Concept Array design for Tidal kite power generators

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ABSTRACT

The Powerkite project is developing a power take-off system (PTO) for a novel tidal energy converter by Swedish developer Minesto known as Deep Green. One of the key deliverables of the project was to develop a conceptual design of the complete offshore array system including substations, cables and grid connection, with the aim to assess the key parameters of the future tidal plant (electrical efficiency, protection systems, fulfilment of requirements from network owners, cost, etc.), without going into a detailed design.

A base case array design was defined with focus on a short time to implementation and low cost, with standard technology as far as possible for the array infrastructure. Relevant standards, regulations and other requirements were identified, based on the assessment that it is an off-shore installation, and the choice of Holyhead Deep site off the coast of North West Wales as reference site.

An array design was developed in steps of 3, 12 and 80 MW. The base concept design was defined as 6 kites (3 MW total), connected to one Tidal Marine Substation (TMS). A floating buoy solution was chosen for the TMS. The design of the tidal power array is established and refined using electrical modelling and simulations. In addition, a base design of the TMS buoy hull structure, layout of electrical equipment, cable handling and mooring solution was achieved.

This first conceptual design study has identified a number of key design issues, both for array and the kite. These are being addressed in the current project and/or will be fed into to the future development.
Alternative technological solutions are explored for future performance improvement and reduced costs of the kite and the system.

Keywords- Deep Green technology, Offshore array system, Powerkite project, Tidal energy

I. INTRODUCTION

Deep Green is a subsea tidal kite that consists of a wing, carrying a turbine underneath, which is attached to the sea bottom with a “tether” containing load bearing rope, communication and electrical cables. The kite is steered in a predefined, 8-shaped trajectory (Figure 1). The wing multiplies the velocity of the water flowing through the turbine using the same physical principle as a sailing boat that sails faster than the wind blows. This enables the converter to operate at lower tidal velocities than other technologies and use less material in construction in relation to installed capacity.

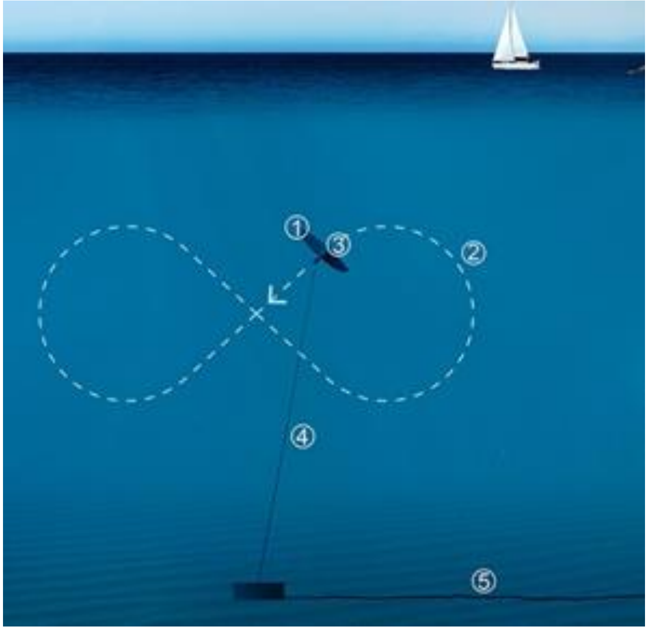

Figure 1. Kite in 8-shaped trajectory

The Powerkite project is developing a power take-off system (PTO) for the novel tidal energy converter by Swedish developer Minesto known as Deep Green.
The overall objective of the Powerkite project is to enhance the PTO for a next generation tidal energy generator to ensure high survivability, reliability and performance, low environmental impact and competitive cost of energy in commercial phases.

One of the key deliverables of the project was to create a concept for a grid connected power system design.
The first step of the design study comprises basic designs for 3, 12 and 80 MW power systems,
The Holyhead Deep site off the coast of North West Wales was chosen as reference site, and whenever possible actual conditions and data was used. Holyhead Deep is the site where Minesto intends to first implement the Deep Green technology in utility scale.

II. RESEARCH ELABORATION

The conceptual design was done in steps of 0.5-3-12-80 MW with low voltage (LV) generators. Later, alternative designs using medium voltage (MV) generators with or without a partial use of a direct current (DC) transmission will be studied with the same models.

