Power Sharing Transmission based Bi-directional to Uni-directional PTO (PST-PTO)

WES Power Take Off
Stage 1 Project
Public Report

Cofely Fabricom

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1 Project Report

1.1 Project Introduction

A key challenge for efficient wave energy converters is to transform the typical bi-directional, reciprocating movement induced by the waves into electricity in an efficient, flexible and robust way. This fluctuating and bi-directional power profile needs to be absorbed by the power conversion technology inside the WEC (Wave Energy Convertor), resulting in grid compliant electricity.

Current solutions generally provide a directly coupled axis between the main generator and mechanical wave energy absorber (cantilever, winch,…), inducing a bi-directional movement into the electromagnetic force field of the wave energy generator. This highly fluctuating power profile induces a suboptimal efficiency within the electrical conversion of 65-75%, having a high impact on the Annual Energy Production (AEP) and thus Levelized Cost of Energy (LCoE). The variability of the waves also implies power peaks and so over- dimensioning of all power equipment (impact on CAPEX and O&M).

An alternative, more robust and low-cost solution with hydraulic circuits and a pumping piston has been used in the past, but has a lower efficiency, high maintenance cost and low optimization possibilities towards device phase control (optimal control of device movement into the waves).

The solution as developed by the Partnership Engie Fabricom-UGENT (University of Ghent) tackles both key issues of wave energy technology: the CAPEX is too high and the yearly energy yield is too low, resulting in a non-bankable business case for current state of the art wave energy convertors.

By introducing a smart solution for conversion of a fluctuating bidirectional movement into a smooth power profile by use of an electromechanical rectifier (instead of a pure electrical or hydraulic rectifier), the conversion efficiency can significantly be improved and the installed power can be significantly be decreased.

This solution was patented by Ghent University (UGent) in 2015. The partnership Engie Fabricom- UGent was established to integrally transfer the paper idea into a real working industrial solution. Engie- as a key player in the renewable future – could/would also act as an integrator of this technology into one of the new energy forms of the next decades.

This stage I project has further evaluated the gains in terms of efficiency, flexibility and robustness of an electromechanical PTO system which transforms the bi-directional movement into a uni-directional rotation that can easily be fed to a generator. The PTO system is under patent application, and includes at its core the intelligent use of a power sharing transmission.

1.2 Description of Project Technology

As a possible solution for the high installed power and low conversion efficiency problems of wave energy the project team (Engie Fabricom - Ghent University) looked at a smart planetary gearbox solution (PST – Power Split Transmission).

A planetary gearbox with 3 axis (1 input, 2 output) will be used to convert the absorbed mechanical power – as introduced by the wave power transfer through the prime mover (and the input axis).

The wave movement introduces a variable power flow through the input axis; This power flow is divided over 2 optimally controlled output axis. One axis - coupled to a flywheel (and main generator) to store possible velocity peaks - is controlled to move with constant, unidirectional speed. The second axis is coupled with a customized algorithm controlled auxiliary machine, correcting all relative movement of the input axis towards a constant unidirectional movement for the main generator axis. By smart control of both axis the power flow to each convertor can be chosen through an extended algorithm, keeping the total control force to the WEC and the efficiency maps (depending on torque and speed) of both energy producing electro-motors (main generator and auxiliary machine) at an optimal level.

In summary, the extra degree of freedom of using 2 coupled machines (with a flywheel for energy storage) gives the overall control system the possibility to optimally manage all 3 power flows (waves in, generator and aux out). So, by smart choice of amount and timing of power transfer to one or both machinery, this degree of freedom allows the total electrical energy (as summation of main generator and control machine) and the WEC movement to be optimized. Use of a flywheel increases the storage possibilities and decreases the over dimensioning of all electric equipment.

A crucial component in this technology is logically the Power Split Transmission (planetary gearbox). An optimal design combines a high conversion efficiency with a long term durability, hence lowering the Cost of Energy.

