Electrical Power and Energy Systems 95 (2018) 137–145

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Design and control strategies for a modular hydroKinetic smart grid

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ARTICLE INFO

Article history:
Received 28 December 2016
Received in revised form 18 July 2017
Accepted 21 August 2017

Keywords:
hydroKinetic smart grid
Energy storage
Droop control
Gorlov turbine
Maximum power point tracking

ABSTRACT

This paper sets out to explore and promote the use of a hydrokinetic microturbine module designed to obtain energy from water streams. It is made up of a hydrokinetic rotor, a permanent magnet generator, power electronic stages and a microcontroller to regulate power production. It is further complemented by a control strategy focused on maximizing the electrical power produced when varying different water velocities. This method is based on three operating zones defined by the electrical frequency produced by the generator, and where different values of direct current set points are defined. It is set in motion in a boost converter power stage, using a maximum current control, with constant off time in the power switch, and continuous or discontinuous mode of operation depending on the current value required. The control strategy has been validated though the use of dynamic simulations.

The microturbine modules are suitable for alignment in rows to increase the power produced. The modules connected in smart grids define the hydrokinetic smart grid concept. A global control strategy for hydrokinetic smart grids has also been proposed and tested.

1. Introduction

Hydrokinetic microturbines generate power, without any dam or other structure, only from the kinetic energy of water streams such as river flows, tidal currents, channel flows, etc. The power obtained is a function of the density of the water, cross sectional area and the speed of the current cubed [1]. For their operation these turbines require a minimum current and water depth. This energy is predictable, as water currents do not fluctuate as intensely from one moment to the next in the way wind or solar insolation do [2]. That makes it important for supplying base loads.

In a global context in which, the International Energy Agency (IEA) envisages a rise of 30% in the demand for energy by the year 2040 [3]; the population of cities will have grown to two-thirds of the global population by 2050 [4]; and the United Nations are considering offering access to energy in the year 2030 to the most poor and vulnerable zones as a key priority [5], hydrokinetic microturbines represent a reliable energy production alternative.

To date, large companies have developed designs of off-shore large hydrokinetic turbines [6] with the objective of harnessing the considerable energy potential of tidal currents, estimated at 800 TWh/year (mainly in USA, UK and Canada) [7]. The majority of these turbines are axial-flow turbines (rotating axis is parallel to the incoming water stream) very similar to modern day wind turbines [8]. These represent the most efficient conversion technology available, with electrical generators also submerged and powers ranging from 250 kW up to 1.5 MW [8]. But, the marine location of the turbines, away from the coast, requires high investments as well as elevated operation and maintenance costs casting doubts as to their feasibility [2].

However, small hydrokinetic microturbines in onshore or inland (rivers) locations have been found to be a good alternative for the near future. In most cases they are cross-flow microturbines (rotating axis is vertical or parallel to the water surface). Their locations in shallow waters [9], close to land, reduce installation as well as operation and maintenance costs. These microturbines are suitable for running even in bi-directional mode; and more efficiently than axial-flow turbines when packaged in arrays [10] (the sum of rectangular sections allow to capture more energy than using circular sections [8]). They are based on different rotor designs: Gorlov [11], Darrieus [12], Savonius or even hybrid proposals [13].

After carrying out a series of pilot experiments, some microturbine based projects remain in the set-up-to run-phase. For example, Roosevelt Island Tidal Energy (RITE) project in New York [14] using 30 units of 35 kW microturbines in an array to provide electrical supply to the city; or the Maine project in the Bay of Fundy (Canada) [15] using 15 units of 500 kW to generate energy for home and business in east Maine. Also different studies propose hydrokinetic microturbines for the electrical supply of remote

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http://dx.doi.org/10.1016/j.ijepes.2017.08.019

areas in states such as Alaska [16], or countries like India [17] or Nigeria [18].

Moreover, the use of hydrokinetic microturbines presents a reliable opportunity of supplying base loads when incorporated in wind and solar powered smart grids, reducing the uncertainty of these energy sources [19]. This fact increases the feasibility of different renewable smart grids proposals, like designs to power water desalination units in remote areas [20,21] or those that include the effect of electric vehicles charging systems [22].