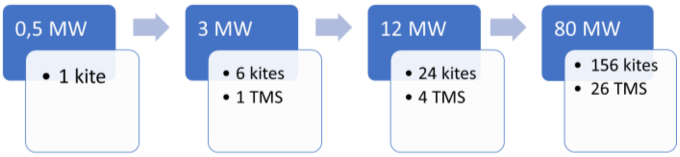

Figure 2. Array design steps

To be able to find and identify relevant standards, regulations and other requirements some basic assessments were made:

- The electrical array is an offshore installation. (Not a marine installation, which implies vessels and do not include fixed installations which are permanently connected to an onshore grid).
- The entire electrical system needs to follow general European requirements for offshore installations.
- Parts of the electrical system needs to follow specific British requirements as parts of the installation is assumed to be erected on British Islands.
- Parts of the electrical system need to follow specific Scottish Power Energy requirements as they have been chosen as a valid representative for the British onshore electrical network.

Then, design prerequisites were established for:

- Deep Green operating principle, PTO, site description, Park size
- Relevant standards and requirements
- Environmental considerations
- Health and safety requirements
- Operation and maintenance strategy
- Installation methodology
- Design targets

Design of the 3 MW array

A sub-array configuration comprising 6 kites connected to the Tidal Marine Substation (TMS) and then to the onshore grid via an export cable was considered as basic array configuration and the building block for the future industrial array (Figure 3). Single line diagram (SLD) of this basic array was used as a starting point for modelling and redesign and then expanded to more complex layouts.

The initial kite design proposal has a low voltage output (500 V). Each kite would be connected to the TMS with the LV (500 V) umbilical cable. The TMS contains a 3.16 MVA stepup transformer 500 V to 33 kV and is connected to the onshore grid substation via a 33 kV export cable (Figure 4). The connection with the local onshore distribution network is supposed to be via an 132/33 kV transformer within the onshore substation. The design of this onshore substation is not within the scope of the project but needed data has been collected from local network owners representing a future possible substation.

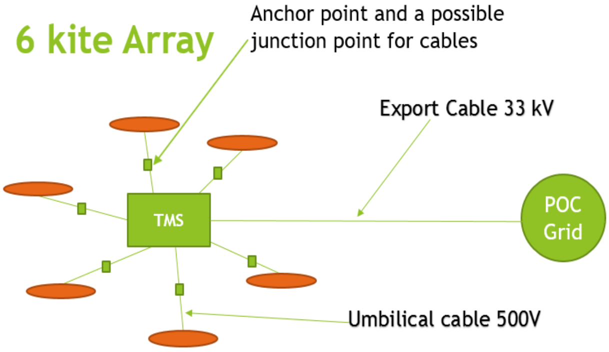

Figure 3. Initial ‘sub-array’ design

Electrical calculations

As part of the design phase electrical calculations were made to verify if the proposed design was able to fulfill project requerements (grid standards, technology components requirements, cost,…).
A number of calculations were executed i.e.:

- Losses
- Short circuit current
- Earth fault current
- (rough estimate of Voltage fluctuations and Flicker)
- Reactive power flow
- Power cables capacity
- Overall efficiency

The modeling software used to analyse the electrical behaviour of the array is EMTP-RV. The 6 kites in the ‘sub-array’ were represented by PQ nodes for the load flow analyses, but they were not represented for the fault current analyses. Their contribution to the fault current was estimated.

The first step was to perform quasi-dynamic simulations (series of load-flows) in which the production fluctuation due to the kite 8 shaped trajectory (Figure 4) was taken into account. This enabled assessment of the efficiency of the transmission chain with a loss calculation as well as the voltage profile along the transmission chain. In addition, it gave an opportunity to assess components of the initial powertrain design proposal (cables, transformers, etc.) and iterate with several alternatives to reach better or optimal solution. The low voltage umbilical cable linking the kite(s) and the TMS are good examples as discussed in the section below.

