Design and Control of a Modular Power Electronic Back-to-Back Converter for Wave Energy Harvesting Applications

Mattia Mantellini, Riccardo Morici
OCEM POWER ELECTRONICS
Via della Solidarietà 2/1 40056
Bologna, Italy
Tel.: +39 051 – 6656698
E-mail: mattia.mantellini@ocem.eu
URL: https://ocem.eu/it/homepage_it/

Marcos Blanco, Marcos Lafoz, Gustavo Navarro,
Jorge Torres, Jorge Najera, Miguel Santos
CIEMAT
Avda Complutense 40 28040
Madrid, Spain
Tel.: +34 – 913357194.
E-Mail: marcos.blanco@externos.ciemat.es
URL: http://www.ciemat.es

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Abstract
Waves are one of the most promising renewable energy sources. Several concepts of wave energy converters (WECs) have been studied, but only few of them have progressed to sea testing. The EU, under the Horizon 2020 framework, is financing the development of an innovative WEC based on a direct-drive power take-off, with a modular back-to-back power electronic converter and an azimuthal multi-translator switched reluctance machine. The paper aims to illustrate its structure and control.

Introduction
The interest in renewable energy sources has recently increased following the world energy demand. New energy sources have been explored, gradually abandoning traditional fossil fuels. According to an estimation by the International Energy Agency (IEA), the world energy consumption stands around 18'000 TWh per year. Although the use of renewable energy has increased since ‘70s, their incidence nowadays is still low in comparison with fossil fuels in the world energy balance. Solar and wind energy are the better known and more widespread renewable sources but with a 71% of the earth's surface area, oceans hide a huge amount of energy. IEA studies say that by fully exploiting ocean energy (ocean current, tides, tidal currents, saline gradient, temperature gradient and waves), a whole potential of 40'000 TWh per year could be obtained.

Wave energy source
Waves are moved by powerful winds caused by temperature gradient on earth surface due to sun heating. The total energy transferred from air masses to ocean masses depends on the wind speed, application time and distances. Thus wave energy distribution is uneven: it is mainly focused between 30 and 60 degrees of latitude in both hemispheres and it's higher in western coasts. Average wave power varies also seasonally: in winter it increases compared to the summer. Many advantages can be found:
- constancy, since waves are present 24 hours a day for seven days a week;
- predictability (intensity can be predicted several days before the arrival);
- little energy losses while travelling very long distances;
- high power density, ranging from 10 up to 70 kW/m (i.e. per meter of wave front) and over.

Also, the energy per square meter from waves is 15-20 times higher than either wind or solar sources. Additionally, a traditional power generation plant occupies an area removed from the earth soil, while a wave energy production plant of the same power size cover half of the area on the ocean surface. Moreover, due to higher constancy, the utilization factor (the ratio between produced energy per year and rated installed power) is two time higher in the case of wave motion than wind technology.
WECs

The development of wave energy conversion can increase the diversity of renewable energy mix creating also a new market sector carrying innovation and employment. Many challenges have still to be faced to demonstrate a long-term economic and energetic potential.

- Reliability problems: maintenance intervention are difficult and expensive.
- Survivability: a WEC can be subjected to high stresses due to weather conditions, so proper overdimensioning and safety systems must be present.
- Conversion efficiency: ocean waves are irregular, so great efficiency allows to operate well even in unfavorable conditions.
- Output electrical energy quality: the generation is very irregular but with energy storage systems and proper control, electrical power output can respect standards.
- Scalability: unfortunately, many WECs reach optimal dimension at a low power level and arrays of multiple WECs brings no advantages in the cost with respect to produced power.
- Environmental footprint: impact on marine ecosystem must be low.
- Production cost: there is no consolidated supply chain since standards lack.

WECs structure

Generally speaking, every WEC is composed of similar sections:

- Hydrodynamic subsystem: it’s the interface between wave motion/force and the PTO.
- Power take-off (PTO): it converts the energy from the hydrodynamic system into electricity in one or more stages. When a single stage is present it’s called “direct-drive PTO”.
- Reaction subsystem: it reacts to the moving hydrodynamic system. For instance a mooring.
- Control: it’s the control algorithm and safety system.
- Power electronics: it performs electric adaptations and energy flux management.

