Final report

This report follows the template provided by Energistyrelsen “template_-_final_report.doc”. The headings of the sections are specified by the template, and contents are as described in the guidelines to the template.

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1.1 Project details

Project title	Digital Hydraulic Power Take Off for Wave Energy
Project identification (program abbrev. and file)	ForskEl12155
Name of the programme which has funded the project	ForskEl
Project managing company/institution (name and address)	Department of Civil Engineering, Aalborg University, Thomas Manns Vej 23, 9220 Aalborg
Project partners	1) Aalborg University, Department of Civil Engineering (AAU-CE). 2) Aalborg University, Department of Energy Technology (AAU-ET). 3) Aalborg University, Department of Electronic Systems (AAU-ES). 4) Floating Power Plant (FPP) 5) Fritz Schur Energy (FSE) 6) Wave Star (WS) NB: • Wave Star A/S resigned from the project by May 12th 2016 due to financial reasons • FSE and FPP replaced Wave Star during the final part of the project, starting on 1 September 2016
CVR (central business register)	29102384
Date for submission	12 September 2013 (application) 31 December 2018 (final report)

1.2 Short description of project objective and results

English version

The project focussed on further development of a digital hydraulic Power Take Off (PTO) system for wave energy conversion. The project has brought together the strongest Danish expertise in this research field. Methods related to experimental testing in wave basins have been developed and huge amounts of data acquired. The further development of two large digital hydraulic PTO test rigs were completed with success. The two test rigs are both placed at Aalborg University, where they can be visited and used in the future. The results of the project are widely disseminated and used by scientists and developers all over the world, and new projects and further developments are planned by the project partners to follow up and continue the development within this R&D field.

Dansk version

Projektet omhandlede en videre udvikling af et digital-hydraulisk Power Take Off (PTO) system til omformning af bølgeenergi til elektricitet. Projektet har samlet de største danske aktører indenfor dette forskningsfelt. Der er udviklet metoder i forbindelse med forsøg i bølgebassiner, og der er indsamlet store mængder data. Den videre udvikling af to store digital-hydrauliske PTO testopstillinger blev afsluttet med succes, og de to testopstillinger er nu placeret på Aalborg Universitet, hvor de stadig kan besøges og anvendes fremadrettet. Projektets resultater er formidlet bredt og bruges af forskere og udviklere over hele verden, og projektpartnerne planlægger nye projekter og yderligere udvikling af PTO-koncepterne for at følge op og fortsætte udviklingen inden for dette R&D område.

1.3 Executive summary

The overall goal of the project was to reduce the Cost of Energy (CoE) from wave energy converters (WECs) by incorporating and improving a new and innovative type of PTO by using digital hydraulics. In brief this was fulfilled by outlining the following tasks in the project:

a) Perform numerical and **small-scale laboratory array interaction tests**

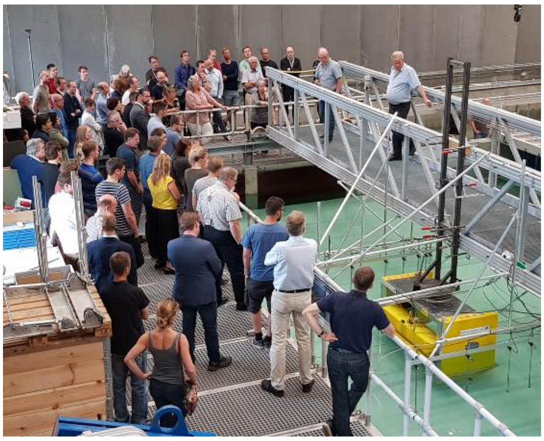
b) Further develop **full-scale digital hydraulic PTO system**.

c) Apply existing methods and do further development on fatigue analysis, **reliability and risk assessment strategies for a digital hydraulic PTO**.

d) **Measure in reality prototype performance of the digital hydraulic PTO** which Wavestar plans on implementing at their demonstrator test machine at Hanstholm.

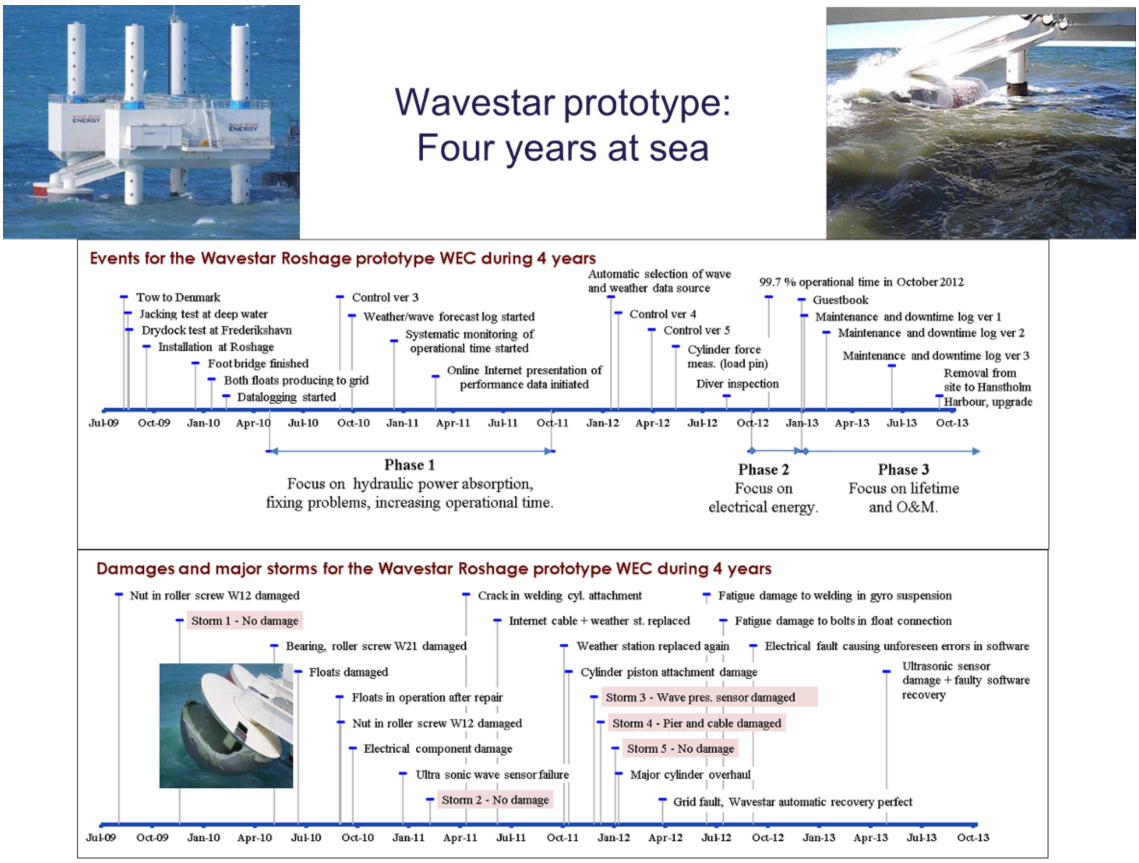
e) Investigate **new control strategies to maximize the power output** of a highly efficient PTO while the minimization of structural loads is taken into account.

The project was successful in all these tasks, except for bullet d "prototype measurements". Tests with a digital hydraulic system could not be done as the Wavestar prototype at Hanstholm was discontinued before the system was ready for implementation. The main results of the other tasks are summarised in the following.
Experimental testing in the wave basins at Aalborg University were completed during several test campaigns with various setups and with both Wavestar and FPP models. Some testing were done in collaboration with master and PhD students, and several test campaigns were completed as part of PhD courses and master courses, most times in the facilities at Aalborg University, but also two times at other facilities (at the wave basin in Nantes in France and Cork in Ireland). The data has been used in many research papers, and researchers from all over the world (more than 100 people in total from more than 20 different countries, out of this more than 50 were PhD students) has actively directly participated and gained knowledge from the work. The testing has also attracted a lot of public interest, with numerous visits, interviews to journalists, TV-shows, youtube, facebook and linkedin posts,... New and innovative strategies for procedures and methods for Wave Energy Converter (WEC) testing have been developed through the period. The new methods and procedures were extended beyond state of the art for how to perform testing on WECs for model validation, so teaching materials has been modified and lectures at courses and workshops were given to spread this knowledge.

