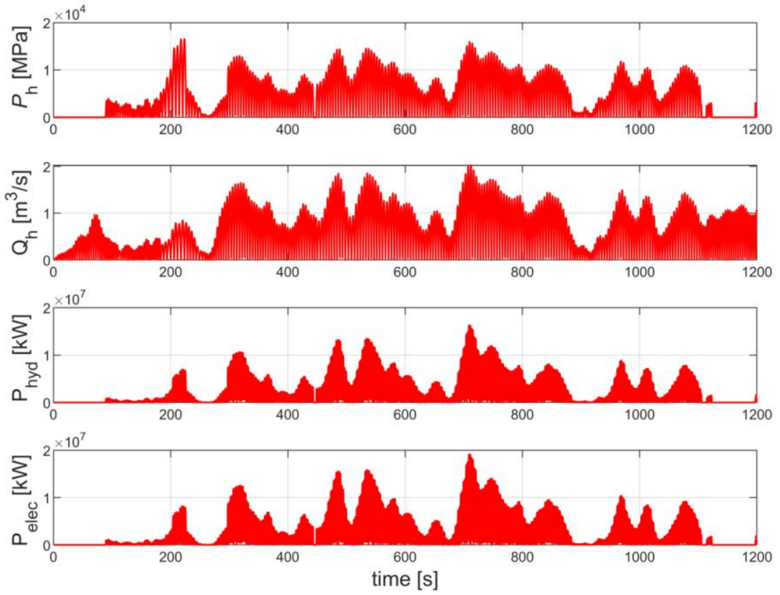


Figure 4.9. P_{h}, Q_{h} and hydraulic power required for instantaneous k_{pto} achievement and required P_{elec} for Case 1

The power capture results for Case 1 are given in Figure 4.9 and Figure 4.10. In Figure 4.9, the simulation results for Case 1 are provided where the necessary P_h and Q_h as well as required P_{hyd} and necessary P_{elec} are presented. The Figure 4.10 shows the simulation results for Case 1, where P_{ins} and P_{ma} captured with instantaneous settings, are illustrated.

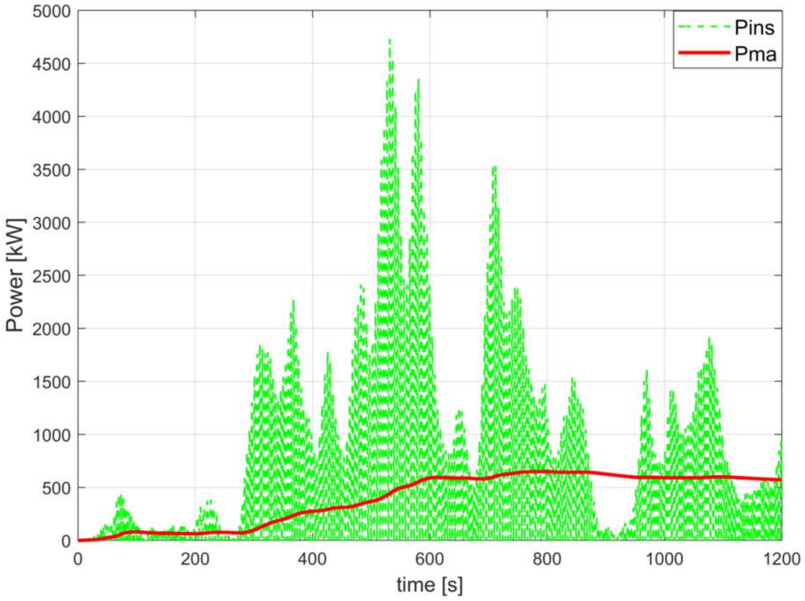


Figure 4.10. Produced power for Case 1

The simulation result indicates that power captured in this case is about 572 kW. In Figure 4.11, the power requirement for adjustment of k_{pto}, power capture performance and related power levels are illustrated. In Figure 4.11, from top to bottom there are 3 subplots illustrating the captured power (P_{ins}), the stiffness adjustment system required power (P_{req}) and the net power (P_{net}), respectively. It can be seen from the figure that the power required for instantaneous achievement of PTO settings is much more than the WEC device actually captures.

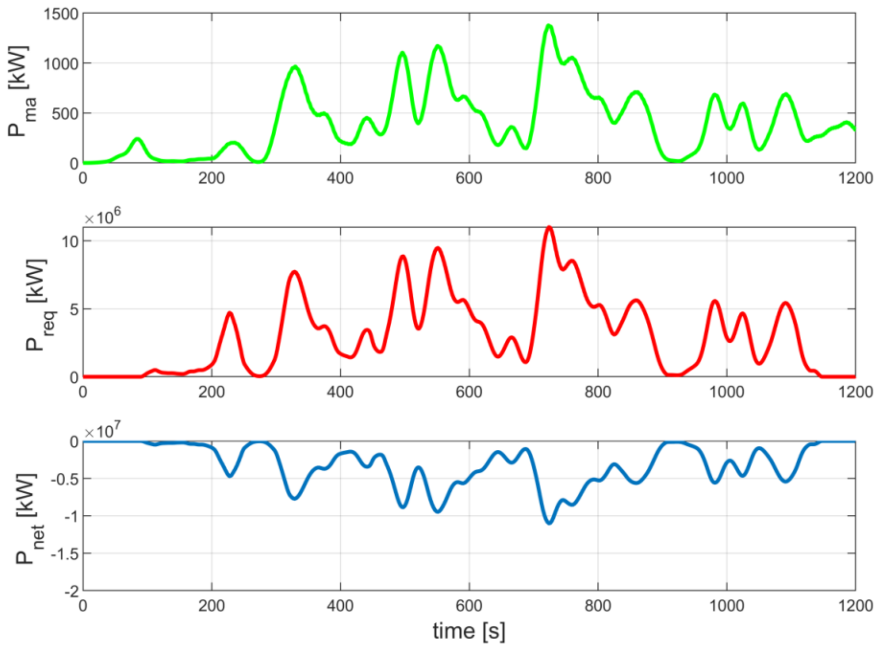


Figure 4.11. Power results for Case 1

In Case 2, k_{pto} settings are implemented in quantized form in a similar way reported by Mistikoglu and Yavuz (Mistikoglu and Yavuz, 2016). For this purpose, the stiffness parameter limits are given in Table 4.5. In this table for the datasets used in the simulation the maximum and the minimum k_{pto} setting levels are listed along with quantization steps (q_s).

For achievement of quantized stiffness (k_{pto}^{q}), as shown in Figure 3.6, the spring couples (8 spring couples positioned symmetrically to each other) are used and with this configuration 8 quantization levels are achieved. Each symmetric couple of springs set are activated by a hydraulic cylinder pushing the springs into action while releasing when they are not needed. The hydraulic cylinders are only used in order to activate or deactivate the springs depending on the required level of stiffness. In Figure 4.12, the k_{pto}^{q} and instantaneously varied stiffness (k_{pto}^{ins}) values are shown. The control approach with quantized k_{pto}^{q} is based on activating spring depending on frequency estimation. However, the tuner selects upper rounding value for stiffness. From this figure it is clear that achievement of quantized levels of stiffness is technically more practical and feasible than that of the instantaneously varied type presented in Case 1.