WECs classification

Many different classifications are possible. Regarding the distance from the shore it’s possible to list shoreline, nearshore and offshore plants: as further from the shore, problems of maintenance and energy transmission arise, but higher power waves are caught and environmental problems are less. According to the operating principle, there are mainly three types of WECs:

- Oscillating Water Columns (OWCs) where a bidirectional turbine extract energy from an air flow pushed and pulled by the oscillating water level inside a special chamber with a top hole.
- Overtopping Devices (ODs) where an hydroelectric turbine extracts energy from water flowing back into the sea from a reservoir above the sea level where waves are collected.
- Wave-Activated Bodies (WABs) where the relative motion of different floating bodies is converted into electricity (for instance by high pressure oil pumping).

Inside the latter category, Buoy Type WECs are placed. They consist of a floating buoy with various shapes: the most common is the Heaving Point Absorber, capable of taking energy from any direction.

SEA TITAN Project

SEA TITAN is a Horizon 2020 European project which aims to design, build, test and validate an innovative and crosscutting WEC based on a direct-drive PTO. The name stands for Surging Energy Absorption Through Increasing Thrust And efficieNcy and the developed PTO technology is suitable for different WECs, so it can bring a sort of standardization. The design is based on the Wedge Global W1 WEC prototype with the W200 PTO tested in Gran Canaria at PLOCAN site in 2014.

Many efforts and studies have been done to increase PTO specific force density and efficiency with the purpose to extend the catchable energy range for many different WEC applications. Since most of common industrial components don’t show high performance levels or reliability with an affordable price to begin a commercial phase, with a crosscutting PTO technology a standardization can be obtained, as well as a dedicated supply chain with lower development costs.

Modularity of the machine also allows an easy adaptation to different WECs technologies.
Thrust and efficiency

The limit to the harvestable power of a wave is given by the machine exerted thrust. A wide range of waves correspond to a wide range of thrusts, so it’s difficult to harvest power from all sea states. Moreover, with actual technology, a wide range of thrust means worse efficiency due to power losses. Thus, higher thrust and efficiency can make a PTO able to harvest a bigger amount of wave energy. In order to better understand this, a model analysis validated by the W1 prototype is shown. The equivalent circuit model represents the simplified motion equation. As visible in Fig. 1 there are two external forces acting on the floater: wave excitation $|U_W|_0$ and PTO force $|U_{PTO}|_0$ and they are coupled through the mechanical impedance of the floater itself $|Z|_\phi$ including radiation, inertia and buoyancy coefficients. Additionally, a parallel resistance $|R_{PTO}|_0$ is added to consider copper losses and efficiency. Currents (i1, i2) correspond to the velocities.

![Model equivalent circuit.](image)

Let’s consider a PTO with a control strategy which maximizes the power for regular waves, a maximum force of 1 MN and 100% efficiency (i.e. $R_{PTO}$ is infinite).

![Comparison between ideal PTO on the left and real PTO on the right](image)

In Fig. 2 left the behavior of an ideal PTO is shown: red curve is the maximum power extracted for each wave period and the blue curve is the corresponding needed force. Orange curve is the actual extracted power since the required force (green) is limited under 1 MN. Only when green and blue traces coincide the actual power (orange) coincides with maximum power (red).

In Fig. 2 right the real PTO is considered, compared with the ideal one (red and blue curve, the same as per left figure). The force limitation is the same as the previous case (1 MN) but the real PTO control strategy uses less force (the green curve is indeed lower than previous graph) to limit losses. In this case the actual force (orange) follows the needed force (blue) just for few periods, so the actual power (orange) is much smaller than maximum power (red). For a real PTO, thrust restrictions and limited efficiency drops down the possible extracted energy in a wide range of wave periods.

An useful parameter to express this situation is the Integrated Power Capture (IPC), which is the area enclosed by the generated electrical power curve for a certain period range (as visible in Fig. 3 left). The ratio between the IPC for a WEC with real PTO (yellow area) and a WEC with an ideal one (red area plus yellow area) is the Integrated Power Capture Ratio (IPCR).

The IPCR can be improved by augmenting thrust, efficiency or both together, as visible in Fig. 3 right: of course higher amount of power needs higher efficiency, otherwise it would be unexploited.

SEA TITAN project aims to increase the IPCR value from (compared to W1 prototype) 19% to 38%.
SEA TITAN main innovation stands in the PTO. In order to get a direct conversion, a Heaving Point Absorber is chosen, coupled to a linear generator direct-drive PTO: in this way energy transformation stages are reduced to minimum and higher efficiency, reliability and controllability are gotten.