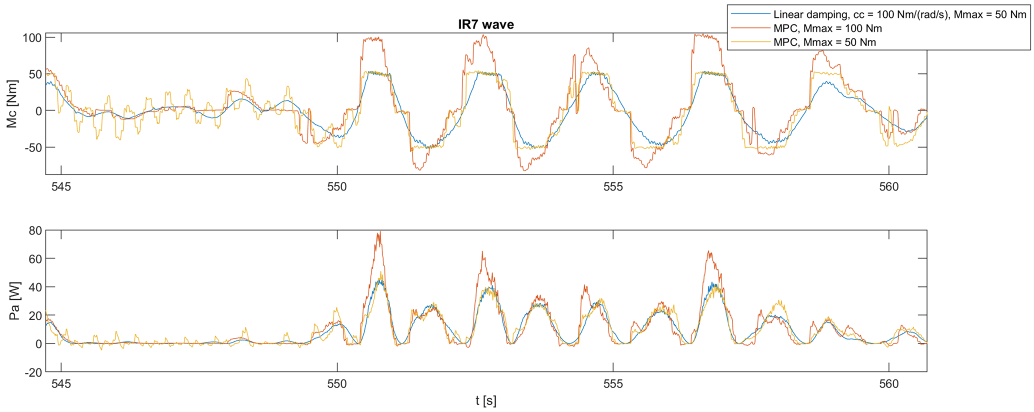


In the project one of the main deliverables were the further development of two large digital hydraulic PTO test rigs. The first test rig was a large scale (~100 kW) used for the wave energy converter Wavestar, where the focus was dedicated to a system based on reactive control, i.e. control where negative power is allowed. The second test rig was a small scale (~3 kW) made to be used for Floating Power Plant, where the control was resistive, meaning that only positive power absorption was allowed. The two test rigs are both placed at Aalborg University, where they can still be visited and used anytime. Both test rigs are currently (end of 2018) used in the further research & teaching, and new research projects are planned to follow up on the current project. As was the case for the wave basin experiments there has been and still is a huge interest and interaction with students, the academic society and the general public.

The third objective "reliability and risk assessment strategies for a digital hydraulic PTO" was completed through a desk study by analysing measured data from the wave basin tests, the digital hydraulic test rig, and from 4 years of data acquired at the Wavestar prototype. The outcome has been new methods and procedures which has been disseminated in scientific papers and teaching material.



The last subject in the project was focussing on new control methods to maximise power output and at the same time minimise structural loads. A method termed Model Predictive Control (MPC) was developed for use with WECs with a simplified controller, and the different versions were tested numerically and experimentally during the test campaigns. The developed method shows a very high potential to increase the power in a good and safe manner, as structural loads and motions can be accurately predicted and controlled by this method. Hereby events, which could otherwise lead to damage, can be predicted and the controller can circumvent problems such as the cylinders hitting the end-stops in high energetic seas. The methods developed are highly advanced and very complicated mathematically, and the stability of the controller has proved to be rather problematic. There is a large potential for further development to be used and optimised in a real case digital hydraulic system. Further R&D is needed within this field before the methods are suited for real-life implementation.



1.4 Project objectives

The project did not evolve as expected, as Wavestar about 2/3 into the project had to resign from the project due to financial reasons. Wavestar was previously the leading Danish wave energy developer, and therefore the main intention of the project was to develop a PTO solution focussing specifically on an optimised solution for the Wavestar WEC. Luckily, when Wavestar resigned, two new partners, Floating Power Plant and Fritz Schur Energy, agreed to replace Wave Star in the project. Some small adjustments to the original project plan were scheduled for the finalization of the project, and this plan was followed to successfully finalise the project, - although with one year delay. The concepts of FFP and Wavestar are rather similar; the motion of multiple floats are capturing the wave energy using hydraulic cylinders, and the captured energy is transferred into electricity using a digital hydraulic system. Therefore, the FPP concept was ideal for taking over Wavestar's role in the project. The new partners further offered new fabulous opportunities, which were not present in the original project. The original project did not include a company specialized in hydraulics. With FSE in the project, it was ensured that the results are anchored and used directly in the Danish private industry.
The continued work with FPP and FSE focussed on extended testing on a new digital hydraulic test bench, and the lab-scale FPP float was equipped with the same kind of sensors that were originally planned for use with the Wavestar prototype. Finishing the project with the new partners required some minor changes to the WPs, and some new tasks were completed as described in the following. A number of already finished tasks and deliverables were updated for use with FPP as "a version 2".

Overview of first set of changes (initiated by 1 September 2016)

The existing purposes from the original application are listed below in bold font type with comments for the actual adjustments in italic. The changes are described in detail in a separate note "Continuation of the ForskEl12155 project with new partners" which was approved by EUDP before the initiation. The following text is from this note.

a) **Perform numerical and small-scale laboratory array interaction tests**.
FPPs wave absorbers are placed perpendicular to the wave direction, as opposed to the Wavestar absorbers parallel to the wave direction, the local array interaction is therefore negligible. However, small scale lab tests are still highly relevant. Existing models and hardware already installed at AAU can be used and significantly reduce the cost of this. To provide the data needed for the project new lab tests with FPP will focus on measurements of the forces on the bearings in combination with the control and dynamics induced by the digital hydraulic PTO used by FPP (which is to be developed, see bullet "b" below).

b) **Further develop full-scale digital hydraulic PTO system**.
The layout and specific component types and characteristics of the digital hydraulic PTO system for the full-scale FPP must be developed. FSE will lead the design, layout, and modelling work.

c) **Apply existing methods and do further development on fatigue analysis, reliability, and risk assessment strategies for a digital hydraulic PTO**.
Continued work on models and methods will use new data for FPP instead of Wavestar. Data will be measured in the wave laboratory and on the test rig on the FPP system.

d) **Measure in reality prototype performance of the digital hydraulic PTO**.
FPP are not planning any offshore tests during the rest of this project. However, the digital hydraulic test stand at AAU can be modified for testing the FPP PTO. The plan is therefore to update the software in the test rig to enable simulation of the FPP WEC. Further, the lab-scale FPP model will be instrumented in the same manner as the original plan was with the Wavestar prototype, i.e. using pressure sensors in the float shell and force sensors by the two main bearings. Hereby the performance of the digital hydraulic PTO can be examined with good accuracy.

e) **Investigate new control strategies to maximize the power output**.
The existing models were developed for use with Wavestar. The models and control strategies will be updated to be used for FPP, and new simulations will be reported.

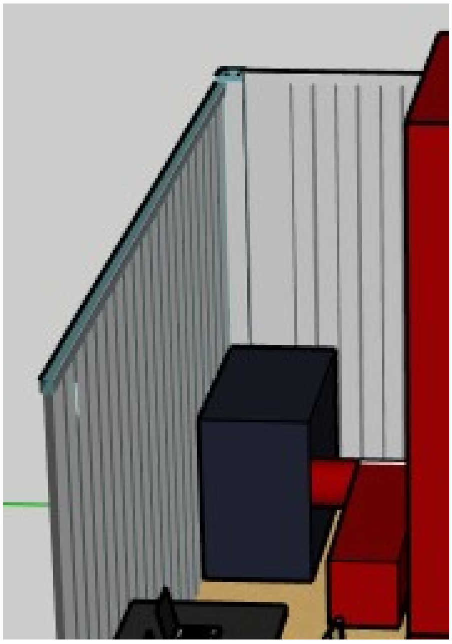
Apart from the changes/comments to the original project purposes mentioned above, some changes and additions to the previous project focuses are relevant. Either because they are a prerequisite for one of the purposes or because a changed focus is more relevant in a FPP context. The main adjustments in relation to FPP are listed below:

- **Basic design and definition of the full-scale digital hydraulic PTO system for FPP (termed "FPP P80 PTO")**.
  This will be the reference design that is relevant to all other work in the project. The reference design must be accompanied by a set of operational parameters.
- **Development of PTO simulation code**.
  A good PTO simulation code is needed for both the PTO test rig and the small-scale lab tests. The developed code will have many synergies with other FPP projects.
- **Research / testing of digital hydraulics valve shifting**.
  The layout of FPPs PTO system is somewhat different from that of Wavestar, as is the control strategy. With a modified hydraulic test stand at AAU, valve shift testing more relevant to FPPs PTO can be carried out. Focus will be shifted towards reducing loads and losses when shifting out a piston area during compression.
- **Model / sensor driven control strategy**.
  The current control strategy of the FPP PTO is reactive and based only on internal PTO parameters and static lookup values. Adopting concepts such as "model predictive controller" and external sensor (e.g. wave sensor) based control is expected to increase the energy capture. By using numerical models for Wavestar it has previously been demonstrated that such strategies can increase power and lower CoE. It is relevant to explore these concepts with FPP first in models, and later also in the lab tests.

