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Innovative tidal turbine with central deflector for the exploitation of river and sea currents in on-shore installations

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ABSTRACT

The paper presents an innovative system for the collection of energy from river and tidal currents, designed with the objective of combining high performance, cost-efficiency and simplicity. The proposed system consists of a kinetic turbine able to be immersed inside water currents and kept in equilibrium by the action of a central deflector and a steel cable anchored to the shore. The size and the orientation of the deflector are defined according to the working conditions and desired equilibrium position. The paper also describes the design parameters of a demonstrative installation at Punta Pezzo (Villa San Giovanni, Italy), located in the Strait of Messina. In the selected site, nearby the coast, the peak current speed reaches 3 m/s (6 kn). The turbine and its components have been designed assuming that the machine will always work under maximum power coefficient conditions. This implies a variable rotational speed, so the use of an inverter becomes mandatory. Preliminary performance estimations show that the system can provide electrical power of about 470 kW, with 43% efficiency when the system works under optimal conditions.

1. Introduction

Tidal currents [1–4] are considered a renewable resource of particular interest taking into account the increasing demand of renewable energy production worldwide due to the strict environmental legislations and the need of gradually replace fossil fuel-based energy sources. Many sites around the world are characterized by the presence of water currents with velocities greater than 3 m/s [5]. Unlike marine currents, tidal currents, are bidirectional and located near coastal areas. These high energy currents are generated by gravitational forces and located in river or marine canals, estuaries, or narrow straits, always located nearby the coast or beside the margin of specific aquatic environments. These tidal currents (as opposed to river and ocean currents) are not affected by climate changes and occur with a constant cyclical period, being perfectly predictable. The installation of traditional off-shore (DeltaStream, Evopod Tidal, Free Flow, Gorlov Helical, Lunar Energy Tidal, Open Center, Seagen, Kobold Turbines [1,2,6–10]) tidal devices intended for the collection of these resources are still at an early stage of development and none of their has demonstrated superiority over the others. They are considerably expensive, time consuming and require high skilled personnel. The installation of on-shore systems is significantly cheaper, simpler and faster. However, their profitability is still conditioned by the presence of sufficient resource, as well as an optimal bathymetric profile, where the depths fall quickly near the coast. The environmental impact of state of the art technologies is also a relevant feature that has been considered for the design of the present turbine, avoiding any interference with the seabed flora and fauna.

The development of a tidal energy farm in a site with sufficient tidal potential (i.e current speeds over 3 m/s) leads to more attractive revenue opportunities, although installation costs may rise the faster the current is, due to the more intense stresses that the system has to cope with. Higher powers can be generated by using one or more turbines fitted to the frame and directly linked to the coast. The main challenge of such a configuration is to keep the turbine(s) in equilibrium inside the currents and harness the maximum amount of energy (i.e oriented frontally with respect to the flow). It is therefore necessary to devise a structure anchored to the coast, able to operate with strong tidal currents and a turbine oriented frontally with respect to the flow, even when it changes direction.

In this context, a basic research has been carried out in collaboration with two companies, Sintenergy Ltd. and Develpack srl of Reggio Calabria, in order to achieve scale models for laboratory testing and measuring. After designing and validating an optimized

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Nomenclature

a_o	gradient lift curve – infinite aspect ratio
A_{rot}	rotor area (m^2)
A_{Defl}	area of the deflector (m^2)
b	length of the deflector (m)
c	cord length of rotor blades (m)
C_D	drag coefficient of the deflector (–)
C_I	first investment of the system (€)
C_L	lift coefficient of the deflector (–)
C_{Lo}	drag coefficient for infinite aspect ratio (–)
C_{lp}	lift coefficient of rotor blades (–)
$C_{material}$	material cost of rotor blades (€/kg)
C_{base}	fix cost of the blades (€)
C_P	power coefficient
C_{blades}	total cost of rotor blades (€)
D_e	external diameter of the turbine (m)
D_i	internal diameter of the turbine (m)
D_r	drag (N)
e	Oswald's factor (–)
E_o	energy flow in input (kW h)
E	hydrodynamic efficiency of the deflector (–)
E_p	hydrodynamic efficiency of rotor blades (–)
$f_{s,ax}$	friction axial coefficient (–)
$f_{s,rad}$	friction radial coefficient (–)
h	distance of the turbine from the coast (m)
i	discount rate (–)
L	length of the frame (m)
L_r	lift (N)
m	diameter of the deflector (m)
M_{st}	available torque at startup (Nm)
$M_{fr,ax}$	friction axial torque at startup (Nm)
$M_{fr,rad}$	friction radial torque at startup (Nm)
M_{electr}	electro-magnetic torque at startup (Nm)
n	width of the deflector (m)
N	rotational speed of the turbine (min^{-1})
N_u	investment duration (years)
P_r	fluid dynamic power of the turbine (kW)
P_e	electrical power of the turbine (kWe)
W	blade weight (kg/blade)
r	radial distance of the rotor blade sections (m)
R	resultant of the forces on the frame (N)
R_{bear}	bearing radius (m)
S_{ax}	axial thrust on the bearings (N)
S_t	tangential action due to the lift thrust (N)
T	dragging force on the turbine (N)
u	peripheral velocity (m/s)
v_o	velocity of the undisturbed current (m/s)
v	velocity of the current in turbine input (m/s)
v_2	velocity of the current in turbine output (m/s)
V_{st}	current velocity at startup of the turbine (m/s)

