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First techno-economic evaluation of array configuration of self-balancing tidal kinetic turbines

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ABSTRACT

Whit the aim to exploit tidal currents as clean, predictable and renewable energy source, the authors have developed a self - balancing turbine prototype, able to work like a kite and moored to the shore by a simple rope.

In the present work, the authors describe how this particular machine could be used in array configuration. First step involved the technical definition and the performances assessment of the array, constituted by several turbines connected each other by tubular elements and floating deflectors. Such a layout allows the array to have an “accordion effect” by extending and gathering it-self, according with the phases of flow and slack tide.

Through an economic model the optimal number and diameter of the turbines has been successively detected which, maintaining the same power of other configurations, minimizes installation costs.

Finally, the proposed methodology has been applied at a particular site (Strait of Messina - Italy), where the yearly energy yield and the levelized cost of energy have been evaluated.

1Introduction

In an ever more problematic energy scenario, characterized by the depletion of traditional sources [1], oceans and seas offer several possibilities for drawing energy from their motion [2]. Tidal currents are a huge and renewable source of energy, generated from the periodic variations of the gravitational attraction between the earth, moon and sun. It is an easily predictable clean source because tides are cyclic [3]. Several works illustrate the potentiality [4] of sites scattered around the world, but at the date, they have been exploited in a minimal part.

The technology for the exploitation of tides is still not effective mostly due to the high cost of the infrastructures supporting the machines and the connections for driving the energy to the end user. More technical improvements are required to make it commercially viable: the main issue, involving many challenges, is the complexity of conversion of sea motion into electricity [5].

Water in constant motion stresses the hardware due to waves and currents large forces meanwhile marine growth and corrosion must be accounted for and prevented. Once the systems generate electricity, it must also be collected and transmitted so the electrical aggregation and transport to shore begins a significant challenge. Cabling and common substation and power electronics solutions [6], used on land, are much more difficult and expensive to set up, requiring special design considerations to protect them from the marine environment while also retaining the ability to access them for necessary maintenance.

Moreover, critical components, such as, Power Take Off (PTO), power electronics gearbox, moorings, and servomechanisms, play a significant role in safeguarding the overall reliability.

Since the captured energy is determined by the blade area, large quantities of energy can be converted by wide turbines, as demonstrated by several pilot plants installed as a first step of development. This solution, characterized by installations stand-alone with a single turbine, involves a number of issues related to the blades structural strength, stability and control also considering the harsh climatic conditions (i.e. storms) together with very large basements or pylons needed to support the turbine and, last but not least, maintenance.

Several marine technologies are quite at Technology Readiness Level (TRL) 7–9 [7], approaching industrial production (pre-commercialization step): at this stage, one of the main challenges is the cost reduction with increased efficiency in order to make any

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Nomenclature

A_{fl}	floating deflectors area [m^2]
A_i	tidal harmonic constituent [m/s]
A_m	tidal harmonic constituent [m/s]
A_{tub}	frontal area of tubular elements [m^2]
A_{rot}	disc or rotors area [m^2]
C	cost [€]
C_D	drag coefficient [–]
$C_{D\ fl}$	drag coefficient of the floating deflectors [–]
$C_{D\ tub}$	drag coefficient of the tubular elements [–]
C_L	lift coefficient [–]
$C_{L\ fl}$	lift coefficient of the floating deflectors [–]
$C_{L\ turb}$	lift coefficient of the turbines deflectors [–]
C_P	power coefficient [–]
C_u	unit cost [€]
D	turbine diameter [m]
D_{defl}	drag force on the deflectors [N]
D_{fl}	drag force on the floating deflectors [N]
D_e	turbine external disc diameter [m]
D_i	turbine internal disc diameter [m]
d_{tub}	diameter of the tubular elements [m]
D_{tub}	drag force on the tubular elements [N]
E	floats profile efficiency [–]
E_p	blades profile efficiency [–]
f_i	tidal current hourly absolute frequency [h]
h	distance from the coast [m]
h	distance at which wakes produce interference [m]
h_{lim}	limit distance from the coast [m]
k	vertical velocity constant [–]
K	power constant [–]
L_{defl}	lift force on the deflectors [N]
L_{fl}	lift force on the floating deflectors [N]
l	length along the array [m]
l_{tub}	length of the tubular elements [m]
L_{tot}	array total length [m]
m	turbine margin under sea surface [m]
M	moment [Nm]
N_{turb}	number of turbines [–]
N_F	floating deflectors number [–]
N_T	turbines number [–]
n	hours number [–]
P	power [kW]
q	safety distance between wakes and turbines [m]
r	generic radius [m]
r	diameters ratio [–]
R	resultant force [N]
R_e	turbine external disc radius [m]
R_i	turbine internal disc radius [m]
T_A	Archimede's Thrust [N]
T	turbines thrust [N]
t	time [h]
V	tidal current velocity [m/s]
V_o	rated/undisturbed tidal current velocity [m/s]
V_b	reduced tidal current velocity [m/s]
V_p	peak tidal current velocity [m/s]
W	turbine weight force [N]
z	vertical depth [m]
z	number of blades [–]
z_o	seabed depth [m]