<u>Overview of second set of changes (initiated by June 2018)</u>

The second and last significant change to the project was done in the final year of the project. The change is described in the note "Budgetændring for ForskEl12155, 13. juni 2018", which was submitted and approved by EUDP. The note is in Danish, and only the main contents are extracted in the following.

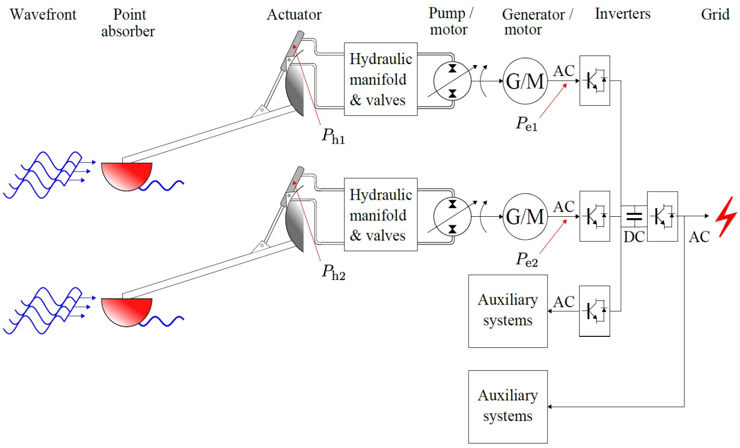
The previous plan was, that the existing Wavestar digital hydraulic test rig should be modified to be operational with the FPP type of system. Unfortunately, this turned out to be not only very costly but also not optimally feasible for the FPP type of system. Further AAU used the existing test rig in the actual configuration in various research and industrial projects, and therefore there was a wish for keeping the test rig unmodified. Luckily another possibility turned up – FPP had an old test rig, which with modifications could be used in the project. FPP agreed to make the modifications to the test rig, and the test rig was put into a container, modified and upgraded, and transported to AAU where testing was completed. FPP agreed that the test rig can stay at AAU available for further research, also after the termination of this project. This gives AAU the fabulous possibility to strengthen and directly continue the research after the project is officially finished.



1.5 Project results and dissemination of results

During the first part of the project Wavestar was a partner and the project focussed on the Wavestar machine, whereas when Wavestar exited the project and the partners FPP+FSE entered the project the project shifted focus to the FPP machine. The first part of the following therefore focusses on the results obtained with Wavestar, whereas the latter part focusses on FPP.

Initially in the project existing data from the Wavestar prototype were analysed to get a base-line for further improvements. The Wavestar prototype was installed in the North Sea in 2009 and it produced electricity to the grid for nearly 4 years from 2010 to 2013. In 2013 it was decided to pause the WEC as all possible tests had been made on the current configuration of the machine. Based on the lessons learn from the existing PTO system, it was concluded that the efficiency of the PTO was insufficient to generate power at a reasonable Cost of Energy (CoE). The Wavestar prototype PTO system was built around a traditional hydraulic system with a cylinder, a swatch-plate hydraulic pump coupled to a generator. Each float was separately controlled for testing and improvement purposes. Analysis of the data showed, that after optimization the prototype PTO had an efficiency of about 60%, excluding electrical loses in the WEC. An overall efficiency of an optimised system was estimated to be about 50 %.

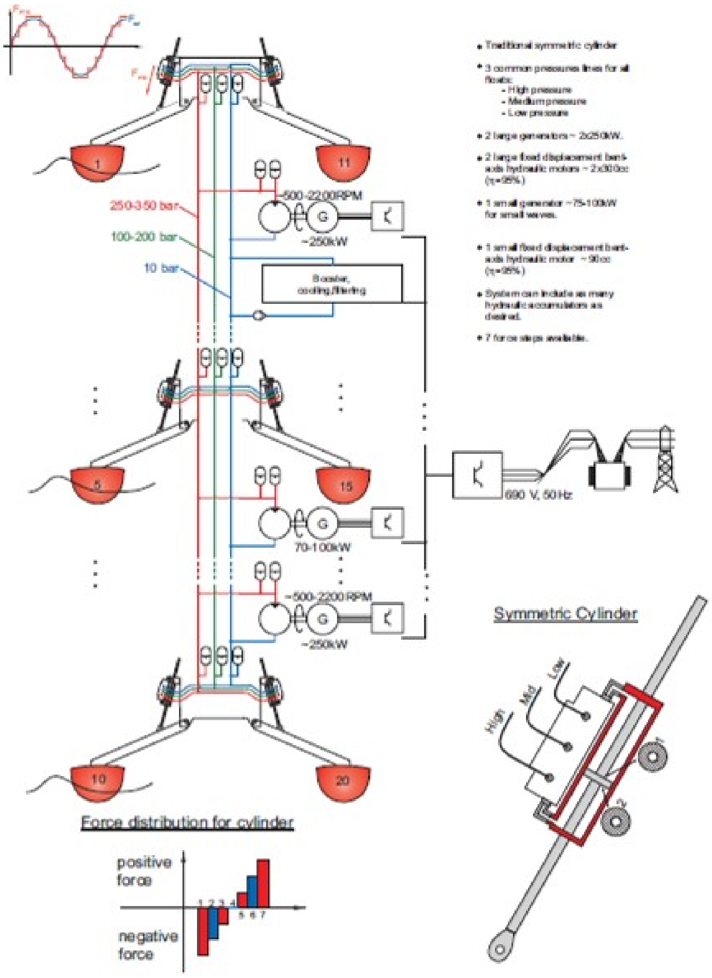


Float 1 & 2									
Month	Operational time (of total time) [%]	Production [%]	Storm (of operational time) [%]	Calm sea [%]	Transitions [%]	Harvested hydraulic energy [kWh]	Generated electrical energy [kWh]	PTO efficiency [%]	Max generated electrical power [kW]
Sep-10	9.8	54.1	9.9	0.0	35.9	739	-69	-9.4	23.6
Oct-10	7.6	88.3	1.5	0.0	10.2	1064	149	14.0	22.9
Nov-10	14.4	73.7	6.1	7.3	13.0	2101	460	21.9	24.7
Dec-10	28.1	73.3	5.2	14.7	6.7	1880	43	2.3	23.4
Jan-11	81.7	80.6	0.0	18.3	1.1	7521	918	12.2	23.1
Feb-11	66.1	59.6	21.5	15.3	3.5	3265	-104	-3.2	25.0
Mar-11	64.1	61.7	3.9	32.4	2.0	5469	790	14.4	23.4
Apr-11	23.1	47.7	14.3	32.0	5.9	830	105	12.7	25.9
May-11	90.7	55.6	2.5	38.8	3.2	4859	827	17.0	25.8
Jun-11	92.3	44.8	3.2	49.8	2.2	4420	1111	25.1	23.2
Jul-11	90.3	71.7	0.8	24.7	2.7	5278	992	18.8	21.5
Aug-11	93.4	61.0	6.4	31.2	1.4	4721	1128	23.9	28.1
Sep-11	78.6	63.3	11.3	23.7	1.7	4941	1127	22.8	25.3
Oct-11	68.6	70.5	3.7	24.1	1.7	6790	3524	51.9	29.0
Nov-11	46.3	36.2	11.8	50.2	1.7	1256	666	53.0	15.9
Dec-11	16.7	73.4	12.7	0.1	13.8	1272	715	56.2	16.3
Jan-12	1.5	77.0	0.0	0.0	23.0	62	24	39.4	4.5
Feb-12	98.4	66.4	9.3	22.3	2.0	5915	3210	54.3	32.8
Mar-12	96.5	79.1	1.0	19.1	0.8	8465	4920	58.1	35.7
Apr-12	93.2	62.3	0.2	35.0	2.5	5131	2901	56.5	30.0
May-12	49.1	63.1	1.8	33.6	1.4	3582	2184	61.0	23.6
Jun-12	88.8	54.4	0.1	44.2	1.4	5129	3185	62.1	27.1
Jul-12	68.8	55.9	0.0	43.1	1.0	3534	2114	59.8	26.1
Aug-12	88.4	40.1	0.1	59.4	0.4	3881	2377	61.2	26.5
Sep-12	84.1	93.3	0.3	5.8	0.7	7752	4599	59.3	23.3
Oct-12	99.7	75.8	0.3	22.9	1.1	8943	5507	61.6	30.1
Nov-12	99.3	90.0	0.9	8.1	1.0	8475	5041	59.5	32.1
Dec-12	99.2	81.2	2.0	15.1	1.8	8544	5046	59.1	32.4
Jan-13	99.7	70.0	4.1	23.4	2.5	7328	4289	58.5	41.6
Feb-13	80.4	74.9	3.8	19.9	1.4	5254	3009	57.3	35.1
Mar-13	99.1	72.3	0.7	25.7	1.3	7261	4227	58.2	29.2
Apr-13	98.6	66.3	1.9	30.3	1.5	5690	3312	58.2	36.8
May-13	73.3	63.9	0.0	35.2	0.9	2582	1314	50.9	23.3
June-13	99.4	56.0	0.0	43.3	0.7	5784	3583	62.0	28.2

The use of digital hydraulic and optimized control system preliminary showed a potential of getting the efficiency close to 80% in any sea state.