Table 4.5. Maximum and minimum required k_{pto} values

#Dataset	$k_{\mathrm{pto}}^{\mathrm{min}}$[kN/m]	$k_{\mathrm{pto}}^{\mathrm{max}}$[kN/m]	q_s[kN/m]
1	-657,86	661,26	165
2	-657,86	450,2	165
3	-474,83	-103,83	165
4	-539,14	67,65	165

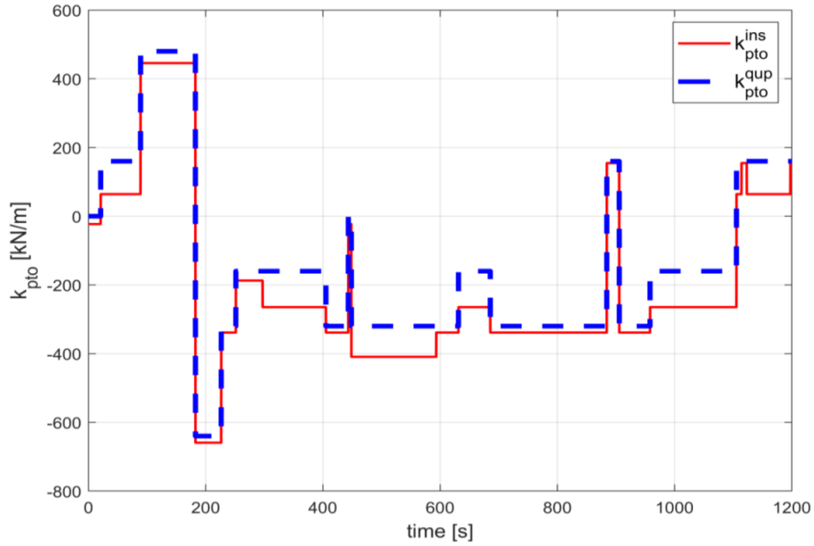


Figure 4.12. Quantized version of the $k_{\mathrm{pto}}^{q}$with the instantaneously varied one $k_{\mathrm{pto}}^{\mathrm{ins}}$.

In Figure 4.13, the wave frequency and the WEC natural frequency details are provided for Case 2. It is shown that there is a slight mismatch due to quantization effect resulting in less power capture relative to that of Case 1.

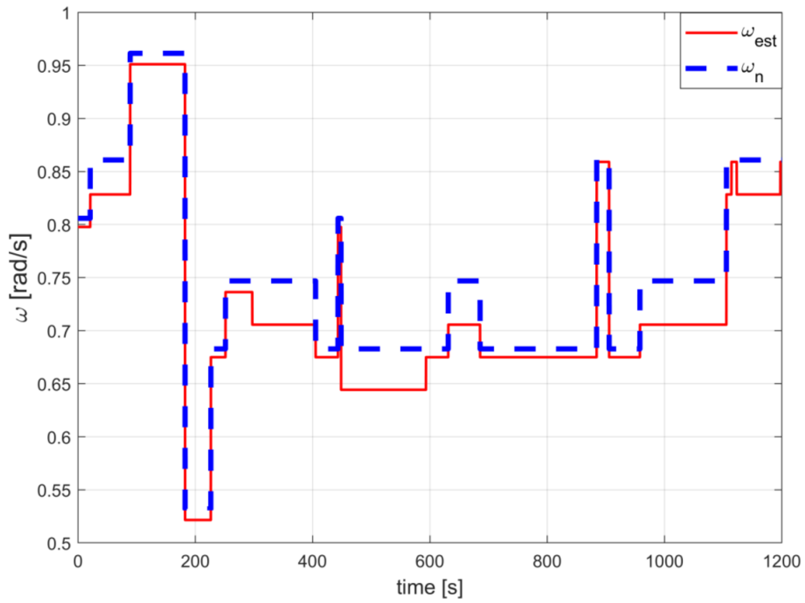


Figure 4.13. ω variations for Case 2

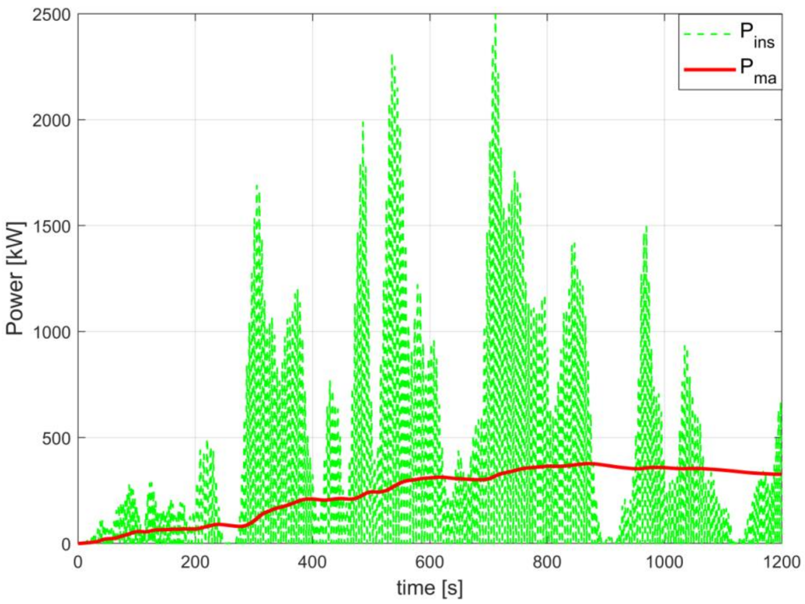


Figure 4.14. Power analyses for Case 2

In Figure 4.14, the simulation results for Case 2 are given. In this figure, instantaneous and moving average power levels are shown. In this approach, the power capture is about 326 kW and this corresponds to approximately 60% of the power capture achieved in Case 1. The main reason for the loss of the captured power is mismatched natural frequencies of the WEC and wave illustrated in Figure 4.13.

In order to compensate for the mismatched frequency related power losses mentioned in Case 2, FL based slow tuning control capability is added to form the Case 3. For this purpose, in order to provide the system with additional capability of compensation of quantization effect, FL based slow tuning is used to vary the total mass of the system. The technique is based on having a water tank on board with tank filling and discharging facility as shown Figure 3.7. In this case, FL based slow tuning technique is used in adjustment of m_{st} to meet the resonance condition.