As for key advantages, current numerical simulations including both device-wave interaction and realistic electrical engine performance estimates the yield increase by up to 25% and the installed power decrease to up to 30%, giving a possible future optimization of the LCOE and so the business cases of wave technology devices. So, depending on the applied wave energy technology and chosen sea climate, the implementation of the PST could have a LCOE reduction of 25 up to 35%. A first real quantification/check of these projections were be executed after the lab testing at Campus UGENT at Kortrijk, Belgium. These first results will be used as input for future improvement and up scaling of the system.

1.3 Scope of Work

During the stage I project, important further R&D steps (in both numerical and lab environment) were taken to push the TRL (Technology Readiness Level) down the projected long term technology development roadmap. The key activities were based on the identification of the key challenges of this development.

These steps included:

- Numerical modelling
  - Hydrodynamic modelling of wave-WEC interaction under global PTO loads
  - Accurate electromechanical modelling of key PTO components: PST, generator, flywheel and auxiliary machine: machine specifications, limit of speed/torques, efficiency estimation, …
  - Long term durability model of PST
  - Design and performance validation of full PTO setup (including overall efficiency and yield)

- Design, built and test of a Proof of Concept PTO (+- 2.5 kW rated power)
  - Design of an integral small scale PTO system
  - Design of a wave emulator system (input axis power flow from wave energy)
  - Design and fabrication of a customized Power Split Transmission
  - Control and safety algorithm
  - Overall commissioning
  - Performance testing: overall behavior, efficiency, force levels, robustness, resilience, flexibility

- First PST robustness check and up scaling principles
  - Measurement of temperature and force levels within planetary gearbox
  - Planetary gearbox- Degradation mechanism principles
  - Draft design for scale 1:2 device

- Preparing the next steps
  - Stage II scope identification
  - Identification of possible suitable WEC developers for future co-operation
  - First feasibility check of upscaling of PTO system

1.4 Project Achievements

During the 6 months of the stage I project the project team was able to proof the basic potential of the technology:

- The PST provides an additional degree of freedom (compared to DiCo solution) to optimize the PTO in terms of different aspects
- Due to this, more electrical energy can be extracted (+25% yield for the same installed power at nominal SS)
- The power quality of the produced electricity can be increased (better power flatness factor)
- The robustness of the PST gear box can reach acceptable levels
- The PST introduces an inherent over-power protection (de-tuning of the WEC is possible), hence increasing survivability and production in higher sea states
- The energy yield is less sensitive to the actual parameters, i.e. the parameters required for the different SS do not differ so much from each other (this means that parameter set for SS-X will give also quite good results for SS-X+1 or SS-X-1).

These project achievements gave confidence to the project team and made it possible to identify the key challenges for the stage II project, in order to confirm and update the technology development roadmap for the coming years.

In the current proof of concept setup the wave energy is in fact on the low side compared to the 12.4 kW planetary gearbox. However, the latter was available off the shelf (reducing cost and delivery time in this phase). Unfortunately, the obtained PTO efficiencies are not yet fully realistic (significant fixed losses of the gearbox compared to the relative low power output) - making it impossible to validate efficiency models for the wave energy conversion system. However, budget, resource and timing (delivery time of customized planetary gearbox and electro machines) impact made it impossible to achieve this rated power level within stage I. Due to these time pressures and issues in sourcing gearbox components a more comprehensive efficiency study could not be completed during stage 1.

1.5 Applicability to WEC Device Types

The suggested solution can be used in all wave energy technologies that directly absorb the bidirectional mechanical power coming from the waves, whether by a winch, cantilever and pulley.

Despite the fact that the technology can be used for several wave energy device types, such as a attenuator, oscillating wave surge converter, oscillating water column and submerged pressure differential. The project team puts first aim further development/cooperation of the technology use within single or multiple point absorber WECs.

Possible suitable technologies are Floating Power Plant, Lifesaver, FlanSea, Laminaria, Nemos. This first market scan however does certainly not exclude cooperation possibilities with other wave technology devices.

1.6 Summary of Performance against Target Outcome Metrics

An actual realistic quantification of some of the stage metrics was hard to accomplish during this rather premature technology development phase. However, a first qualitative assessment gave further confidence of the current TRL and sets key goals for future Metric optimizations.