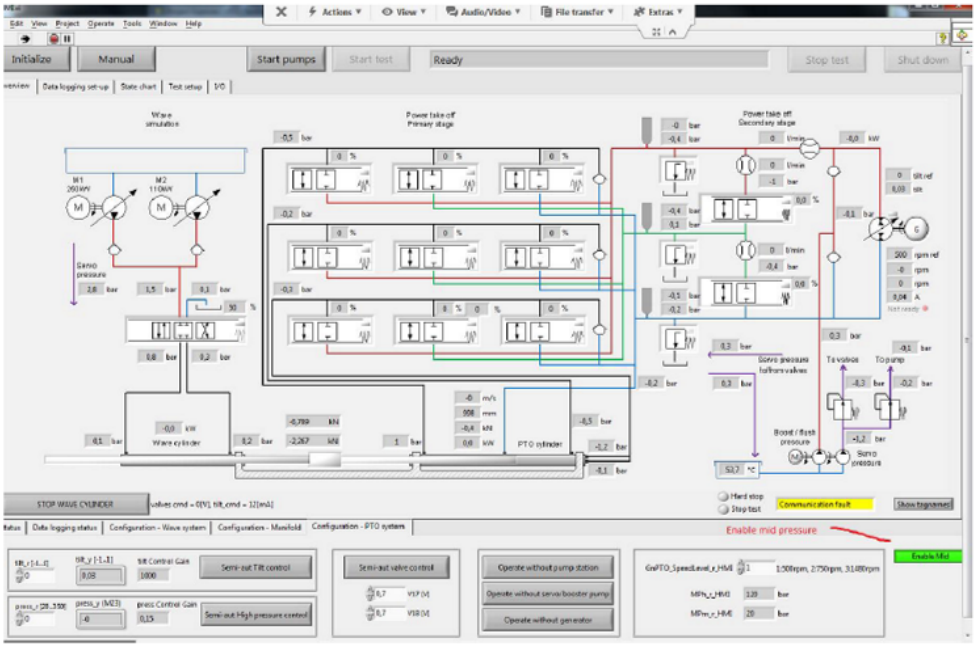
Analysis of the optimal system topology

The concept of the digital hydraulic PTO was developed and the focus was on a complete system, which could be use on the commercial Wavestar WEC with 20 floats in operation.



The main idea of the concept was to use different pressure lines (high, medium and low) combined with a range of accumulators on the lines, and connect the high pressure line to a range of hydraulic motor-generator, which were started one by one dependent to the sea state (few generator running in small waves and all generators in high waves). In that way, each generator performs close to optimal and provides a high efficiency.

A topology has been developed for the test bench facilities, taking into account the future components to be used on the WEC.



The building of the Wavestar digital hydraulic test bench was already initiated when the current project started. The test bench consist of a wave generator (hydraulic cylinder simulating the wave displacement), a multi-chamber PTO cylinder to extract the energy from the waves, a switching manifold with high speed valves, three separate pressure lines, an hydraulic motor and a generator to produce energy to the grid. The system allows to run different sea states and to test control strategies on the PTO manifold.

First version of switching manifold using proportional Parker valves

A model was developed to verify the dynamic properties of the all system and to analyse the switching time and strategies to be applied. This allowed the team to define the opening and closing characteristics of the valves and to develop new and better control strategies and numerical models for the Wavestar converter.

The results below show the performance in three irregular waves with reactive control. The efficiency is measured for the hydraulic power generated by the cylinder to the power received by the hydraulic motor. The test results show efficiency between 88.5-90.5% using reactive control.

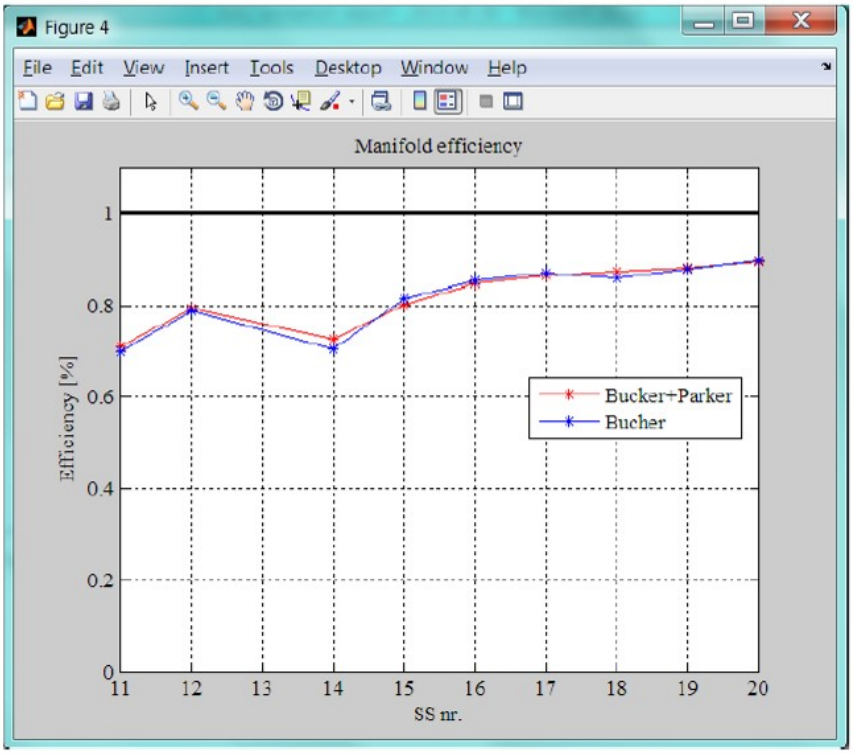
	P_in_avg	P_out_avg	P_in_peak	Eff DDC	Bc [SI]	Kc [SI]
H_m0=1.8,T_02=4.5	15.19 kW	13.76 kW	80 kW	90.57%	10e5	-7e5
H_m0=1.3,T_02=4.5	9.67 kW	8.59 kW	75 kW	88.81%	7e5	-7e5
H_m0=1.3,T_02=3.5	8.3 kW	7.35 kW	75 kW	88.58%	6e5	-7e5

Table 1: Tested sea states and results

The results demonstrate that the use of the digital hydraulic system together with the switching manifold apparently met the requirements. However, there was a huge issue with the first version – the Parker valves required hydraulic power for the control, and the stand-by consumption for driving them was relatively too large to be economic feasible, as it is shown subsequent in the section about CoE.

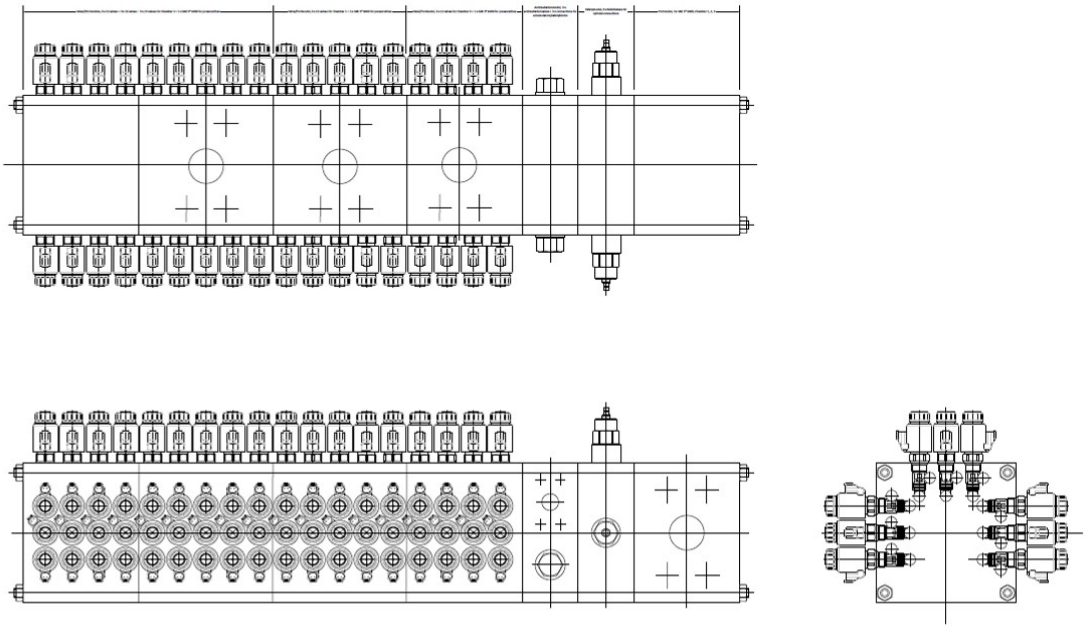
Development and optimization of switching manifold

Besides the large stand-by consumption of the Parker valves the system was also unsuitable for future upscaling of the system, as the costs were increasing inappropriately for larger systems. It was decided to change to another on/off type of valves from the company Bucher. The existing Parker valves were replaced on the existing manifold by the new developed on/off valves from Bucher, capable of taking high flow and having a response time of less than 15ms. The same efficiency results of the manifold were obtained using the Bucher valves as with the Parker valves.