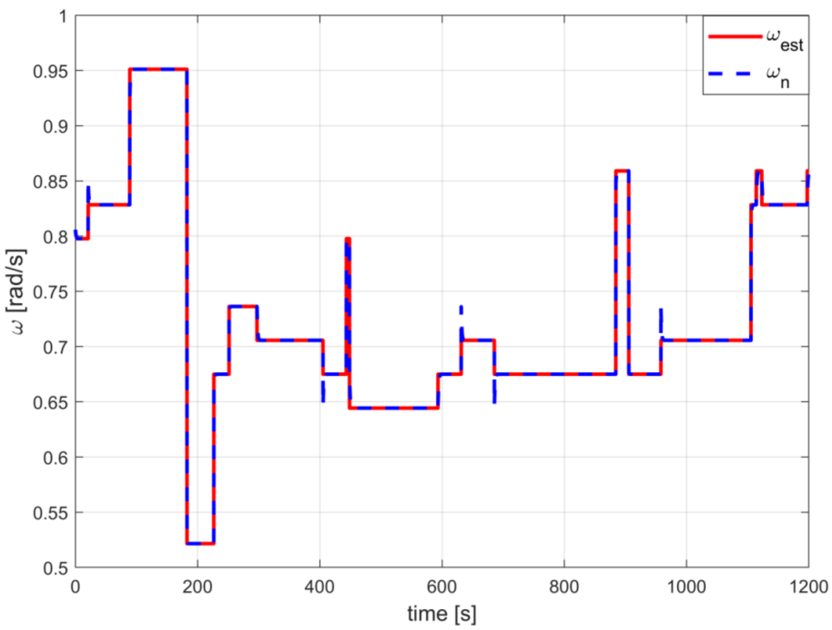
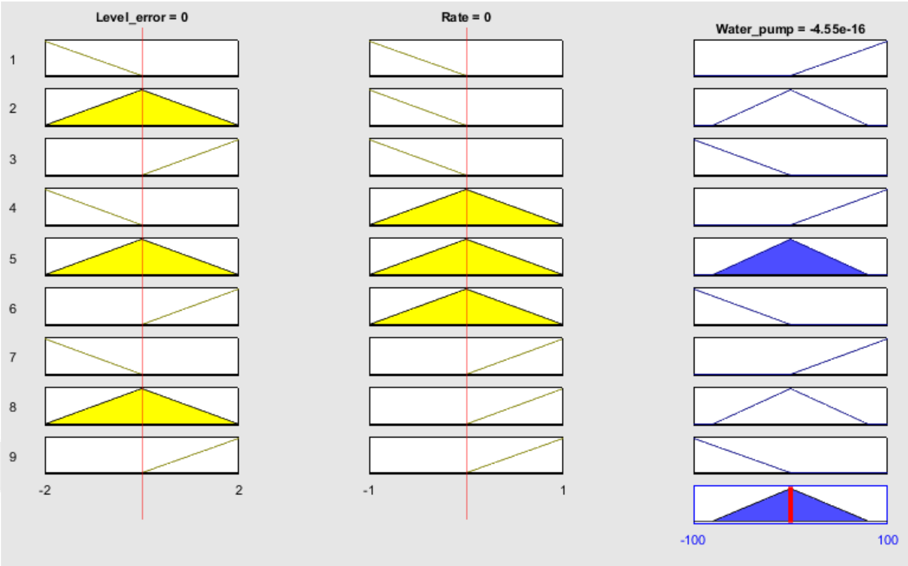
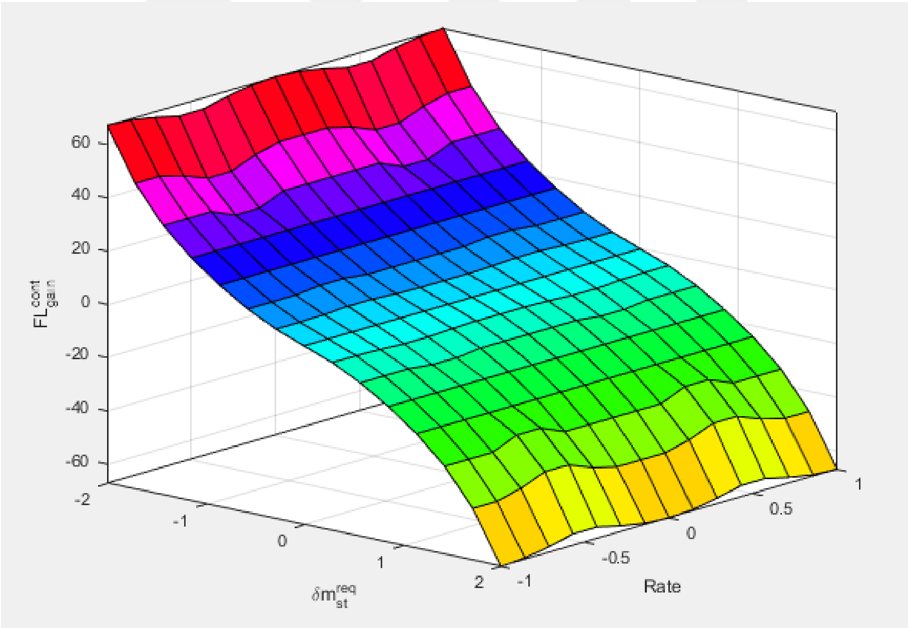


Figure 4.15. ω variations for Case 3

In Figure 4.15, the simulation results of Case 3 are presented for wave and WEC natural frequencies. It is shown that the frequencies match almost perfectly. This approach does not actually use instantaneous stiffness adjustments and therefore it does not require high running costs and related energy. To achieve this, it employs a quantized stiffness with FL based slow tuning technique utilising m_{st} adjustment. Four symmetric pumps are placed to pump water in to a tank to control m_{st} of WEC to meet the resonance conditions. These pumps are driven by FL controller depending on the forecast-based incident wave frequencies and required m_{st} in the water tank. The FL controller rules are given in Figure 4.16.a where details of the control rules are provided. In this figure, a picture of the FL controller window is provided where the error level and the rate of flow inputs are shown. The result of the control action is provided on right hand side where the active rules and resulting control action is illustrated. In Figure 4.16.b, the FL slow tuning controller's control surface is illustrated. In this figure, the output for the controller (FL_{gain}^{cont}) presented with the input parameters (i.e., rate and δm_{st}^{req}) of the controller. As can be seen from the control surface illustrated in Figure 4.16.b, the FL slow tuning control gain is dominantly determined by the control input of required mass of water in the tank represented by the symbol of δm_{st}^{req}. On the other hand, rate of change of total water mass in the tank plays relatively less important role in determination of the FL slow tuning control gain.



(a)



(b)

Figure 4.16. FL controller rules (a) and control surface (b) for Case 3

The power capture performance related simulation results for Case 3 are shown in Figure 4.17. The captured power for the Case 3 is determined to be around 556 kW. It can be seen that the drop in power capture performance caused by mismatched frequency, due to quantisation effect presented in Case 2, is eliminated.

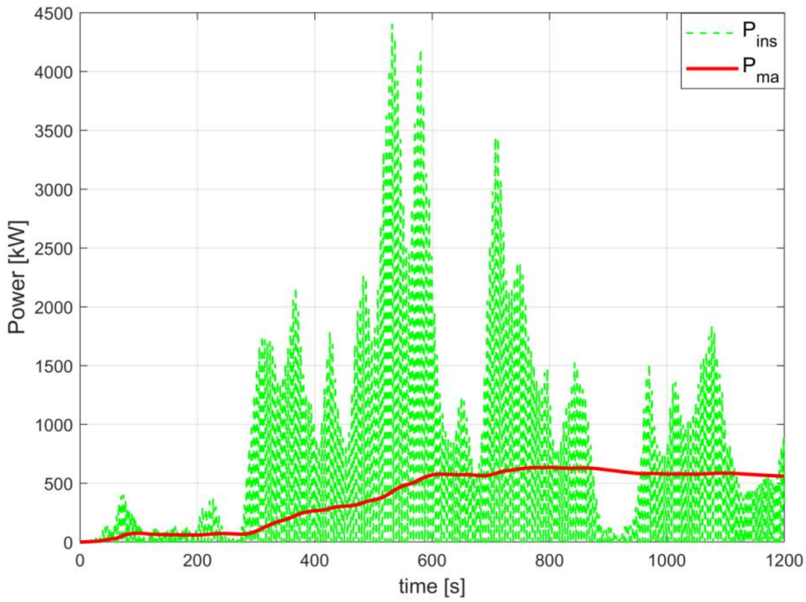


Figure 4.17. Power results for Case 3

In Figure 4.18, the power comparison for all cases is illustrated. It is shown that the presented new practical technique performs as good as the idealistic and non-realistic case presented in Case 1.

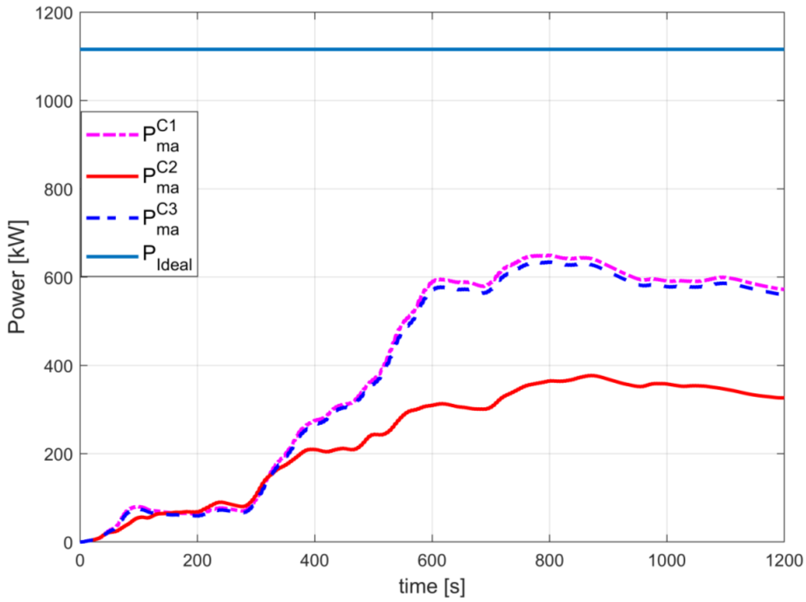


Figure 4.18. Power capture analysis for all cases and comparison with ideal power