The innovative direct-drive PTO is based on an Azimuthal Multitranslator Switched Reluctance Machine (AMSRM). It’s simple, robust and cheap, while it’s noisy, it has relevant cogging torque and copper losses due to high currents for high forces (for a certain power, speeds are low).

The W200 prototype Fig. 4 was a Rectangular Multitranslator Switched Reluctance Machine.

The underlying idea of the multitranslator arrangement consists of increasing the airgap surface of the machine with a limited impact on its volume to get compact and high force density PTO.

The AMSRM has been designed to house copper coils on the sliding translator (active part) with a ferromagnetic stator (passive part) as visible in Fig. 5: Heaving Point Absorber WEC (a) and AMSRM PTO (b).

In the final configuration the idea is to room also the power electronics section on the translator. The multitranslator configuration allows to improve the overall force density and it erases the transversal force. In traditional linear multitranslator machines the magnetic flux passes through intermediate stators (where coils are located) and it closes through end stators (with significant amount of iron). The azimuthal shape eliminates end stators since the flux follows an azimuthal path through intermediate stators. The azimuthal configuration also allows the circular shape, an easy solution for many PTOs (whose geometry is often circular).
Preliminary analysis of the Power Take Off

The PTO encompasses the electric machine (AMSRM), the power electronic converters and its control system. The active part of the AMSRM houses the power electronic and a control unit. Several modules can be stacked sharing the same passive part (ferromagnetic) to reach different force levels. An AMSRM module has a rated thrust of 40 kN and a rated speed of 3 m/s. The power electronic converter consists of a Grid-Tied Converter (GTC) linked through a DC link to several Generator-Side Converters (GSCs), each one inside an AMSRM module. Every GSC is composed of three single-phase H bridge converters to get a proper control of each phase. The AMSRM is a long linear machine with a large air gap, a significantly saturated magnetic circuit and low current slopes. Thus, several phases must be energized simultaneously, and a proper management of phase current dynamic is essential to take advantage of the AMSRM characteristics.

The SEA TITAN PTO prototype consists of one module of AMSRM (and its 125 kVA GTC).

Selection of the AMSRM basic Module

Modelling of innovative PTO and WECs, has been performed. A PTO Optimization Model (POM) has been developed to determine basic characteristics (rated stroke, velocity, and force) of a PTO design tailored to a given location and WEC. The POM uses the W2W model to approach the PTO design as an optimization problem. The problem has been faced as a multi-objective optimization problem, with two search-space variables (nominal thrust and stroke) and two target functions (average electricity production and cost, to be maximized and minimized respectively), and it has been solved by means of a differential evolutionary algorithm.

This analysis has been carried out for 8 cases: 4 WEC designs (CorPower, SeaCap, Centipod, Wedge Global’s W1) assessed at 2 locations. The PTO rated thrust and stroke ranged between 109 - 384 kN and 2.2 - 4.4 m respectively. The results for the optimisation of Wedge Global’s WEC design at PLOCAN location is shown in Fig. 6 with an indication of the corresponding Pareto Frontier. When plotting the power/cost ratio (Fig. 6Fig. 7), the optimal solution is at 109.26 kN thrust and 2.664 m stroke.

![Fig. 6: Pareto Frontier of Wedge Global’s W1 at PLOCAN with respect to the search space variables a), b) and c) and with respect to the optimization functions d).](image)

Once the optimum PTO size has been obtained, the optimum AMSRM has been determined. AMSRM module dimensioning must find a trade-off between simplicity (the bigger the AMSRM module, the lower the number of modules for each PTO) and excessive resulting force (i.e. overdimensioning of the full PTO configuration due to the integer nature of the number-of-modules variable).

Fig. 7 shows the parametric study to determine the AMSRM module selection. Following the two aforementioned criteria, the solution obtained is a 40 kN module, which minimizes the excess PTO thrust for the 8 cases and provides simple PTO configurations (i.e. with low number of modules). In terms of velocity, the compromise solution has been set at 3 m/s, which covers most of the operating sea conditions for the 8 cases considered (most recurring wave period is 10 s).
In consequence, project SEA-TITAN has designed a PTO with an AMSRM composed of 40 kN 3 m/s modules. The final PTO will incorporate two modules, mounted in a back-to-back configuration for the laboratory dry tests: one module will behave as the actuator (motor) and will drive the second one, which will act as the generator. Both modules can be easily re-configured to operate as a common generator. Finally, the power electronics has been tailored to final thrust and velocity characteristics.