Comparison of the use of Parker and Bucher valves for Digital hydraulic PTO.

The efficiency of the manifold was tested with the new valve configuration together with the cylinder efficiency and a new control system.



New manifold design with Bucher high speed valves installed on the test bench

The results showed a very efficiency of the system, with an average efficiency around 84%.

eta[%]		T0,2		
		3,5	4,5	5,5
Hm0	0,25	-	-	
	0,75	70	70	
	1,25	79	81	
	1,75		85	86
	2,25		87	88
	2,75			90

Efficiency results for different sea states. Efficiency of the system depending on wave height (Hm0 in m) and wave period (T0,2 in s), the efficiency is given in %

Development of control strategies

Different control strategies for control of the PTO were tested and improved during the project. For the PTO one of the focusses has been on the valve switching time. Several algorithms were developed and tested with the Bucher valve configuration in order to decide on the final configuration.

Efficiency	T = 50 s	T = 100 s	T = 150 s
Algorithm A2	82.18%	81.34%	80.43%
Algorithm A4	82.05%	79.51%	75.70%

Parallel to this, testing and optimisation was done experimentally in the wave basin at AAU.

The PTO test with the new control settings have been repeated in the configurations in the basin. These measurements form the basis for a complete analysis of the data (efficiency, loads transfer, adjustment of parameters). Further the use of Model Predictive Control (MPC) was explored, by taking account of not only optimal power absorption but also the influence of the loads on the structure and on the PTO.

Cost of energy

The benefit by the updated PTO systems on the global Cost of Energy for the Wavestar WEC is shown below. For comparison a reference case with the conventional hydraulics is included as Case A, with an efficiency of about 50%. The CoE has been calculated for different cases using the new digital hydraulic PTO together with the Parker valves configuration or the Bucher valves configuration; the cases take also in consideration the standby consumption of the valves. It is seen that the use of digital on/off valves (2nd and 3rd generation digital PTO, Case C and D) provides a significant reduction of the CoE. It should be noted that Case D was not finalised when Wavestar stopped, and the results in the table were based on preliminary indications.

Case	**PTO type**	**PTO cost [*1000 EUR]**	**PTO eff. (%)**	**Yearly energy excl. stand by [MWh]**	**Stand-by [kW]**	**Yearly energy incl. stand-by [MWh]**	**Total CoE [EUR/kWh]**	**CoE reduction ref. case A [%]**
A	Conventional PTO solution (like existing Hanstholm PTO with one pump per float)	1400	50	1097	18	940	1.81	0
B	1st generation digital PTO (Parker valves)	935	70	1754	112	685	2.40	-32
C	2nd generation digital PTO (Bucher valves)	784	70	1754	34	1395	1.12	+39
D	3nd generation digital PTO	500	80	2119	10	2032	0.78	+57

The key hypothesis of the project was, as stated in the application, that
It is possible to reduce the Cost of Energy from Wave Energy Converters by utilizing Digital Hydraulic Power Take Off.

The results obtained in the project has demonstrated that this statement is indeed true.

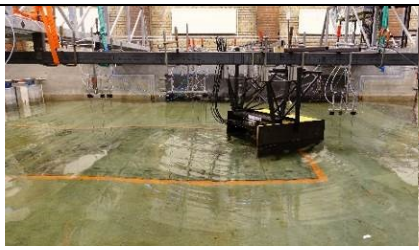
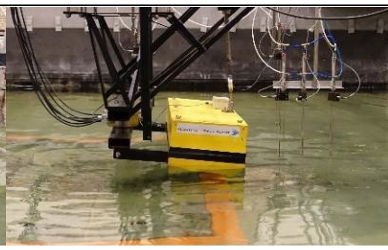
Experimental flume and basin tests on the FPP device

The experimental small-scale wave basin testing of the FPP device was following up on previous tests in the FPP series of tests termed Commercial Design Development (CDD). The project took the development from the last part of CDD3 (first table below) and onto CDD6 (fourth table below). Funding for the CDD5 tests at Oceanide in France was received from the EU project Marinet 2.

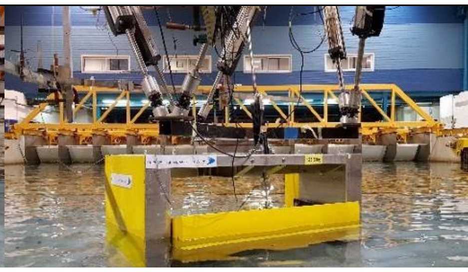
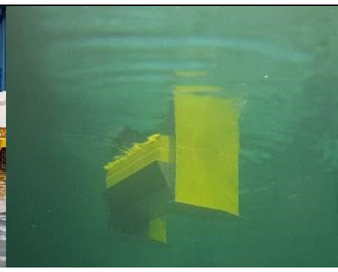
Name	Test CDD3
Date	2015-2016
Location	Aalborg University (AAU), Aalborg, Denmark (old facility)
Type	Wave flume
Description	A new foam model was built with precise specifications (mass, moment of inertia, centre of gravity). Variations of configurations of the single absorber and a substructure were tested in a large range of wave conditions. Different ballast conditions were also tested. A linear actuator is used for the PTO in a large enough scale to allow the application of accurate control algorithms. The main aim was to obtain highly accurate data for comparison to numerical model calculations.
Scale	1:30 scale of the P80
Key Results	Data from motion sensors, pressure sensors, wave gauges and PTO was acquired for a large range of hydrodynamic configurations. The high level of detail allowed for validation and extension of single degree of freedom numerical models



Name	Test CDD4
Date	2016-2017
Location	Aalborg University (AAU), Aalborg, Denmark (old facility)
Type	Wave basin
Description	The same foam model as used in Test CDD4 was moved to a wave basin. Variations of configurations of the single absorber and a substructure were tested in a large range of wave conditions with different PTO strategies
Scale	1:30 scale of the P80
Key Results	The effects of the wave flume walls were eliminated, created a 3D wave field. Data from motion sensors, pressure sensors, wave gauges and PTO was acquired for a large range of hydrodynamic configurations. Power calculations were validated for different PTO control strategies. The effects of asymmetry were analysed and modelled

Name	Test CDD5
Date	2017
Location	Oceanide, France
Type	Wave basin
Description	A new foam model was built, representing a single double-width absorber within the starboard half of the substructure. The substructure was attached to a robot called a hexapod which moved the substructure with a precalculated motion in both individual and combined degrees of freedom. The same linear actuator PTO was used as Tests CDD3 and CDD4, allowing accurate application of PTO algorithms. The absorber was allowed to pitch relative to the moving substructure in reaction to the incoming waves.
Scale	1:30 scale of the P80
Key Results	The interaction effects within the numerical models were validated for the relative motion between the substructure and the absorbers

Name	Test CDD6
Date	2018
Location	Aalborg University (AAU), Aalborg, Denmark (new facility)
Type	Wave basin
Description	The same device as Test CDD5 is further tested in the new AAU facility with two main purposes: 1) Testing advanced PTO algorithms and 2) Detailed investigation of the interaction effects caused by the chamber surrounding the absorber. Wave measurements inside the chamber were acquired.
Scale	1:30 scale of the P80
Key Results	The MPC model was demonstrated to provide a high power absorption and at the same time keep the motions and forces within defined limits. However, the stability of the MPC proved to be problematic. Waves inside the chamber are strongly affected by the chamber geometry.