From Bernoulli Equation, the flow is assumed to be incompressible (Çengel and Cimbala, 2018) and there is no loss in the water transfer system. As stated by 1st law of Thermodynamics, the energy is conserved (Çengel and Boles, 2006) for the system being studied.

$$E_{in} = E_{out} \tag{4.2}$$

$$W_{in} + PE_{in} + KE_{in} = W_{out} + PE_{out} + KE_{out} \tag{4.3}$$

$$W_{in} + mgh_{in} + KE_{in} = W_{out} + mgh_{out} + KE_{out} \tag{4.4.}$$

$$h_{in} \cong h_{out} \tag{4.5}$$

then,

$$PE_{in} = PE_{out} \, , \tag{4.6}$$

these two terms therefore eliminated, then the new form of the Equation (41) becomes

$$W_{in} + KE_{in} = W_{out} + KE_{out} \tag{4.7}$$

Where E, PE, KE represents energy, potential energy and kinetic energy, respectively. Also, W, g, h and m represents work, gravitational acceleration, height and mass, respectively. The subscripts "*() in*" and "*() out"* are used to represent the input and the output form of the relevant parameter.

The stationary water has zero velocity therefore the kinetic energy term is zero for the input seawater, either from the tank to the sea or vice versa. However, kinetic energy is provided for the water to flow from one side to the other, hence the output side of the flow possesses kinetic energy. The system is not expected to do any work on output side. Therefore, output work equals to zero (W_{out}=0). Hence, the energy equation takes the following form

$$W_{in} = KE_{out} \tag{4.8}$$

The time dependant m_{st} setting defines the system operation on the direction of the flow required and the FL controlled pumps either to fill the tank with seawater or to discharge the tank water out to the sea. W is the energy given to the system due to pumping work that in return provides the water with necessary kinetic energy for the transfer.

$$KE = \frac{1}{2} m_{st} \left(u^2 \right) \tag{4.9}$$

where m_{st} is the mass of the water in kg and u is the velocity of water in m/s.

The m_{st} is given in Fig. 18. As shown in the figure, the total operation time of the pumps take only a small part of the simulation time. This leads to low power requirements for the pumping system. During this period, the pumped water is only aimed to be relocated almost horizontally about 2 m from source to sink in a few seconds.

The required KE is calculated using Equation (60) and this information is then taken into account during net power calculation.

Table 4.6. Simulation results summary for all Cases

Case No	Power (kW)	Results
Case 1	572.35	The energy requirement to operate with servo-hydraulic system is much more than the produced energy.
Case 2	326.39	The energy production reduced due to mismatched resonance condition. The energy requirement of this case is about 50 kW.
Case 3	556.51	FL based slow tuning control increases the energy production. The energy required to operate the pumps work for a short period of time. The energy required for simulation time is calculated about 110 kW

In Table 4.6, the simulation results for the cases are summarised. The results achieved for Case 1 appears to be the best of all. However, as mentioned earlier and also illustrated in Figure 4.11, the cost of achievement of instantaneous k_{pto} appears to be very high and requires too much power. The operation power requirement of the control system for this case is many times more than the power captured by WEC using this technique. Therefore, it appears to be impractical and unfeasible. The results for Case 2 indicate that the net power captured is positive indicating some future promising results. The power requirement for the control system appears to be around 50 kW. Therefore, the control approach presented in Case 2 appears to be practical although the mismatched frequency issue leading to some level of captured power loss. The results presented for Case 3 appears to be most promising one as it uses quantized k_{pto} and avoids high cost as well as high operational energy requirements. It also utilises FL based slow tuning technique to compensate for the mismatched frequency issue experienced due to quantization effect. At the last stage of the study, a renewable energy-based application is performed. The modelled 1 DOF heaving WEC system is used for supplying energy for a RO desalination system. The main idea behind this application is the fresh water is a critical and vital resource that humanity needs as much as energy.

The wave elevation results for these four datasets are presented in Figure 4.19. These types of irregular waves are generally created by means of the superposition of linear components of waves with different frequencies at a uniform frequency range. These irregular waves are generally defined by their typical spectral characteristics.

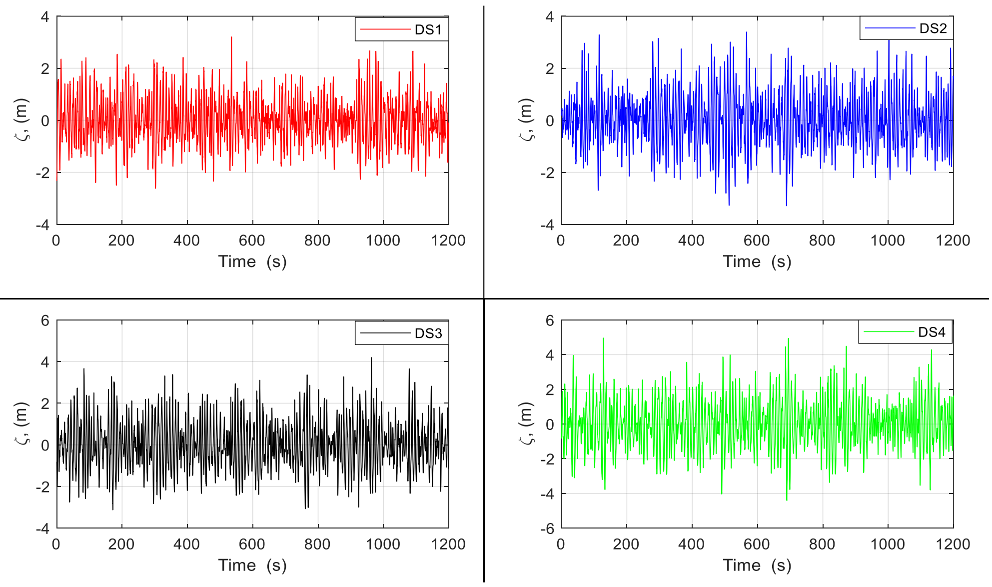


Figure 4.19. Significant wave height data for datasets (DS1-DS4)

The WEC systems mainly suffer from irregular nature of the sea waves. Consequently, the continuous control of PTO parameters of the WEC system is needed to ensure meeting the optimal operation related resonance conditions. Hence, an adaptive controller is used to adjust the PTO tuning parameters to keep the WEC in desired continuous resonance.

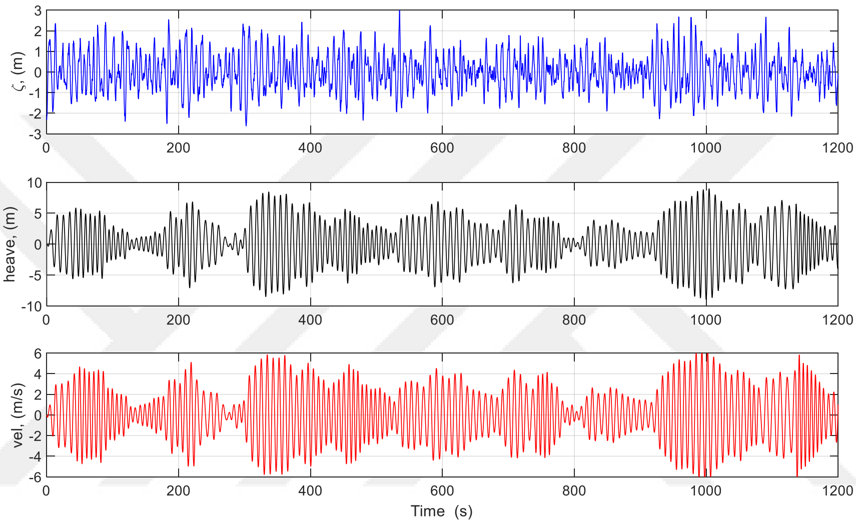


Figure 4.20. Wave elevation, heave and velocity information for waves and WEC for DS1

In Figure 4.20, the wave elevation, the heave motion and the velocity of the WEC related simulation results are presented for DS1. The simulation is performed for a 1200 s time period. It can be seen that the heave motion and the velocity of the WEC is high at some points. This indicates that the energy density of the relevant waves is relatively higher than that of the other sections of the dataset.