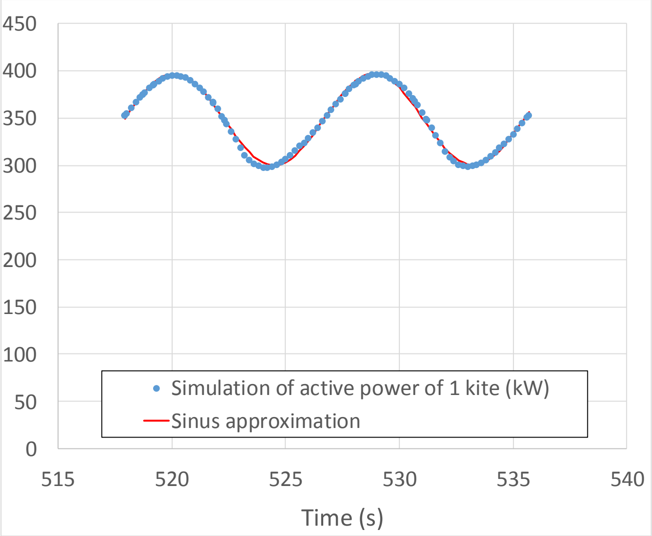

Figure 4. Simulation of the production of 1 kite

Design iterations

The umbilical cables are passing through the specially designed tether that connects the kite to the sea floor. One major challenge is to find an acceptable compromise between the size of cables and the size of the tether. Larger cables reduce electrical losses, but increase the tether size (cross section area) which creates additional drag and thereby reduces the power produced.

Several alternatives for the LV umbilical cable have been considered in order to reduce electrical losses but still be able to accommodate the power cables within the tether:

1) In the first alternative, the LV umbilical cables are composed of 4x50mm² conductors per phase (in total 200 mm² per phase), of a length of 500 m. The use of 4 conductors per phase allows for more physical flexibility of the cable (e.g. lower stiffness). This solution proved to be inefficient as losses in the umbilical were on average 10% of the production.

2) Increasing the total cross section to 280 mm² over the full length of the umbilical LV cable (500 m) did not lead to a significant reduction in electrical losses, but increased cable weight and size which is negative for the operation of the tidal kite.
3) The third alternative was to split the LV umbilical cable in two parts: first a 100 m cable ‘flying’ part in the tether with the smaller total cross-section of 200 mm², followed by a 400 m cable laid on the sea floor and with a much bigger total cross-section (740 mm² per phase) in order to lower electrical losses. With this solution, the losses were reduced to 7% of the production.
4) Alternative design work of the umbilical cable continues and is focusing on a higher voltage level or the use of DC cables.

In addition to studying umbilical cable alternatives, other nominal voltage outputs of the kites have been simulated (1.1 kV, 2.2 kV, 3.3 kV). As expected the array presents a better performance with higher nominal kite voltage. The design of the medium voltage generator for the kite solution is addressed in another work package of the Powerkite project.

In addition, modeling identified design limitations of the kite and transmission chain that would restrict the compliance with the local network requirements and propose alternative solutions. In particular the power factor at the point of connection to the grid wasn’t always within the specified limitations. Several solutions to this issue were considered. A first option is to install reactive power compensation units or use the kites to manage the reactive power. Another option is to use an online tap changer at the power transformers.

The kite(s) power production variation of 15% around the average production value results in fluctuations in the output voltage level that are outside of required limits (flicker issues). This needs to be addressed. One way is by phase-shifting the power production from kite to kite in order to control the fluctuation of the array output. In the load-flow simulation of the 6-kite array, several phase shifts have been considered. A phase shift of 60° between the kites allows smoothing of the power exported to the grid, although the power and voltage fluctuations remain the same at the kite output. More detailed quantification of flicker emissions and start-up voltage fluctuation are ongoing.

The second step was to proceed with short-circuit simulations, in order to assess the adequacy of the circuit protections and thus the assets safety. This exercise resulted in proposal of mitigation measures for very low fault current that might be difficult to detect by the overcurrent protections. The mitigation measure was to adapt the section of the earthing wire in the LV cable. The result was a larger cross section of the earthing wire which allowed for higher fault currents that could be more easily detected.

Design of the 80 MW array and first results

The results from the 3 MW simulations allowed to continue with the design options for larger arrays at the reference site. Intermediate design results for the 80 MW case are described below.

Several options for the configurations of the full-scale array were studied with one choice considering the division of kites in 3 parallel export strings and thus export cables (Figure).

The strings are composed of up to 9 TMSs in a daisy chain, each TMS connecting 6 kites. The cross-section of each MV cable connecting the TMSs is adapted to the cable location, considering that cables closer to the onshore substation will require higher capacity.