Greek letters

α	incidence angle of the deflector (°)
α_p	rotor's optimal incidence angle (°)
β	position angle of the turbine (°)
β_p	attack angle of rotor blade (°)
λ^*	blade aspect ratio (–)
λ	tip speed ratio (–)
ρ	fluid density (kg/m^3)
η_m	mechanical efficiency of the system (–)
η_E	electrical generator efficiency (–)
σ	rotor solidity (–)

prototype, it is possible to build real-scale systems for deployment in suitable areas for large diameter turbines. Rotors between 10 and 12 m. are capable of delivering hundreds of kW and be competitive in the renewable energy market.

2. Operating principle of proposed solution

The proposed system [11] takes into consideration the possibility of operating a turbine moored to the shore with a non torsion and non bending anchoring system. A solution for this purpose is shown in Figs. 1–3. The turbine is connected to the coast by means of an extensible steel cable, led by a rigid rod, rather short, hinged to the coast. The rod can suitably rotate for a given angle β and the cable can extend to the desired length L, so that the turbine can reach a distance $L\sin\beta$ from the coast (see Figs. 1 and 2). This system allows the turbine to find a symmetric equilibrium position when the current changes direction.

When the inversion of the tide occurs, a special mechanism does the following actions, in sequence:

- rewind the rope, so that the turbine moves from position 1 of Fig. 1 at positions 2 and 3 without changing the angle β_1;
- rotate the rod, so the turbine passes through the positions 4 and 5;
- release the rope, so that the turbine, after passing position 6, finds a new equilibrium in position 7, characterized angle β_2.

The rope, indeed, is subjected to a pure tensile stress. For this purpose, the turbine is equipped with a central deflector visible in Fig. 2 and 3. The deflector (see Fig. 4) is suitably inclined with respect to the current direction at an angle α and produces a lift force equal to L_r, compensated by the force T, due to the rotation of the machine. This action allows the system to remain in equilibrium in the desired position. Fig. 2 illustrates the forces involved in the system: all the forces involved are combined into a resultant R, which is aligned to the system ground connection. This device has therefore suppressed any bending effects of on the supporting structure, being subjected only to a tensile stress always aligned with the horizontal frame.

Fig. 3 represents the overall design of the turbine (frontal & side views). The torque exerted on the turbine's rotor is fully counterbalanced by the effect of a buoyant system, as seen in Fig. 3 (right). The buoyant system is connected to a floating structure that will host the generator/alternator. The rotational motion is transmitted to the generating device by a drive shaft with bevel pinion connected through a sprocket. The alternator/generator will have a built-in Maximum Point Power Tracker (MPPT, able to vary the shaft's rotational speed in order to convert the maximum available power), so the turbine will work at variable rotational speed. In addition, a rigid frame (see Fig. 3) has been projected in order to connect the rope to the vertical diameter of the turbine and, therefore, guarantee vertical equilibrium.

The turbine's weight and the sustaining effect of the buoyant system create a stabilizing momentum opposing to that developed by the blades' thrust and overall drag and the reaction of all the forces on the cable. The eventual vertical deviation has been estimated in an angle of few degrees, which would not have significant effects over energy conversion. Eventual misalignments between the rope and the rod are a solvable problem (using, for example, pulleys or a simple counterweight), although this matter is not among the objectives of the present work.