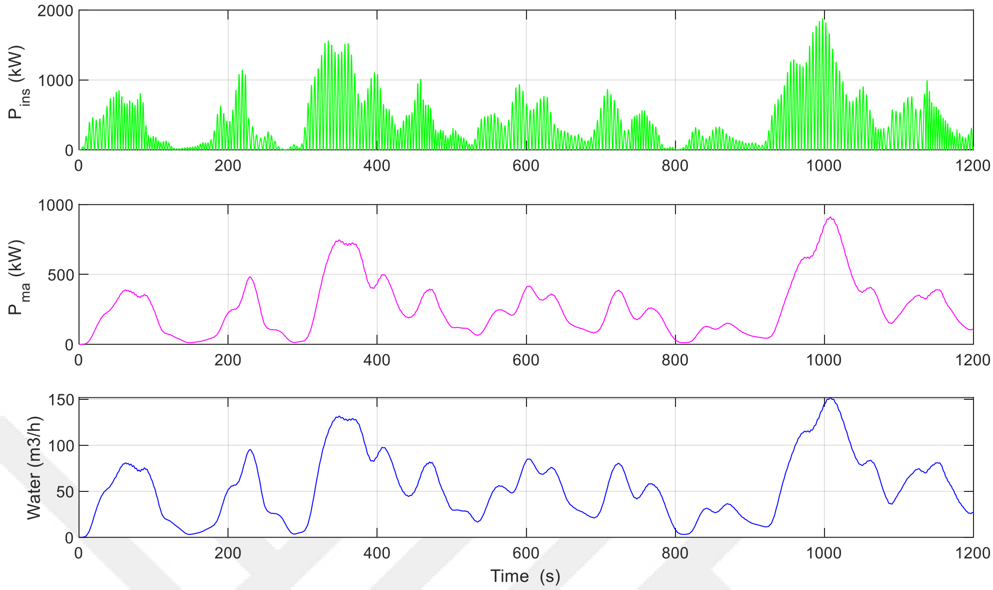


Figure 4.21. Instantaneous power produced and the desalinated water production rate for DS1

In Figure 4.21, the simulation results for DS1 are presented where the instantaneous power captured by WEC and the water production rate of desalination plant related details are illustrated. It can be clearly seen from this figure that the instantaneous power is higher at some regions. These results are mainly related to successful tuning of the WEC when there are highly energetic incident waves at the same time. At these points, the WEC captures high levels of power, hence the water production rate is also increased.

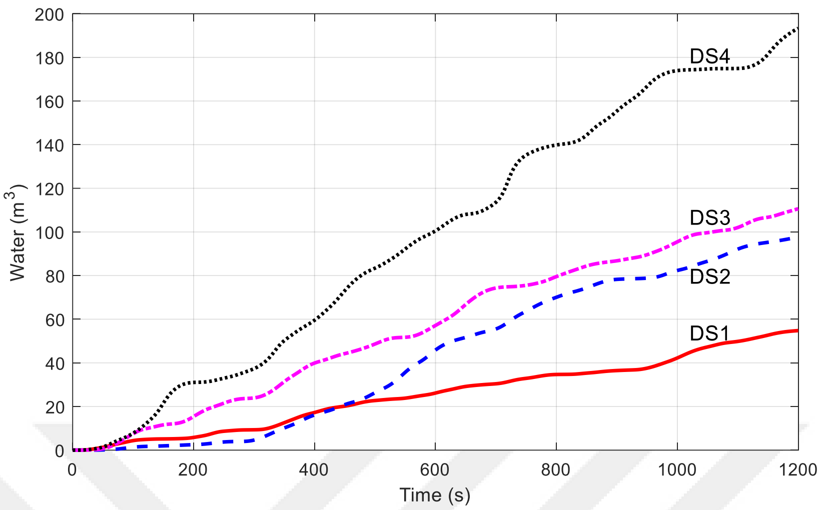


Figure 4.22. Produced water levels for DS1, DS2, DS3 and DS4

The irregular water output behaviour of the desalination system production rate is a problem to be solved. In order to solve the issue, water storage tank is proposed as a temporal storage facility to be used before sending the water to the system. The results of the stored water capacities are given in the Figure 4.22. The water levels for four datasets are presented. The final values of the produced water volumes for DS1, DS2, DS3 and DS4 are 54.8 m^3, 97.6 m^3, 110.6 m^3 and 193.3 m^3, respectively.

5. CONCLUSION AND FUTURE WORK

The renewable energy sources have become indispensable sources with the increasing energy need. It is now actively used with further research and development. This study presents a wave energy conversion system from renewable energy sources, a control system and a model of the wave energy-based RO desalination system. Due to the high energy density of waves, it has been shown to be a more intense energy source than all other renewable energy sources. For the designs of wave energy converters used for the extraction of energy from this dense energy source, it has been clearly stated that the adjustment of system parameters, analysis and control applications can increase the efficiency of the system.

In this study, the main purpose of the study is to determine the system parameters properly, to adjust these parameters, to catch the resonance conditions according to the operating conditions of the system, to develop control applications with all these conditions, and to increase the operating performance of the system. In addition, the wave energy conversion system is used to reach a clean water, which is the most basic need of humanity. Using this desalination process made with the RO principle, it was necessary meeting the required energy by wave energy while complementing each other's deficiencies as an integrated systems and making the overall system environmentally friendly.

As the first part of the study, an investigation on the effect of the variation of the PTO damping coefficient over radiation damping on the power capture performance of WEC is performed. In literature, generally the PTO damping is accepted as equal to the radiation damping. So, the PTO damping coefficient set equal to frequency dependent radiation damping coefficient (b_{rad}) in the first part of the simulation study. In the second case study, it is proposed that b_{pto} should be evaluated different from $b_{pto}=b_{rad}$ relation. The PTO damping is remodelled and the simulations are performed with the varying gain of alpha. The results given in previous part of the study indicated that the power produced is increased while the b_{pto} is higher than brad. It was clearly seen that the captured power results are increased between 1.64% and 10.38%. Also, the average of alpha gain value is 1.67 and related power capture increase is 5.95%. Finally, it can be concluded that there is an obvious need for optimization of b_{pto} in control applications especially while studying for irregular sea state conditions. It can also be stated that the proposed approach based on increasing b_{pto} beyond b_{rad} may be more beneficial than simply assuming that b_{pto} equals to brad. In such an application the variation of brad against wave frequency becomes the main tool therefore accurate hydrodynamic modelling of radiation damping also becomes a vital issue. Besides, determination of the wave frequency data from wave elevation data also becomes important as it determines the damping coefficient (b_{rad}) used in optimization related calculations.