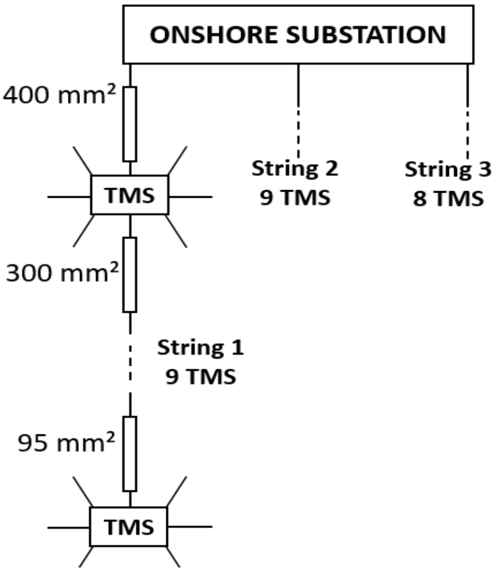

Figure 5. Schematic of the 156 kite array (80 MW)

In the simulation of the full array the switch was made from 50 MVA to 100 MVA transformer at the onshore substation. The cross-section of the export cable between the onshore sub-station and the closest TMS is 400 mm$^{2.}$

Again the modeling software EMTP-RV was used to analyse the electrical behaviour of the full array. The 156 kites were represented by PQ nodes for the load flow analyses. However for the fault current analyses, they were represented by three-phase voltage sources behind a short-circuit impedance. This allowed to take into account their contribution to the fault current, considering that their contribution was not negligible as was assumed for the 6 kite array.

The load flow, short circuit and flicker calculations on the 80 MW array are ongoing.

Conclusions electrical design

The initial design of the umbilical cable between the PTO and the TMS and the use of a low voltage system, (500 V from the PTO to the TMS) resulted in high electrical losses. Alternative designs of the umbilical cable in conjunction with a higher voltage level were defined and appear to be a way to reduce these losses to acceptable levels.

Fluctuation in the output voltage level needs to be balanced to stay within required limits. One possible mitigation is grouping six kites together as one production group with 60 degrees shifting between each power kite. Other solutions are currently being studied.

The Power Factor requirements at POC are difficult to ensure. A shunt-reactor at the coupling point to adjust the Power Factor is most likely needed.

A number of relevant standards and requirements for the design and installation of an offshore power generating system have been investigated, identified and used in the design work.

Operation, maintenance, safety and environmental considerations and analyzes has been executed concurrently during the design process.

TMS buoy

A tidal marine substation (TMS) is required to receive the generated power from the tidal kites, transform it into the correct electrical supply for transmission to shore, and connect to the export cable. This substation needs to be housed in some way. Here the base case design is presented: the TMS Buoy Concept, which is a buoy solution with integrated HV switchgear for connection to next TMS and/or export cable. There are two main design challenges connected to this concept, one concerning the mooring system and the other regarding the umbilical cables connected to the TMS buoy, which need to be solved to make the concept feasible. The TMS Buoy Concept was designed to meet these challenges and resulted in a cylindrical TMS buoy, moored to the seabed by a three-legged mooring system and with eight 8 electrical Cables (6 umbilicals and 2 inter-array cables) connected to it.

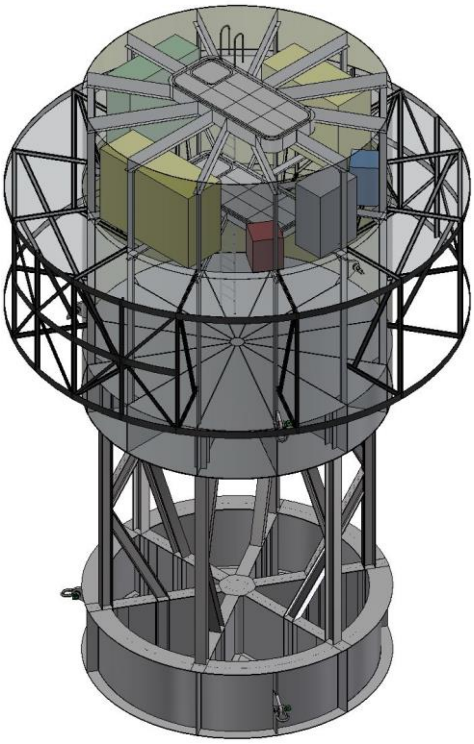

Figure 6. TMS buoy

The TMS buoy has a diameter of 8m, 17,5m in height and a weight of 110T when fully equipped. The electrical control equipment and cables are housed in the hull in the upper part of the buoy. There is a ballast base in the bottom, connected to the upper hull by a lattice structure. The buoy's integral buoyancy is 6T but needs to be increased to 45T to provide enough tension on the moorings. The mooring system is an individual system with separate anchors. Each mooring leg consists of a mooring line, clump weight, ground chain and mooring anchor. The mooring line is a polyester fiber rope taut leg riser with a bridle connected at upper and lower padeyes on the buoy lattice structure. One of the challenges with the design of the mooring system is the small spread in relatively shallow water, a diameter of 250m in 85m depth.

