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Performance of a hydrokinetic energy system using an axial-flux permanent magnet generator

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ABSTRACT

The high density of water has been an important factor for harnessing kinetic energy from marine current flows, tides, flowing rivers, or other artificial water channels. Thus, new technologies are being developed to generate electricity. A good example is HKES (hydrokinetic energy systems), which are devices that extract and convert energy from the motion of flowing water into electricity. Although these non-polluting machines and/or devices are still in their pilot phases, they have been growing as a sustainable source of new electric power generation. In this paper, the performance of a horizontal hydrokinetic energy system with variable-pitch blades using an axial-flux generator is evaluated. Particularly, very simple sheet blades have been used to keep system cost down. The evaluation is based on maximum power extraction and energy conversion efficiency normalized by system cost through a simpler electro-mechanical design for the hydrokinetic system. Experimental results have demonstrated that the proposed prototype possesses higher efficiency with reduced energy losses and manufacturing costs. It represents a cost-competitive alternative energy for power supply for civilian applications in remote areas or an option for expeditionary applications.

1. Introduction

Alternative energies are derived from replenishable natural resources that do not use up nonrenewable natural resources or harm the environment [1]. Since these alternative energies have been considered as a viable and non-polluting source of renewable power, new methods of generating electricity have been developed. Additionally, sustainable energy technologies have been increasing significantly and have become more cost-effective.

In the last several years, both the focus and improvement of power generation from hydrokinetic energy have grown rapidly due to environmental concerns and decreased fossil fuels. Hydrokinetic energy is currently the second largest source of alternative systems and is the cheapest way to generate electricity [2]; however, the payback period for this energy is longer than for other types of energy production. Hydrokinetic energy systems are gaining more interest around the world, since the significant environmental impact of conventional hydroelectric systems has caused their production to decrease more than 10% from 2009 [3].

Hydrokinetic systems are defined as electro-mechanical systems that have moving electrical devices and electronics and stationary mechanical components [4]. Such systems extract and convert the kinetic energy from flowing water into a feasible source of power. Moreover, low investment costs and maintenance fees make hydrokinetic systems more cost-effective when compared to other renewable technologies. At present, hydrokinetic systems are not economically competitive with conventional electrical energy production methods; however, technological advancements and system level optimization are expected to elevate hydrokinetic technology to a level where it becomes a viable source without any government push for the technology.

The configuration of these systems requires technical design and a study of economic factors. The mechanical and electrical schemes are extensive, but most of the prototypes are developed from wind turbines [5,6]. Some of the work that has been developed for free-flowing rivers is associated with the axis of the turbine, number of the blades, and efficiency [7,8].

The turbine unit can be placed inclined or straight (horizontal or vertical); these configurations define the pitch of the blades to optimize the angle of attack. Some designs include fixed-pitch blade as Darrieus, Gorlov, and Savonius turbines [9]. Other options have a variable-pitch blade that can be manually adjusted to multiple positions depending on water flow or can be changed automatically. This change means adding an electrical controller to

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optimize the operation of the turbines, but raises the cost of the system; in addition, most of the pitch controllers that have been developed are derived from wind energy [10–12]. The Squirrel Cage Darrieus, the Italian Kobol, and the large ring gear turbines of Salter and Taylor are examples of this type of configuration [13].

Other studies for hydrokinetic turbines with variable pitch are related to computer simulations. For instance, Goralczyk et al. [14] predicted the operational characteristics of axial flow hydrokinetic turbines. Hu et al. [15,16] have reported a reliability analysis for composite hydrokinetic turbine blades with variable pitch. Sheng et al. [17] performed a hydrodynamic analysis of a vertical axial tidal turbine with fixed and variable pitch using CFD (Computational Fluid Dynamics) simulations. Lazauskas et al. [18] predict how variable pitch maximizes the performance of the Darrieus turbine.

On the other hand, conventional studies are focused on the number of the blades, which directly influences the solidity of the system: more blades represent higher solidity because with more surface area the torque is enhanced; but they also represent more manufacturing costs. The TSR (tip speed ratio) optimizes the number of blades in the generator; in Ref. [13] the discussion presented, torque at low TSR can be improved by increasing solidity using cambered, inclined, or helical blades. However, starting torque can be enhanced only when variable-pitch blades are used, but the chord length is affected because the blades are less strong. Some designs are related with fewer number of blades; e.g., the SeaFlow turbine with full-span control. The SeaGen turbine has a twin rotor mounted on a monopole structure; and the SMD-Hydrovision TidEl turbine has two H-axial counter-rotating rotors. All these systems consist of two blades [19].