PTO test rig for resistive digital hydraulic control, the FPP test rig

During the summer of 2018 it was decided in the project consortium that the best option for fulfilling the plans for performing "dry-tests" of the developed PTO control strategies on a PTO test stand that realistically can represent FPPs PTO system, was to repurpose FPP's existing PTO test-stand. The repurposing of the existing test-stand had three principal elements. The test-stand hardware had to be upgraded to provide higher peak input power and improved data logging; the test-stand had to be moved from FPPs Bandholm office to AAU; a closed loop model driven wave and absorber emulator had to be implemented.

A plan and a budget for how to achieve this were quickly developed and submitted to the ForskEl project officer as a request for a budget change. The request was approved in June 2018 and the work were quickly started. In the following the modifications performed to the test-stand in order to fulfil the new purpose within the "digital hydraulics" project is described.

FPP's existing test-stand was originally constructed as part of FPP's offshore tests of the half scale prototype P37. The test stand consists of a PTO house and a dry-test foundation with a test cylinder. The PTO house were the same unit that were also tested offshore on the P37 platform. The dry-test foundation and test-cylinder were used to commission and improve the PTO-system before and after offshore tests. During dry-testing the test-cylinder were controlled by the PTO control system in a closed loop position mode.

Figure 1. The P37 PTO system during dry testing between offshore tests.

Figure 2. The (same) PTO system on the P37 platform during offshore testing.

In order to both make the necessary modifications and upgrades in the cheapest possible way, and get the system up and running quickly and easy after it was shipped to AAU it was decided to put the entire test-stand in a shipping container.

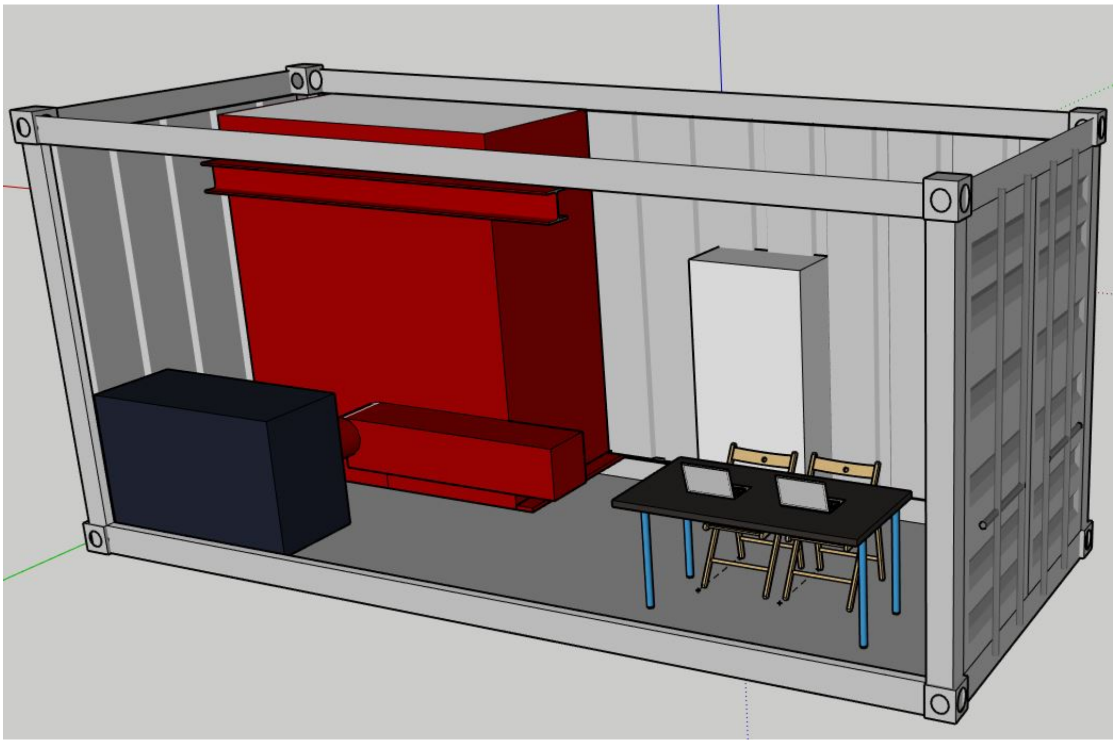


Figure 3. Principle illustration of the PTO test-rig build into a shipping container.

In the original test-rig setup the PTO house was placed on top of the dry test foundation, with the test cylinder fitted between the two. This setup was too high to fit inside a standard shipping container. However, if the PTO were placed directly on the floor, and some excess part of the top PTO house were removed, then it would just exactly be possible to fit the PTO house inside a high-cube shipping container. This setup required that the test-cylinder were fitted above the torque arm of the PTO house, and attached to a new support beam welded to the side of the PTO house. To make it possible to mount the test cylinder above the Torque arm the “head” of the arm were cut off and turned upside down and reattached. At the same time a HEB beam with a cylinder attachment bracket were fitted on the side of the PTO house. The physical / steel modifications were completed, and the PTO house were thoroughly cleaned and repainted. The top flange of the PTO oil tank was also removed, and the tank was visually inspected. A visual inspection of the tank is very complicated after installation in the container due to low headspace over the tank. When the physical modifications off the PTO house were completed, the PTO house and other components were installed in the container.

Figure 4. The modified and repainted PTO house are being pushed into the container.

In order for the test-cylinder to operate in a model-driven closed loop, the control of the cylinder was moved from the existing Siemens industrial servo controller into a compiled real-time Simulink model. For this purpose, a new junction box was built. The junction box contains a National instruments I/O connection plinth and terminals that connects to the proportional valve on the test-cylinder and to position and cylinder pressure signals from the PTO control system. The junction box was built and wired such that the container could be delivered in Aalborg with the test-cylinder control still controlled by the Siemens controller. But with the option for easily switch to xPC / Simulink control once the new controller hardware was installed.

In the hydraulic system of the PTO system the cylinder area selection valves were changed to soft shift valves. A new pressure sensor measuring the hydrostatic pressure at the bottom of the oil tank were installed. The whole hydraulic system had a service where filters were changed, oil topped op, accumulator pre-charge pressure were checked etc. In the Test-cylinder / HPU hydraulic system, an extra accumulator was added to the HPU. At the same time flow restrictors in the accumulators were removed. Bot modifications to enable a higher peek flow/power from the HPU. The test-cylinder was installed and fitted with new custom-made hoses. A defective pressure controller was repaired, and the pressure control were optimized.

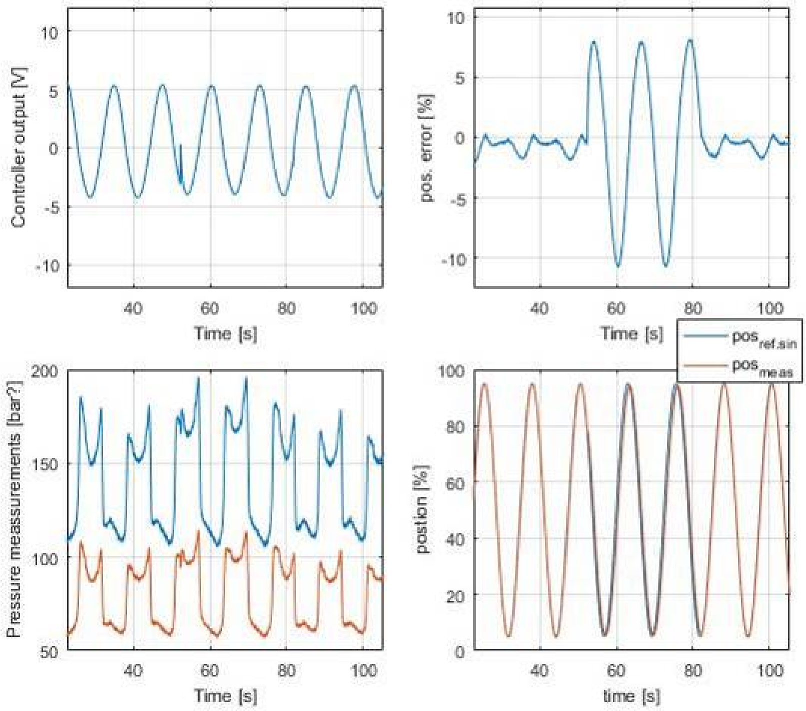
The modifications of the PTO house and installation of units in the container, were carried out at FPPs address in Bandholm Lolland. FPP shares address with the company BM steel construction who carried out the main steel work and mechanical installation. Electrical installations and modifications were carried out by FPP at the Bandholm location.

Figure 5. Loading of the container in Bandholm.