Greek letters

α	slope of the cost function when plotted on log-log chart [–]
β	positioning array or turbine angle [°]
δ	opening wake angle [°]
η_{Em}	electro-mechanical efficiency [–]
λ	tip speed ratio [–]
φ_i	phase of the harmonic component [°]
ρ	water density [kg/m^3]
θ	generic radius angle [rad]
ω_i	angular frequency of the harmonic component [Hz]

investment for deployment economically viable and attractive.

In order to reduce costs and risks, the next step of development focused on a few main points: small scale machines, components and supply chain optimization, no seafloor structures.

The small scale solution implies the design of several machines (installed in array) to reach the same power as a wider one, involving a cost reduction due to a cheaper learning scale of production, low risks, mainly during the early phase of the test (lower loads on the structures, increasing survivability during operations), and lower maintenance costs and challenges.

Nowadays the companies working in this field, which reached competitive T.R.L. (8–9) by testing their full-scale prototypes in a real environment, plan to develop turbine arrays whose installed power is significantly large (5–10 MW).

Minesto is developing a 1.5 MW Deep Green demonstrator array, and planned a 10 MW array in the future [8].

Marine Current Turbines Ltd (MCT), with RWE Npower Renewables, submitted a consent application for a power plant of 10 MW, a tidal turbines array on the North West coast of Anglesey [9]. In November 2007, the British company, Lunar Energy [10], announced the intention of building the world's first deep-sea tidal farm off the coast of Pembrokeshire in Wales.

British Columbia Tidal Energy Corp. planned to deploy three 1.2 MW turbines in the Campbell River or in the surrounding coastline of British Columbia by 2009 [11].

Alderney Renewable Energy Ltd [12] was granted a licence in 2008, planning to use tidal turbines around Alderney in the Channel Islands, assuming that up to 3 GW could be extracted. OpenHydro's turbine was selected for a tidal energy demonstration project in the Bay of Fundy, Nova Scotia, by Nova Scotia Power, and Canada and Alderney Renewable Energy Ltd for supplying tidal turbines in the Channel Islands [13].

Verdant Power Ltd [14], already developed some array solutions for increasing the productivity and reducing overall machine dimensions.

The above-described solutions involve high initial capital increasing the Levelized Cost Of Energy (LCOE) [15] to a still not competitive value, so that these are frequently defined as "planned installation" and, in several cases, there is a leak of updated information, owing to the fund raising issues. For these reasons up to now no significant array installation has been developed.

The present paper approaches a possible solution to the above issues, through the study of a specific marine turbine typology installed in an array configuration.

This turbine, developed by the authors in several research years, operates like a kite being connected to the coast by a simple rope, and, thanks to some specific components, it is always able to find an equilibrium position in the sea, which does not change when a tidal current change happens. Several works gave further evidence of the idea [16,17] by numerical simulations and equilibrium equations,