Moreover, there are turbine systems with multiple numbers of blades such as the Atlantisstrom, the Kobold, and the Neo-Aerodynamic [19]. However, the three-blade configuration represents the optimum balance among solidity, cost, efficiency, and power extraction. Developments include Verdant Power turbines with different capacities, the Free Flow turbine, the WPI (Water Power Industries) turbine, and the Hydro Venturi [20]; all have airfoil profiles on their blades and have higher manufacturing costs. To increase efficiency, prototypes such as the Current Hydro Turbine, the Tidal Energy Pty, and the Lunar Energy Rotech Tidal Turbine also include duct installation for higher water inflow velocities. Ponta et al. [21] introduced some of this work.

All the former work reports progress in hydrokinetic energy systems; however, significant research remains to solve the need for energy conversion more economically. A previous work proposed a hydrokinetic energy system with simple, low-cost, and fixed-pitch blades using a radial PMG (permanent magnet generator). To improve this energy conversion efficiency is the basis of this work, which consists of a detailed study of the electro-mechanical design, development, and performance of a HKES (hydrokinetic energy system) with variable flux generation. This type of technology enables the level of power production and cost-benefit from wind or water turbines at low RPM (Rotation Per Minute) and flow velocities [22–24].

In particular, this paper is related to the extraction of maximum available energy, torque production, and final power generation from the design of a HAHT (horizontal-axis hydrokinetic turbine) with variable pitch to speed up the starting torque and reduce vibration problems. Moreover, a coreless, axial-flux PMG was constructed, similar to [25–28] to increase efficiency, but using a simple controller; the design differed mainly on the number, grade of the magnets, and the number of the coils to increase electrical output and efficiency. According to Ref. [25], round magnets are more powerful than rectangular but are more expensive. The current generator has huge power output at very low rotation rate because it has larger diameters that augment the torque compared to radial PMG that needs to revolve above 1500 RPM to generate significant power [29].

Experimental tests were conducted by commercial low-cost blades consisting of two different diameters and blade numbers, where the coefficient of power (c_p) was greater when more blades were used, but the rotor rotation rate stayed almost constant. Furthermore, the current configuration produces more power, operates with greater efficiency and requires less maintenance for small-scale applications. The results demonstrate that the cost-benefit of the hydrokinetic energy system was improved by balancing the simplicity of design, development, reliability, performance complexities, and costs using low-cost blades; but some design parameters might still need to be changed.

2. Method

2.1. Experimental methodology

This work is related to extracting maximum available energy, torque production, final power output, and power coefficient from a ∼19 in diameter rotor with variable pitch. The rotor was tested with three and six commercial blades inside the water tunnel; the test section had dimensions of 3 m × 1 m × 1.2 m with water flow velocity up to 1.3 m/s, thus the maximum power available from the system is 220 W. The pitch of the blade was varied manually from 20° to 45° where maximum energy was extracted, but it was fixed inside the tank. These experiments were carried out inside a laboratory under an average temperature of 25 °C, 60% humidity, and potable water from the tap to feed the water channel.

2.2. Testing setup

An electro-mechanical design was developed to improve power output and the cost-benefit from a hydrokinetic energy system with axial flux generation. The hydrokinetic energy system consists of four subsystems: (a) the hydrokinetic energy converter that includes untwisted, uniform cross-section, low-cost blades with variable pitch; a gearbox and a torque sensor to measure the mechanical power extracted; and the transmission shaft which is integrated by a chain, a 4:1 sprocket ratio; (b) the support structure, a mounting frame that was designed to give more support and avoid bending problems at higher rotational rates due to the torque produced from the PMG; (c) the electrical power converter, an axial-flux generator, which has a proximity sensor attached to the frame to count the RPM; (d) a steel tank with a capacity of 3400 l, the acrylic tunnel, and the artificial water flow system. Fig. 1 provides an overall view of the configuration of the hydrokinetic energy system.

2.3. Mechanical design of the HKES

From a commercial set blade with fixed pitch, a new rotor was designed to use those simple blades, but with variable pitch to enhance efficiency. This assembly is integrated by the hub, blade mount, and the blade mount pivot; all these components are made of stainless steel to avoid corrosion problems inside the water. Plasma cutting was used for easier manufacturing of geometries.

The hub has a cone geometry that allows easier water flow through the blades. The blades were welded to each component, but they can be removed from the hub. The blade mount pivot allows the blades to rotate at the desired pitch. The pivot was manually turned and fixed, so it did not vary inside the tank. Thus, the pivot needed to be changed every time for a different position during testing. Fig. 2 shows a transition from the original set-blade to the variable-fixed-pitch blade.