Analysis of the power electronics behavior

The behavior of the power electronics has been evaluated using a mathematical model of the AMSRM and a simple power converter model as shown in Fig. 8a. Moreover, the power electronics design has been carried out for the most critical power losses situation which has been identified analyzing the whole range of velocity/current operational points of the model of one 40 kN 3 m/s AMSRM module.

![Fig. 8 General scheme of the power electronics (a), FEM analysis of the AMSRM prototype (b).](image)

The AMSRM model (Fig. 8b) consists of a mathematical equation per machine phase (see (1) [2]) where magnetic flux ($\lambda$) and thrust have been calculated by means of a 3D FEM model. These terms are function of the phase current ($i$) and of the relative position ($x$) between active and passive part. Additionally, a hysteresis band switching strategy current control has been implemented [3].

The data obtained are defined for an AMSRM machine with requirements of 40 kN and 3 m/s. The power electronics module required for the FEM simulation must meet electrical requirements of 350 A and 900 V DC.

$$\frac{di}{dt} = \frac{V_{dc} - R \cdot i - \frac{\partial \lambda}{\partial x} \cdot \omega}{\frac{\partial \lambda}{\partial i}}$$  \(1\)

First, simulations at constant current and velocity have been carried out to obtain proper positions to activate/deactivate each phase current. A differential evolution algorithm has been used to maximize AMSRM generated power. In this case, the optimum linear positions to activate AMSRM phases have been calculated using an analogous rotational 6/4 SRM. This parametric evaluation is required to maximize the generated power. An example is shown in Fig. 9a and b (values are in red). These results have been obtained for each velocity/current operational point (see Fig. 9c, d and e).
Fig. 9: Generated power (a), mechanical power (b) VS equivalent switching angle and extracted power (c), activation angle (d) and deactivation angle (e) for all operating points VS current and speed.

From those results and using the aforementioned process, all the operation points have been evaluated, the phase current and speed operation range from 0 to nominal value of 350 A and 3 m/s. Once the optimum values of the activation/deactivation angles have been obtained, current and speed values are the main variables of the power electronics losses. Losses can be addressed in two different terms [4]: switching losses, which depend on the switching frequency and current level, and conduction losses, which are function of conduction time and current level on IGBTs and diodes. The DC link voltage is another parameter with an important impact in power losses. All parameters are shown in Fig. 10.

Fig. 10 Most relevant variables responsible of the power losses in the AMSRM: (a) Average current; (b) switching frequency; (c) average current on the IGBTs; (d) average current on the Diodes.

Fig. 10 shows that the maximum conduction losses occur at maximum current and speed references. Moreover, the switching losses have two critical points: low current reference at high speed (switching frequency maximum value) and high speed and current (maximum value of average current). Given these results, the most critical scenario to design the power electronics is 350 A and 3 m/s. Therefore, these values have been considered, first as constant values to select the semiconductors, then as peak values of sinusoidal waveforms in simulations to avoid an oversizing in the power electronics design due to oscillating behavior of PTO. The period of this sinusoidal oscillation is 10 seconds, the most common period the ocean waves in the considered locations.
**Power electronics design**

The power electronics (Fig. 8a) has been designed for lab dry test with no dimensional or cooling issue, but the solution is modular, compact and suitable for marine confined spaces and liquid cooling. The system is a back to back configuration, where a commercially available 125 kVA 1000 VDC GTC linked to the grid is coupled through a common DC bus to one or more GSCs. Starting data for power electronics dimensioning have been: 350 A of maximum current value for each machine phase, 900 V DC-link voltage and 1 kHz maximum average switching frequency in a cycle. Dimensioning has been carried out with detailed MATLAB Simulink and Plecs simulations (Fig. 11) where steady-state waves with a 10s period and 3 m/s amplitude speed profile has been considered.

![Fig. 11: Overall system Simulink simulation (a), power electronics PLECS circuit details (b).](image)

The upper block “Current Control” takes as inputs (orange) a reference current and a reference speed and produce driver commands for the power electronic circuit (yellow). A machine model calculates output currents and voltages (“SRM” lower gray block). The GTC has been modelled with a 900 V DC source and a parallel LR circuit with a time constant of 100 ms (200 mΩ and 20 mH). Fig. 12 reports the generator phase current and the generator winding voltage.