Affordability

A first cost analysis was made on the effective cost of the integral Proof of Concept Lab setup (although hard to mirror for a prototype). This cost was projected towards stage II and further PTO generations. By applying realistic scale effects and a learning curve for future device development, there can be concluded that the current cost is at acceptable level compared to the projected cost Metric by WES.

Performance

The working principle of the PTO setup has been confirmed for both regular and irregular waves. Next to that, the measured key parameters (speeds, torques, forces, control …) gave a good link with the numerical model. Performance optimization by control (software) and component (e.g. electromotor, planetary gear,…) refinements has been identified as key goals for stage II. The power conversion efficiency from the model gave better results compared to the direct coupled model, as set forward in the project proposal. The system can be easily scaled without problematic performance, manufacturability or maintenance issues.

Availability

The availability of the PST-PTO can be very high due to the use of well-known and robust components, being a planetary gearbox and standard electric motors/drives. The durability model of the gearbox under the measured loads will further be validated towards components lifetime. The availability of the PTO will certainly not be dominant compared to the other key WEC parts (mooring lines, shafts, ballast systems and structure) .

Survivability

The extra degree of freedom, combined with the use of a flywheel increases the survivability of the PTO system compared to a directly coupled electrical solution. This flexibility allows to produce energy in higher sea states without exceeding the safety and durability limits of the PTO.

1.7 Communications and Publicity Activity

- The numerical results the stage I project have been summarized in an academic paper for the 2016 International Conference on Environment and Electrical Engineering (EEEIC, Florence - Italy): 'Modeling of a Power Sharing Transmission in a wave energy Convertor', by Kristof De Koker et al.

- An ENGIE project promotion poster has been presented in Brussels, Belgium at the Engie Innovation week Seminar, 9/06/2016

1.8 Recommendations for Further Work

The project team believes there are a number of challenges still to be addressed in order to achieve a high performance and durable PST-PTO technology. The following key challenges should be tackled in a stage 2 project:

1. **(Stress) testing on existing test bench.** The current prototype has been focused on a relatively small power rating and simple control. The main goal was to proof the feasibility of a PST WEC and to obtain a test bench that can be used to test different aspects. This has worked very well, still more information can be extracted from the existing test setup. We have e.g. observed that there are small differences in the dynamics of the test setup compared to the simulations. This could maybe be attributed to the stiffness of the axis, however additional tests need to be done to confirm this.

2. **Move to higher power ratings (25-50 kW e.g.)**. Moreover, this needs to be done in such a way that the PTO becomes a versatile device that can be applied to many WECs. We believe a modular approach could be put in place in that respect. Already, preliminary steps have been taken during the stage 1 project to prepare and check the feasibility of higher power ratings, though a more detailed design needs to be done, especially with respect to the planetary gear box and the occurring forces and profiles.

   Now that we better understand the balance between the energy yield and the life time of the gearbox, this balance needs to be explored further in the design process.

3. **Gear ratio optimization** We believe the gear ratios of the current test setup should be further optimized to enhance the performance.

4. **Additional control algorithms** need to be implemented on the test setup. Further efforts should also be oriented towards proving the improved power quality (e.g. peak shaving) of the PTO. In this respect we can see some

potential of further reducing the installed power compared to the obtained energy yield (today the installed power for the PST case was taken identical to that of the DICO to obtain a fair comparison) as such increasing the LCOE.

5. The current PST system is optimized for one-way power extraction, e.g. a double PST system would allow to **extract energy in both direction**s. However, the added value of this is still unclear and dependent of the type of WEC coupled to the PST. This can be evaluated through simulations (and possible future PoC Tests). Another issue to be tackled-assessed is the long term durability of the PST and total setup with torques in **both direction** (one directional torque transfer as installed now gives a fatigue and durability advantage).

6. **Numerical link with WEC developer.** Given the steps above, one or more points preferably are done in collaboration with/with a WEC developer in mind. The first intention meetings with possible WEC developers are ongoing. Idea is to link the numerical model of the PTO with the hydro dynamical closed loop model of the WEC developer.