In the second part of the study, a FL controller based slowing tuning technique is introduced for controlling a heaving wave energy converter. The controller utilises the quantization technique, requiring low energy for operation, and the FL based slow tuning technique for compensation of the losses due to the quantization effect. Therefore, the overall control technique proves to be more energy efficient and far more practical. At implementation stage of the control approach to the modelled system, three different cases are considered, related simulations are performed and simulation results are presented. The studied cases, Case 1, Case 2 and Case 3 are defined with instantaneously varied control settings, partly instantaneous and partly quantized settings and a FL based slow tuning added version of previous case, respectively. In Case 1, the system has the ability to match the resonance condition and capture more power than the others. However, the power requirement for control approach itself is calculated to be higher than the power actually being captured. In order to reduce the required operational energy, the quantized system is proposed as a practical solution as presented in Case 2. In simulation results of this case, captured power figures appear to be less than that of Case 1 due to quantization effect. However, the same quantization effect makes the control approach far more practical and feasible for Case 2. In Case 3, to regain the energy loss due to mismatched natural frequencies, FL based slow tuning technique is proposed. The approach proposed in this case appears to be far more efficient and practical. The technique presented proves that using combined form of quantization effect and FL based slow tuning technique improves the overall performance of the WEC and the net captured power levels of the system. In the first case the produced power is found as 572.35 kW but the energy requirement to operate with servo-hydraulic system is thousands of times of produced energy. In the second case of this part, the produced energy decreased to 326.39 kW. The energy production reduced due to mismatched resonance condition. The energy requirement of this case is about 50 kW. On the third case, the produced power is regained. FL based slow tuning control increases the energy production. The energy required to operate the pumps work for a short period of time. The energy required for simulation time is calculated about 110 kW

As third part of the study, the heaving WEC system is used for supplying the energy need of the RO desalination plant model. The overall system is simulated into two consecutive stages. In first stage, the wave frequency is estimated from timed wave elevation data with sliding DFT technique and wave force is calculated using the developed transfer function. The irregular and the complex nature of the real sea states make the TD modelling of the system a technically difficult issue. But, the controller in this WEC model successfully adjusts the PTO parameters at nearly optimal operational conditions. Hence, the power capture performance is increased by tuning PTO control parameters. In the second stage, overall model of the system that combines the WEC model and RO based desalination model is executed. It is observed that the production rate of the desalination model mainly depends on the power capture rate of the heaving WEC. The form of the produced power from the WEC system is naturally irregular. Nevertheless, the RO desalination system successfully handles the irregular power produced by WEC system. The proposed overall TD model of the system eliminates some of the disadvantages of both WEC and RO desalination systems and generates a synergetic effect by compensating each other's weaknesses. The simulation results show the stored fresh water levels for each dataset. The produced water levels in the storage tanks for DS1, DS2, DS3 and DS4 are 54.8 m3, 97.6 m3, 110.6 m3 and 193.3 m3, respectively. The fresh water production varies based on the variation of wave height and the related WEC power capture rate. Although the captured power results vary with varying properties of the irregular real sea states, the proposed system model copes with the variations and manages to generate a more or less regular fresh water flow rate.

To summarize, the main contributions of the study are:

1. A reliable analysis of the irregular nature of real sea conditions to adjust the tuning parameters for the WEC system.
2. Successful power generation from irregular and complex real sea conditions using a wave energy conversion system.
3. The development of a model which enables use of irregularly generated power for a continuous process of RO desalination.
4. The successful implementation of wave energy-based RO desalination and storage of the produced fresh water.

It can be clearly seen that this synergetic solution can be far more feasible and effective especially for offshore applications. The proposed system model and related approach appears to be a good solution to overcome the shortcomings of both systems. As conclusion, the use of off-grid WEC system powering a RO desalination system provides both renewable based energy solution and also meets the fresh water demand for remote locations. However, the fully renewable energy powered RO desalination system with sustainable operation requires more research to be conducted on the issue and it would most probably provide a much more viable and environmentally friendly solution.

REFERENCES

Amy, G., Ghaffour, N., Li, Z., Francis L, Linares RV., Missimer, T., and Lattemann, S., 2017. Membrane-based seawater desalination: Present and future prospects. Desalination, 401: 16-21.

Anderson, CG., 1985. First Assessment of the Magnetic-Hydrostatic Main Bearing Proposed for the Duck Wave Energy Converter. Edinburgh University, PhD Thesis, Edinburgh, 201p.

Astariz, S., and Iglesias, G., 2015. The economics of wave energy: A review. Renewable and Sustainable Energy Reviews, 45 397-408.

AW Energy, https://aw-energy.com/ [accessed 11.11.2021]

AWS Ocean, https://www.awsocean.com/archimedes-waveswing/ [accessed 18.11.2021]

Babarit, A., Duclos, G., and Clement, A., 2010. Comparison of latching control strategies for a heaving wave energy device in random sea. Journal of Applied Ocean Research, 26:227-38.

Bergdahl, L., 1979. The Swedish Wave Energy Research Programme. Proceedings of a Symposium on Wave Energy Utilisation, Gothenburg, Sweden.

Bergdahl, L., 1992. Review of Research in Sweden. Proceedings of a Workshop on Wave Energy R&D, Cork, Ireland.

Bjarte-Larsson, T., and Falnes, J., 2006. Laboratory experiment on heaving body with hydraulic power take-off and latching control. Ocean Engineering, 33:847-877.

Black, J.L., 1975. Wave forces on vertical axisymmetric bodies, Journal of Fluid Mechanics, 67(2):369-376.

Bouchafaa, F., Hamzaoui, I., and Hadjammar, A., 2011. Fuzzy Logic Control for the tracking of maximum power point of a PV system. Energy Proceedings 6:633-642.

Boyle, G., 2004. Renewable Energy, Power for a Sustainable Future, 2nd edition, Oxford University Press, Oxford, 464p.

Bracewell, R.H., 1990. Frog and Ps Frog: a study of two reactionless ocean wave energy converters. Lancaster University. PhD Thesis, Lancaster, UK, 228p.

Budal, K., and Falnes, J., 1975. A resonant point absorber of ocean-wave power. Nature, 256:478–479.

Budal, K., and Falnes, J., 1980. Interacting point absorbers with controlled motion. In B.M. Count (ed.), Power from Sea Waves, Academic Press, London. 381–399.

Burgaç, A., and Yavuz, H., 2019. Fuzzy Logic based hybrid type control implementation of a heaving wave energy converter. Energy 170:1202-1214.

Burgaç, A., and Yavuz, H., 2020. Power capture performance of a heaving wave energy converter for varying b(rad)/b(pto) ratio. SN Applied Sciences, 2:1-10

Burgaç A., and Yavuz H., 2021 Renewable energy based freshwater production utilizing reverse osmosis desalination. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-15.

Chen, Z., Yu, H., Hu, M., Meng, G., and Wen, C., 2013. A Review of Offshore Wave Energy Extraction System. Advances in Mechanical Engineering, 5:1-9.

Çengel, Y.A., and Boles, M.A., 2006. Thermodynamics: An Engineering Approach. 5th edition, McGraw-Hill, New York, 1024p.

Çengel, Y.A., and Cimbala, J.M., 2018. Fluid mechanics: fundamentals and applications. 4th ed.: McGraw-Hill, Higher Education, New York, 2036p.

Clemente, D., Rosa-Santos, P., and Taveira-Pinto, F., 2021. On the potential synergies and applications of wave energy converters: A review. Renewable and Sustainable Energy Reviews, 135(110162):1-17.

Coventry University, 1986. The Development of the circular SEAClam. Coventry Polytechnic and SEA Energy Associates, ETSU Report No. WV-1676-P1.

Cruz, J., 2008. Ocean wave energy current status and future prespectives. Springer, Berlin, 431p.

Dambrosio, L., 2017. Data-based Fuzzy Logic Control Tenchnique Applied to a Wind System. Enrgy Proceedings, 126:690-697.

Edinburgh University, 1979. Wave energy-Salter's Duck Fifth Year Report, Edinburg Wave Power Project, ETSU Report Number WV 1512, Parts 4A-4C.

ETSU, 1985. The Department of Energy's R&D Programme 1974-1983. ETSU Report R-26.

ETSU, 1994. An Assessment of Renewable Energy for the UK. ETSU Report Number R-82.

Evans, D.V., Jeffrey, D.C., Salter, S., and Taylor, J., 1979. Submerged cylinder wave energy device theory and experiments. Applied Ocean Research, 1(1):3-12.

Falcão, A.F.O, 2010. Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews, 14:899-918.

Falcão, A.F.O., and Henriques, J.C.C., 2016. Oscillating-water-column wave energy converters and air turbines: A review. Renewable Energy, 85:1391-1424.