After installation in Bandholm the container was transported to Fritz Schur Energy's workshop in Albertslund. Here the hydraulic system was modified and upgraded, and the finished system was tested. After the testing the container was made ready for shipping and transported to Aalborg.

The code in the Siemens PTO controller and the datalogging python script were changed to fit with the changed hardware and to increase the datalogging rate. The implementation of the of the new test-cylinder controller based on a real-time model of the wave and wave absorber interactions with the PTO system were performed by AAU-ET and AAU-CE.

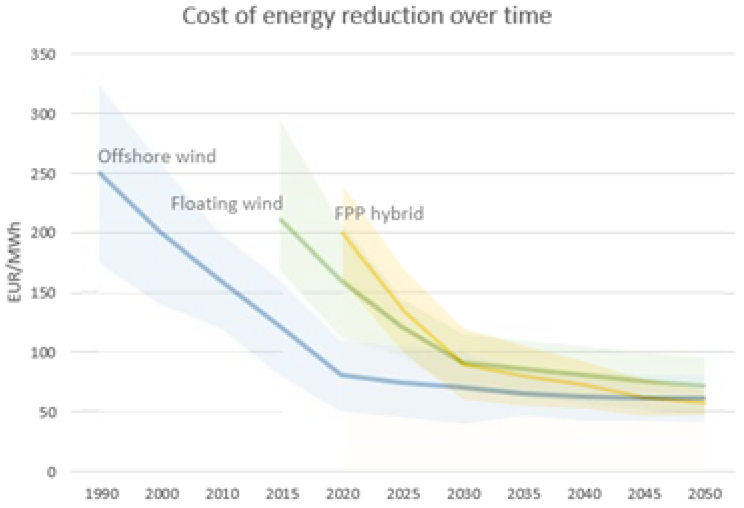
A simple position control was implemented in the xPC control system. Two control strategies are implemented, firstly a proportional position controller and secondly a proportional position controller and a velocity feedforward controller. The velocity feedforward was based on inverting the orifice equation and assuming a constant pressure drop across the servo valve. The figure below contains some results from the testing at Aalborg University, showing the performance of the implemented proportional controller with and without velocity feedforward. One should note, that very little effort was used on the controller. Better performance is expected if optimization is done, especially if supply pressure and tank pressure are fed back. The velocity feed forward term is turned off at app. 50 s and on again at 82 s.



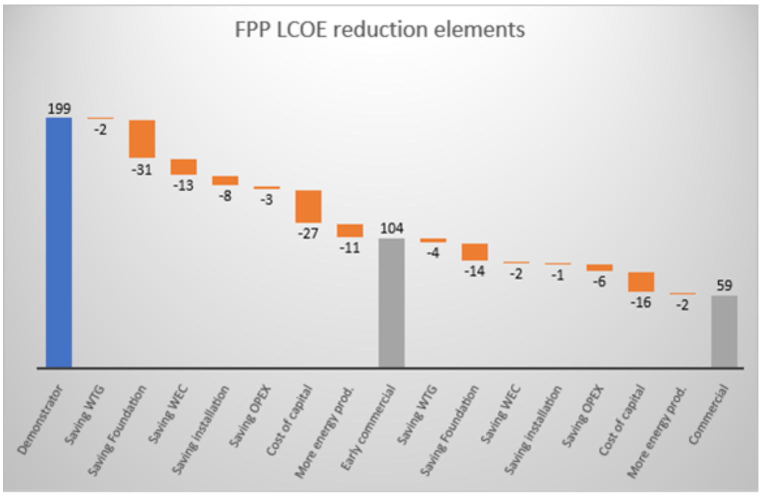
A simulation model was built in Simulink. The model may be seen as three parts, the load/wave system, the PTO system and the mechanical coupling of the load/wave and the PTO system. The model load/wave model includes the wave cylinder and the servo valve controlling it. However, the HPU for the load/wave side is unmodelled, assuming constant supply and tank pressure. The model of the PTO system includes only all the important parts for the functional operation, and safety components and systems are not included. The model includes the two PTO cylinders, the eight check valves, and four on/off valve connecting the PTO cylinders to the tank and system pressure. Furthermore, the model includes the three accumulators, the hydraulic motor and the pressure relief valve. The mechanical coupling model consists of a geometric translation of cylinder forces into torques on the main rotation of the PTO system. The main rotation is modelled with Newtons second law. Control of the PTO system is coded in a Matlab function executed with a sampling time of 10 ms. The PTO control is based on the pseudo code of the test container PLC and includes only the control of the generator torque and the valve setting. The control of the load/wave system is a simple proportional controller with velocity feedforward.

Cost of Energy (CoE) reduction path for Floating Power Plant

Results from the digital hydraulics project is directly relevant to FPP commercialisation process. The purpose of this process is to bring down the CoE from FPP's hybrid units to a fully commercial level. This cost reduction is driven both by economy of scale going to larger production volume, by going to more energetic sites, and by increasing the efficiency and reducing stresses on the PTO. The figure below shows the reduction in CoE (levelized cost of energy including capital cost) projected by FPP. The FPP concept has the potential to reduce the CoE more than "Offshore wind" and "Floating wind" as shown in the figure below.



The project results and their future application is relevant to several of the cost reduction contributions (saving WEC, Saving OPEX, More energy prod.) as illustrated in the following figure.



Dissemination

As described in Section 1.3 one of the main deliverables were the further development of two large digital hydraulic PTO test rigs. The two test rigs are both placed at Aalborg University, where they can still be visited and used anytime. Both test rigs are currently (end of 2018) used in the further research & teaching, and new research projects are planned to follow up on the current project.
Experimental testing in the wave basins at Aalborg University were completed during several test campaigns with various setups and with both Wavestar and FPP models. Some testing were done in collaboration with master and PhD students, and several test campaigns were completed as part of PhD courses and master courses, most times in the facilities at Aalborg University, but also two times at other facilities (at the wave basin in Nantes in France and Cork in Ireland).
The data from the PTO and basin tests have been used in many research papers, and researchers from all over the world (more than 100 people in total from more than 20 different countries, out of this more than 50 were PhD students) has actively directly participated and gained knowledge from the work. The testing has also attracted a lot of public interest, with numerous visits, interviews to journalists, TV-shows, youtube, facebook and linkedin posts,...

New and innovative strategies for procedures and methods for Wave Energy Converter (WEC) testing have been developed through the period. The new methods and procedures were extended beyond state of the art for how to perform testing on WECs for model validation, so teaching materials has been modified and lectures at courses and workshops were given to spread this knowledge. Nationally, the findings were e.g. disseminated through the Partnership for Wave Power at the biannual seminars. Further, the results were incorporated in a natural manner in all the other wave energy projects where the actors in the current project are involved.
Publications and conference presentations were targeted according to the direction of the findings and complementary conference and journal special issue topics were taken advantage of. A publication list is included in the annex.

1.6 Utilization of project results

The work is directly used in the commercial development of Floating Power Plant's technology. The analysis of the cost of energy for the digital PTO system shows a significant benefit due to improvements in the efficiency and reliability. This is important for the business case for Floating Power Plant, and thereby an important step closer towards a market.

As described in the dissemination section by the end of Section 1.5 the project findings and procedures are used extensively in the ongoing and planned research at Aalborg University. Further, the findings and procedures have been disseminated to the national wave energy developers and wave energy community, including a variety of international scientific communities. Thereby, these companies and groups will gain by the project findings in their own development.

The two digital hydraulic test rigs at Aalborg University will stay at the location in Aalborg after the project is finished. The reactive rig (the Wavestar PTO) is owned by the University. The resistive rig (the FPP PTO) is owned by FPP, but the agreement is that it will stay at the Aalborg University address as long as Aalborg University find it beneficial. The two test rigs are important demonstrators to show visitors the systems, and they are also used in in future teaching, research and development.

1.7 Project conclusion and perspective

The project has successfully demonstrated that a digital hydraulic power take off (PTO) system can reduce the cost of energy from wave energy converters. New models and methods have been developed, which are important tools in the toolbox of the designing engineer.

Two unique and large PTO test rigs have been further developed, and used to practically demonstrate, through hardware in the loop simulations, the usefulness and potential of digital hydraulic systems in relation to realistic and efficient wave energy conversion. The test rigs are used as demonstrators of the technology to the public, but even more importantly they are key components in the current and future research in the area. The benefit by having these facilities available at Aalborg University is unique, and together with the in-depth expertise places Aalborg University in a leading position within this field worldwide. It is believed, that digital hydraulics has a huge potential not only within wave energy but within a wide range of applications and technologies, where reliable and efficient components are needed which can handle large forces at relatively limited costs. New projects and research activities are therefore planned to follow-up on the current project. As the current test rigs are significantly smaller than realistic full-scale systems there is a need to develop and built new larger systems in order to examine, prove and demonstrate the efficiency and capabilities of the systems in a controlled dry environment. Such large systems should be developed, built, tested, possibly modified a number of times, and thereby by the end presumably proven, before applying the technology to real actual wave energy prototypes at sea.