![Fig. 12: Phase current (a) with detail (b) and voltage of AMSRM generator (c).](image)
Thermal simulations

Switching and conduction losses have been implemented in the model with thermal PLECS analysis. Since in each AMSRM coil current is unidirectional to reduce the hysteresis losses by maintaining the polarization of the magnetic field, only one out of two IGBTs of each branch works. Nevertheless, complete half bridge modules (two IGBTs and two diodes) have been chosen due to availability on the market and better thermal behavior. Six 1700 V SEMiX603GB17E4p IGBT modules have been used. IGBT junction temperature has been monitored thought 600s of simulation. From 368 K (95°C), with the heatsink at 358 K (85 °C) and the ambient at 313 K (40 °C), IGBT junction temperature oscillates with a maximum peak of 376 K (103 °C). This is compatible with datasheet limit of 423 K (150 °C). Thermal coupling inside a module has not been investigated but safety margins have been considered. To dissipate a thermal power of 600 W (see Fig. 13) with 313 K (40°C) ambient temperature and 358 K (85°C) maximum heatsink temperature, heatsink thermal resistance must be lower than 0.075 K/W. The chosen heatsink (RMRES0020 by Priatherm) with a length of 200 mm, has 0.071 K/W thermal resistance with an airflow of 2.9 m/s maintained by three fans (PMD2407PTV1-A GN by Sunon).

![Fig. 13 Total heat flux for a single H bridge.](image)

DC-link

To limit the DC voltage oscillation, GSC DC-link has been designed without considering the GTC capacitors. Using simulations, six 2030 µF 416.85V.1720 capacitors by Ducati Energia have been chosen. Voltage oscillations are less than 160 V, which is an acceptable result for this application. With 80 Arms current on each capacitor ESR, the power dissipation is about 10 W. With a hot-spot thermal resistance to ambient of 22 °C/W, capacitor temperature rise is about 20°C with respect to the external temperature (which is 55 °C due to the exhaust hot air from the heatsink).

Control electronics

The control has been designed taking into account the modularity of the AMSRM. Each converter has its own control module, but only one master control system supervises all modules (see Fig. 14a) The selected master control system is a CompactRIO (cRIO) from NI, i.e. a reconfigurable embedded system with a processor running on a RTOS and a reconfigurable FPGA. The microcontroller TMS32F28M35 has been identified as the master control system for a future industrialization phase. The cRIO is programmed with the real time WEC energy extraction control, which sets the AMSRM reference thrust based on its velocity. Starting from wave profile, site data and WEC hydrodynamic characteristics, the cRIO sends the current reference for each module to extract the desired power. The communication between power electronic converters and cRIO is performed via CAN protocol.

![Fig. 14: Modular control interconnection scheme (a) and adaptation and control boards (b).](image)
A hysteresis double-band regulator has been implemented inside a control module to control the current in each AMSRM following the cRIO current setpoint [1]. Each control module is composed of a microcontroller (TMS32F28335 by TI) and an adaptation board which adapt signals from sensors and carrying control signals to the power section, see Fig. 14b.

**Mechanical layout**

Inside a single cabinet GTC and GSC are placed. The two sections are separately air cooled. The sizing of the GSC ceiling fan has been calculated for a maximum input/output air temperature difference of 15 °C and a total heat flux of 1890 W (i.e. 600 W for each H bridge with an increment of 5% for ancillary equipment). The resulting air flow is 430 m³/h and a proper fan (A3G300-AK13-01 by Papst) has been selected. In Fig. 15 pictures of the GSC are shown.

![Fig. 15 Single H bridge (a), complete GSC cabinet (b) and picture of the real GSC cabinet (c).](Image)

Short circuit currents are limited by fuses. The DC fuse has nominal current of 160A and it can limit the current below 10 kA. Output phases are protected by fuses with 200 A nominal current. The solution is very compact and easy adaptable for a marine environment, since single H bridges can be placed independently one from another and the heatsink is easily replaceable by a liquid coldplate.

**Conclusions**

Wave energy harvesting applications are very challenging because both control and hardware must respect strict requirements, efficiency and reliability must be high and variability of the source brings more difficulties. SEA TITAN project wants to introduce a crosscutting solution by increasing thrust and efficiency, with the purpose to enhance a standardization phase for ocean wave energy harvesting. Detailed simulations and calculations have been done in order to find the best solution. The power electronics design has been done with the same purpose of modularity and adaptability.

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