Falnes, J., 1997. Principles for capture of energy from ocean waves phase control and optimum oscillation. Norwegian University of Science and Technology, Norway, 8p.

Falnes, J., 2002a. Optimum Control of Oscillation of Wave-Energy Converters. International Journal of Offshore and Polar Engineering, 12(2),147–155.

Falnes, J., 2002b. Ocean waves and oscillating systems. Cambridge University Press, Cambridge, 287p.

Farrok, O., Islam, M.R., Islam-Sheikh, M.R., Guo, Y., Zhu, J., and Lei, G., 2018. Oceanic Wave Energy Conversion by a Novel Permanent Magnet Linear Generator Capable of Preventing Demagnetization. IEEE Transactions on Industry Applications, 54(6),:6005-6014.

Faÿ F-X., Robles, E., Marcos M., Aldaiturriaga, E., Camacho E.F., 2020. Sea trial results of a predictive algorithm at the Mutriku Wave power plant and controllers assessment based on a detailed plant model. Renewable Energy, 146:1725-1745.

French, M.J., and Bracewell, R., 1985. Heaving Point Absorbers Reacting Against an Internal Mass. IUTAM Symposium Conference Proceedings, 247- 255, Lisbon, Portugal.

French, M. J., and R. H. Bracewell. 1987. P.S. FROG A point-absorber wave energy converter working in a pitch/surge mode. Proceedings of Energy Options Conference, Berkshire, UK.

French, M.J., and Hurdle, D.P., 1982. Research on Wave-Energy Conversion Using Small Bodies Moving in Surge (‘Flounder’). Report for SERC., 1982

Folley, M S, 1991. The Design of Point Absorbing Wave Energy Converters. Lancaster University. PhD Thesis, Lancaster UK.

Fry, R., and Jeffery E.R., 1979. Tank trials of model Kaimei. CEGB Laboratory Note, R/M/N1072.

Fuzzy Logic Toolbox. https://www.mathworks.com/help/pdf_doc/fuzzy/ fuzzy.pdf [accessed 13 July 2021].

Ghafari, H.R., Ghassemi, H., and He, G., 2021. Numerical study of the Wavestar wave energy converter with multi-point-absorber around DeepCwind semisubmersible floating platform. Ocean Engineering, 232:1-17.

Ghenai, C., and Bettayeb, M., 2021. Data analysis of the electricity generation mix for clean energy transition during COVID-19 lockdowns. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1-21.

Guillaume, S., 2001. Designing fuzzy inference systems from data: An interpretability-oriented review. IEEE Transactions on Fuzzy Systems, 9(3):426-443.

Guo, B., and Ringwood, J.V., 2021. Geometric optimisation of wave energy conversion devices: A survey. Applied Energy, 297(117100):1-27.

Halder, P., Samad, A., and Thévenin, D., 2017. Improved design of a Wells turbine for higher operating range. Renewable Energy, 106:122-134.

Hannon, M., van Diemen, R., and Skea, J., 2018. Examining the effectiveness of the UK's wave energy innovation system since 2000. International Sustainability Transitions, Manchester, 170p.

Henriques, J.C.C., Gato, L.M.C., Falcão, A.F.O., Robles, E., and Faÿ, F.X., 2016. Latching control of a floating oscillating-water-column wave energy converter. Renewable Energy, 90:229-241.

Hotta, H., Washio, Y., Yokozawa, H., Miyazaki, T., 1995. On the Open Sea Testing of a Prototype Device of a Floating Wave Power Device: Mighty Whale. Proceedings of the Second European Wave Power Conference, 404-406, Lisbon, Portugal.

Kim, J., Park, K., Yang, D.R., and Hong, S., 2019. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Applied Energy, 254:1-16.

Korde, U.A., Robinett, R.D., and Wilson, D.G., 2016. Wave-by-wave control in irregular waves for a wave energy converter with approximate parameters. Journal of Ocean Engineering and Marine Energy, 2:501-519.

Korsmeyer, F.T., Bingham, H.B., and Newman, J.N., 1999. A panel method for transient wave body interactions. Research Laboratory of Electronics, Massachusetts Institute of Technology Press, Cambridge, MA, 75p.

Kristiansen, E., and Egeland, O., 2003. Frequency dependent added mass in models for controller design for wave motion damping. IFAC Proceedings Volumes, 36:67-72.

Lancaster University, 1988. Design Study of the Engineering of a Reactionless Wave Energy Converter Buoy Working in Pitch and Surge (PS Frog). ETSU Report on Contract Number E/5A/CON/1681/1852.

Lee, C.H., and Newman, J.N., 2005. Computation of wave effects using the panel method. Numerical models in fluid structure interaction, (S.K. Chakrabarti Editor). WIT Press, Southampton UK, 211-251p.

Lehmann, M., Karimpour, F., Goudey, C.A., Jacobson, P.T., and Alam, M.R., 2017. Ocean wave energy in the United States: Current status and future perspectives. Renewable and Sustainable Energy Reviews, 74:1300-1313.

Leijon, M., Danielsson, O., Eriksson, M., Thorburn, K., Bernhoff, H., Isberg, J., Sundberg, J., Ivanova, I., Sjöstedt, E., Ågren, O., Karlsson, K.E., and Wolfbrandt, A., 2006. An electrical approach to wave energy conversion. Renewable Energy, 31(9):1309-1319.

Lejerskog, E., 2016. Theoretical and Experimental Analysis of Operational Wave Energy Converters. Uppsala University, PhD Thesis, Uppsala, Sweden, 68p.

Lockett, F.P., 1991. The CLAM Wave Energy Converter., International Mechanical Engineering Seminar on Wave Energy. London, UK.

Longuet-Higgins, M.S., Cartwright, D.E., and Smith, N.D., 1963. Observations of the directional spectrum of sea waves using the motions of a floating buoy. In Ocean Wave Spectra. Proceedings of a conference arranged by the National Academy of Science, Prentice Hall Inc. Englewood Cliffs, N.J., 111–136.

Maria-Arenas, A., Garrido, A.J., Rusu, E., and Garrido, I., 2019. Control Strategies Applied to Wave Energy Converters: State of the Art. Energies, 12(16):1-19.

Matas, A., 1992. Project OLAS-2000 Wave Energy in Spain, Proceedings of a workshop on Wave Energy R&D. Cork, Ireland.

MATLAB version 9a, 2009. Massachusetts: The MathWorks Inc 3 Apple Hill Drive.

McCabe, A.P., Bradshaw, A., and Widden, M.B., 2005. A time-domain model of a floating body using transforms. 6th European Wave and Tidal Energy Conference, Glasgow, UK.

Mistikoglu, S., and Yavuz, H., 2016. Quantized control settings based tuning of a heaving wave energy converter in irregular seas. International Journal of Green Energy, 13:1281-1291.

Miyazaki, T., 1995. Japanese Wave Energy Devices. Proceedings of the Second European Wave Power Conference, Lisbon, Portugal.

Nafey, A.S., and Sharaf, M.A., 2010. Combined solar organic Rankine cycle with reverse osmosis desalination process: Energy, exergy, and cost evaluations. Renewable Energy, 35(11):2571-2580.

Neill, S.P., and Hashemi, M.R., 2018. Fundamentals of Ocean Renewable Energy Generating electricity from the sea, Elsevier Academic Press, Cambridge, USA, 339p.

Newman, J.M, and Mei C.C., 1979. Wave power extraction by Floating bodies. Symposium on Ocean Wave Energy Utilization, Gothenburg, Sweden.

Nunes, G., Valerio, D., Beirao, P., and Costa, J.S., 2011. Modelling and Control of a Wave Energy Converter. Renewable Energy, 36(7):1913-1921

Olgivie, T.F., 1963. First and second order forces on a cylinder submerged under a free surface, Journal of Fluid Mechanics, 16:451-472.

Peatfield, A.M., 1991. The Economic Viability of the Circular Clam for Offshore Wave Energy Utilisation. International Mechanical Engineering Seminar on Wave Energy, London, UK.