Extensive laboratory wave basin experiments have been completed in the project, with valuable data containing new findings. New state of the art procedures for performing experiments have been developed, providing new standard procedures to the community. A large effort has gone into teaching the outcome to new and existing engineers. Engineering students have been confronted through courses both at master level and through dedicated PhD courses on the subject both nationally and internally. Many wave energy developers and wave basin facility managers have visited the setups developed in this project, and several have copied or adopted the procedures, methods and equipment for building their own setups. Testing of future wave energy converters in wave basins thereby benefit from the outcome of the project. As an example the work and methods are now directly used in ongoing international standardisation work for wave energy by the group IEA-OES-Task10. However, new and additional testing and data, are required for that specific standardisation purpose, and therefore additional tests are planned by the Task10-group.

The Model Predictive Control that was used and further developed within the project was tested numerically and experimentally during the test campaigns. The developed method shows a very high potential to increase the power in a good and safe manner, as structural loads and motions can be accurately predicted and controlled by this method. Hereby events, which could otherwise lead to damage, can be predicted and the controller can circumvent problems such as the cylinders hitting the end-stops in high energetic seas. The methods developed are highly advanced and very complicated mathematically, and the stability of the controller has proved to be rather problematic. Additionally, there is a large potential for further development and optimisation for a real case full-size digital hydraulic system. Further R&D is needed within this field before this method is suited for real-life implementation.

The work has proven the basis for the PTO design of future full-scale Floating Power Plant wave energy converters. Furthermore, the analysis of the cost of energy for the digital PTO system shows clearly a positive benefit as the efficiency of the system is increased and the component prices for the PTO decrease. This is important for the business case for Floating Power Plant, and thereby a significant step closer towards a market. Further development and tests of the digital hydraulic technology are however needed, before the technology can be directly included in a real wave energy converter at sea.

Annex

Only publications that have been through a peer review, and which are available at recognised journals or external organisations, are included in the list below. Reports, posters, internally published material and other published documents are not included.

Journal / Event name	Year	Publication Title	Lead Author	Co-Authors
Applied Ocean Research	2014	Constrained Optimal Stochastic Control of Non-Linear Wave Energy Point Absorbers	M.T. Sichani	J.B. Chen, J. Li,M.M. Kramer, S.R.K. Nielsen
Ocean Engineering	2014	Optimal Control of an Array of Non-Linear Wave Energy Point Converters	Søren R.K. Nielsen	Q. Zhou, B. Basu, M.T. Sichani, M.M. Kramer
ICOE2014	2014	Wavestar - 4 years of continuous operation in the North Sea	Laurent Marquis	-
ICOE2014	2014	Competitive cost of energy from Wavestar	Laurent Marquis	B. Kristensen, M. Kramer, E.V. Sanchez
JFPS2014	2014	Validation of Simulation Model for Full Scale Wave Simulator and Discrete Fuild Power PTO System	Anders Hedegaard Hansen	H.C. Pedersen, R.H. Hansen
JFPS2014	2014	Avoidance of Pressure Oscillations In Discrete Fluid Power System with Transmission Lines – An analytical approach	Anders Hedegaard Hansen	H.C. Pedersen
ICASP12	2015	Reliability-based Calibration of Partial safety Safety Factors for Wave Energy Converters	Simon Ambühl	M. Kramer, J.D. Sørensen
DFP15	2015	Avoidance of Transmission Line Pressure Oscillations in Discrete Hydraulic Systems – By Shaping of Valve Opening Characteristics	Anders Hedegaard Hansen	H.C. Pedersen, M.M. Bech
Journal of Risk and Reliability	2015	Operation and maintenance strategies for WECs	Simon Ambühl	L. Marquis
FPMC2015	2015	Energy Costs of Avoiding Pressure Oscillations in a Discrete Fluid Power Force System	Anders Hedegaard Hansen	H. Clemmensen
MSC2015	2015	Model Predictive Control of a Wave Energy Converter	Palle Andersen	T.S. Pedersen, K.M. Nielsen, E. Vidal
EWTEC2015	2015	Control of Point Absorbers and their Performance in Experiments	Morten Møller	F. Ferri, M.M. Kramer
EWTEC2015	2015	Different Reliability Assessment Approaches for Wave Energy Converters	Simon Ambühl	M. Kramer, J.D. Sørensen
Energies	2016	Structural Reliability of Plain Bearings for Wave Energy Converter Applications	Simon Ambühl	M. Kramer, J.D. Sørensen
ISOPE	2016	Risk-based Operation and Maintenance Approach for Wave Energy Converters Taking Weather Forecast Uncertainties into Account	Simon Ambühl	M. Kramer, J.D. Sørensen
Ocean Egineering	2016	Optimal Configuration of Discrete Fluid Power Force System Utilised in the PTO for WECs	Anders Hedegaard Hansen	H.C. Pedersen
9th FPNI	2016	Reducing Fatigue Loading Due to Pressure Shift in Discrete Fluid Power Force Systems	Anders Hedegaard Hansen	H.C. Pedersen
IMechE	2016	Reducing pressure oscillations in discrete fluid power systems	Anders Hedegaard Hansen	H.C. Pedersen
Marine Energy	2016	Characterization of loads on a hemispherical point absorber wave energy converter	Morten Møller Jakobsen	S. Beatty, G. Iglesias, M.M. Kramer
OMAE2016	2016	Experimental validation of a nonlinear mpc strategy for a wave energy converter prototype	Hoai Nam Nguyen	G. Sabiron, P. Tona, M.M. Kramer, E.S. Vidal
IFAC2017	2017	Optimizing Control of Wave Energy Converter with losses and Fatigue in Power Take off	Kirsten Mølgaard Nielsen	T.S. Pedersen, P. Andersen, S. Ambühl
EWTEC2017	2017	Applicability of linear and non-linear potential flow models on a Wavestar float	Pauline Bozonnet	V. Dupin, P. Tona, M.M. Kramer, C. Chauvigné
Renewable Energy	2017	RANS-VOF modelling of the Wavestar point absorber	E. J. Ransley	D Greaves, A Raby, D Simmonds, M Jakobsen, M Kramer
OMAE2017	2017	Validation of a Quasi-Linear Numerical Model of a Pitching Wave Energy Converter in Close Proximity to a Fixed Structure	Maria del Pilar Heras López	S. Thomas, M.M. Kramer
EWTEC2017	2017	Validation of Hydrodynamic Numerical Model of a Pitching Wave Energy Converter	Maria del Pilar Heras López	S. Thomas, M.M. Kramer
COER2017	2017	WEC experiments and the equations of motion	Morten Kramer	-
WWEC2017	2017	Modelling and Validation of a Hybrid Floating Platform for Wind and Wave Energy	Pilar Heras	-
Energies	2018	Model Predictive Control of a Wave Energy Converter with Discrete Fluid Power Power Take-Off System	Anders Hedegaard Hansen	M.F. Asmussen, M.M. Bech
ICCMA 2018	2018	Valve shifting time in a digital fluid power system : Energy efficiency versus fatigue loading	Anders Hedegaard Hansen	M.F. Asmussen, T.O. Andersen
Energies	2018	Physical and Mathematical Modeling of a Wave Energy Converter Equipped with a Negative Spring Mechanism for Phase Control	Amélie Tetu	F. Ferri, M.M. Kramer, J.H. Todalshaug

The project has also contributed to films/videos for the general public, examples are given in table below.

Organised by	Filmed by	Description	Direct link
EU-commission	Edouard Dufrasne, AFP-Services	Video about renewable energy intended for download and use by TV stations	http://ec.europa.eu/avservices/video/player.cfm?sitelang=en&ref=I095960
Undervisningsministeriet	Lars Agersø, Adventurefilm.dk	Video for teaching in “Folkeskolen”. Center for Undervisningsmidler (CFU)	https://www.youtube.com/watch?v=JZh6qSUcHH0
Undervisningsministeriet	Sune Gudmundsson, www.bureautank.dk	Video for teaching in “Gymnasiet”. EMU Danmarks læringsportal	https://vimeo.com/mediehuset/review/153230313/244e95115e