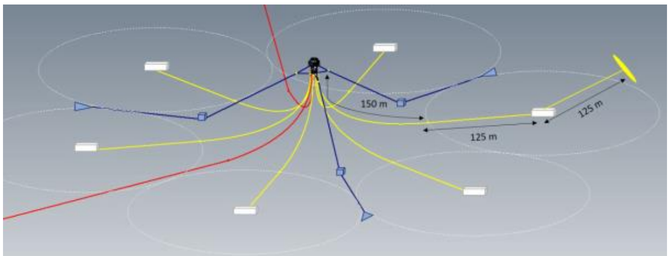

Figure 7. Schematic of 6 kites sub-array with TMS buoy, cables and moorings

Figure shows a schematic of the 6 kite setup. Mooring lines are in blue color, the umbilical electrical cables in yellow and the export cables in red.

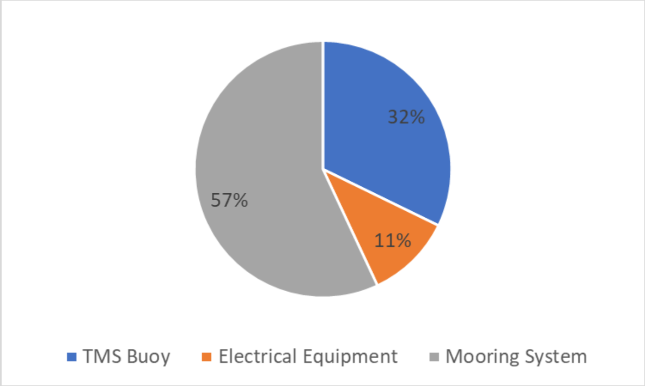

Figure 8. TMS cost. Total estimated cost 2.2 M€

Total cost for one TMS buoy for the 80MW array (26 pieces) was estimated to be ~2.2M€. The electrical equipment cost is based on budget prices from standard electrical components. The main parts of buoy were designed in detail and their weights generated by the CAD software. The price for the buoy is the weight multiplied by 7.5 €/kg, (including classified steel, welded and painted) to which is added estimated costs for auxiliary systems and 20% contingency.

Installation costs are included, but not cables or cable installation.

The mooring system is the most expensive part (57%), followed by the buoy itself (32%), while the electrical system is relatively cheap because of the use of standard equipment.

III. RESULTS & FINDINGS

A modular design for the tidal kite array has been proposed, consisting of the 6 kites connected to the Tidal Marine Substation (TMS). This base sub-array will allow easer building up of any future industrial array.

The array infrastructure design included standard components chosen for their robustness and with focus on a short time to implementation and low(er) cost. For the TMS buoy, the mooring system is the costliest part, the electrical components are comparatively cheap.

The TMS buoy design includes: hull structure, layout of electrical equipment, cable handling and mooring solution. The TMS hull contains LV and HV transformers and switchgears allowing connection of up to 10 TMS in a daisy chain arrangement. The movements of the kites and the TMS buoy during operation proved to be a design challenge for the cable connecting systems, as cables of high endurance and robustness combined with high flexibility are required.

The efficiency, power quality and asset safety for the grid connected 6-kite tidal power array has been analyzed using power system simulations. More optimal solutions and /or mitigation measures for issues encountered have been proposed. Using the modular property of the array design the full-scale array for the project reference site has been modeled and simulation of the electrical behaviour is ongoing.

IV. CONCLUSION

In conclusion, the conceptual design of the array infrastructure and simulation performed have allowed identification of important design issues both for the array and the kite design. These are being addressed in the current project and/or will be fed into to future development.

The next steps include live testing and measurements on the full scale (500kW) kite components, in order to have real data inputs for more detailed and accurate dynamic power system simulations

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