Parmeggiani, S., Kofoed, J.P., and Friis-Madsen, E., 2013. Experimental Study Related to the Mooring Design for the 1.5 MW Wave Dragon WEC Demonstrator at DanWEC. Energies, 6:1863-1886.

Pelc, R., and Fujita, R.M., 2002. Renewable energy from the ocean. Marine Policy, 26:471–479.

Pierson, W.J., and Moskowitz, L., 1964. A Proposed Spectral Form for Fully Developed Sea based on the Similarity Theory of S.A. Kitaigorodskii. Journal of Geophysical Research, 69(24):5181-5190.

Rafiee, A., and Fiévez, J., 2015. Numerical Prediction of Extreme Loads on the CETO Wave Energy Converter. 11th European Wave and Tidal Energy Conference, Nantes, France

Renzi, E., Doherty, K., Henry, A., and Dias, F., 2014. How does Oyster work? The simple interpretation of Oyster mathematics. European Journal of Mechanics - B/Fluids, 47:124-131.

Qiao, D.; Haider, R., Yan, J., Ning, D., and Li, B., 2020. Review of Wave Energy Converter and Design of Mooring System. Sustainability, 12(19):1-31.

Olatomiwa, L., Mekhilef, S., Ismail, M.S., and Moghavvemi, M., 2016. Energy management strategies in hybrid renewable energy systems: A review. Renewable and Sustainable Energy Reviews, 62:821-835.

Sabuncu, T., 1983. Gemi Sevki, İTÜ Gemi İnşaatı ve Deniz Bilimleri Fakültesi Ofset Baskı Atölyesi, İstanbul, 219p.

Salter, S.H., Jeffrey, D.C., and Taylor, J.R.M., 1976. The architecture of nodding duck wave power generators. Naval Architect, 21-24.

Salter S.H., and Rampen, W.H.S., 1993. The Wedding Cake Multi Eccentric Radial Piston Hydraulic Machine with Direct Computer Control of Displacement. Proceedings of 10th International Conference, on Fluid Power, Brugge, Holland, 47- 64.

Salter, S., and Lin, C-P., 1995. The Sloped IPS Wave Energy Converter. Proceedings of the Second European Wave Power Conference, Lisbon, Portugal.

Shahzad, M.W., Burhan, M., Ang, L., and Ng, K.C., 2017. Energy-water-environment nexus underpinning future desalination sustainability. Desalination, 413:52-64.

Shwater Ltd, 1992. Bristol Cylinder Wave Energy Device; Consultancy to Review of Wave Energy. Shawater Ltd., ETSU Report Number WV 1692, 1992.

Spiegel, M.R., 1965. Schaums's outline of theory and problems of Laplace transforms. Schaum Publishing, New York, USA, 261p.

Stillwell, A.S., and Webber, M.E., 2016. Predicting the Specific Energy Consumption of Reverse Osmosis Desalination. Water, 8(12):1-18.

Suganthi, L., Iniyan, S., and Samuel, AA., 2015. Applications of fuzzy logic in renewable energy systems – A review. Renewable and Sustainable Energy Reviews, 48:585–607.

Tapered Channel Wave Energy, https://taperedchannelwaveenergy.weebly.com/howdoes-it-work.html [accessed 11.11.2021]

Thorpe, T.W., 1993. Methodology for Reliability and Economic Assessment. Wave Energy Converters: Generic Technical Evaluation Study, Danish Wave Power Aps.

Thorpe, T W, 1995. An Assessment of the ART OSPREY Wave Energy Device. ETSU Report Number R-90.

Thorpe, T. W., 1999. An Overview of Wave Energy Technologies: Status, Performance and Costs. ETSU Report Number R-120.

Van der Wal, A.J., 1995. Application of fuzzy logic control in industry. Fuzzy Set Systems, 74(1):33-41.

Vining J.G., Muetze A., 2007. Economic Factors and Incentives for Ocean Wave Energy Conversion. Industry Applications Conference, New Orleans, USA, 756-63.

Vining, J., 2005. Ocean wave energy conversion, ECE 699: Advanced Independent Study Report. University Of Wisconsin, Wisconsin, USA, 44p.

Wakeel, M., Chen, B., Hayat, T., Alsaedi, A., and Ahmad, B., 2016. Energy consumption for water use cycles in different countries: A review. Applied Energy, 178:868-885.

Wang, Z.; Zhang, Y.; Wang, T.; Zhang, B.; and Ma, H., 2021. Design and Energy Consumption Analysis of Small Reverse Osmosis Seawater Desalination Equipment. Energies, 14:1-18.

Weinstein, A., Fredrikson, G., Parks, M.J., and Nielsen, K., 2004. AquaBuOY - the offshore wave energy converter numerical modelling and optimization. Oceans '04 MTS/IEEE Techno-Ocean '04, 4:1854-1859.

White, P., 1989. Developments in Norwegian Wave Energy. Proceedings of a Conference on Wave Energy Devices, Coventry, UK.

Whittaker, T.J.T., 1995. Implications of Operational Experiences of the Islay OWC for the Design of Wells Turbines. Proceedings of the 2nd European Wave Power Conference, Lisbon, Portugal.

Yavuz, H., 2011. On Control of a Pitching and Surging Wave Energy Converter. International Journal of Green Energy, 8(5):555-584.

Yavuz, H., McCabe, A.P., Aggidis, G., and Widden, M.B., 2006. Calculation of the performance of resonant wave energy converters in real seas. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 220:117–28.

Yavuz, H., Stallard, T., McCabe, A.P., and Aggidis, G., 2007. Time series analysis-based adaptive tuning techniques for a heaving wave energy converter in irregular seas. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 221:77-90.

Zadeh L.A., 1965. Fuzzy sets. Information and Control, 8:338–353.

Zeng. H., 2012. Bio-Inspired Inertial Sensors for Human Body Motion Measurement. The Ohio State University. PhD Thesis, Ohio, USA, 113p.

Zhang, Y., Zou, Q.P., and Greaves, D., 2012. Air–water two-phase flow modelling of hydrodynamic performance of an oscillating water column device. Renewable Energy, 41:159-170.

CURRICULUM VITAE

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APPENDIX

A.1. PUBLISHED ARTICLES

Burgaç, A., and Yavuz, H., 2019. Fuzzy Logic Based Hybrid Type Control Implementation of a Heaving Wave Energy Converter. Energy, 170:1202-1214.

Burgaç, A., and Yavuz, H., 2020. Power Capture Performance of a Heaving Wave Energy Converter for Varying b(rad)/b(pto) Ratio. SN Applied Sciences, 2:1-10.

Burgaç, A., and Yavuz, H., 2021, Renewable Energy Based Freshwater Production Utilizing Reverse Osmosis Desalination. Energy Sources, Part A: Recovery, Utilization and Environmental Effects.

A.1. CONFERENCE PAPERS

Burgaç, A. and Yavuz, H., 2016. Control Techniques for Oscillating Wave Energy Converters. IRENEC, 6th International %100 Renewable Energy Conference, İstanbul, Turkey.

Burgaç, A. and Yavuz, H., 2017. Fuzzy Logic Based Complex System Control Implementation on Wave Energy Converters. 10th International Conference on Sustainable Energy & Environmental Protection, Bled, Slovenia.

Burgaç, A., and Yavuz, H. 2017. Evaluation of a new hybrid tuning technique for optimum operation of heaving type Wave Energy Converters. 1st International Advanced Researches Engineering Congress, Osmaniye, Turkey.

Yavuz H., ***Burgaç A.,*** and Akbıyık, H., 2018. Active tuning based fuzzy logic control of a heaving wave energy converter in irregular seas. 3rd Renewable Energy Sources - Research and Business RESRB

Burgaç A., and Yavuz, H., 2019. A Research of the Damping Coefficient Effect on Power Capture Performance of a Heaving Wave Energy Converter 6th International Multidisciplinary Studies Congress, Gaziantep, Turkey.