In order to promote the use of microgrids using hydrokinetic microturbines, this research work includes a detailed design of a hydrokinetic microturbine module (hereinafter referred to as module) and a control strategy to obtain the maximum power at different water velocities. The strategy is based on adjusting the direct current value, produced by the module to a predefined one, depending on the electrical frequency in the PMG. The paper also defines how to apply the strategy within the module.

The simplicity of the design (using off-the-shelf components) and control strategy result in a highly feasible set with reduced costs of installation, operation and maintenance.

Moreover the investigation presents a new approach to smart grid called hydroKinetic Smart Grid (KSG) [23]. The KSG is based on an array of modules perfectly aligned, interconnected using the same bus with loads, energy storage modules and grid tide inverter (in case of connection to the main grid).

2. Microturbine module design

The generic microturbine module is basically made up of (Fig. 1): a hydrokinetic rotor, coupled up using an axis to a Permanent Magnet Generator (PMG) (taking into account recommendation exposed in [24]); a power rectifier and a boost converter (connected to the PMG); with a microcontrol unit (MCU) to regulate the production of microturbine power. An optional gearbox is included to match up the rotational speeds of PMG and rotor if needed.

The components are assembled adhering to a mechanical proposal that allows the easy extraction of the rotor to facilitate operation and maintenance tasks. These include the rotating elements, a floating structure and an assortment of mechanical pieces to support the complete set (Fig. 2). The latter used for the supporting objective are: a non-rotative axis with axial and radial bearings; and different pieces to support the rotor blades and the PMG.

2.1. Hydrokinetic rotor

In this specific case a Gorlov rotor has been selected because its high efficiency [13].

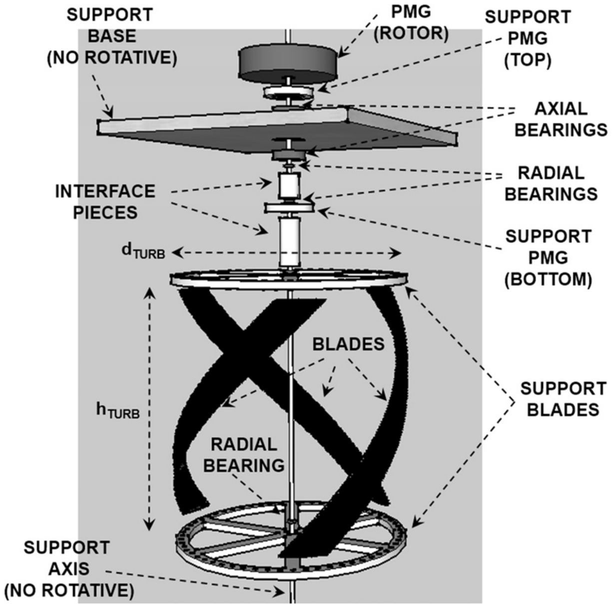

Fig. 2. Mechanical design of a module.

The following expressions, (1)–(3), are used to calculate the hydraulic power that the rotor can extract from the water

$$P_h = \frac{1}{2}\cdot\rho\cdot h_{rotor}\cdot d_{rotor}\cdot C_f(\lambda,\beta)\cdot v^3 \tag{1}$$

$$C_f(\lambda,\beta) = c_1\cdot\left(\frac{c_2}{\lambda}\cdot c_3\cdot\beta - c_4\cdot\beta^x - c_5\right)\cdot e^{\frac{c_6}{\lambda}} \tag{2}$$

$$\lambda = \frac{w\cdot R_{rotor}}{v} = \frac{n_E\cdot\pi\cdot R_{rotor}}{30\cdot v} = \frac{n_E\cdot\pi\cdot d_{rotor}}{60\cdot v} \tag{3}$$

where P_h (W) is the hydraulic power, ρ (kg/m^3) is the water density; v (m/s) is the flow velocity; h_{rotor} (m) is the rotor height; d_{rotor} (m) and R_{rotor} (m) are the diameter and radius of the rotor; $C_f(\lambda,\beta)$ is the rotor efficiency ratio; λ is the rotor Tip Speed Ratio; β (degrees) is the rotor pitch angle; w (rad/s) and n_E (rev/min) are the rotational speeds of the module; c_1 to c_6 and x are coefficients that depend on the type of rotor [9].

The rotor obtains power from a stream in a range of velocities from a minimum value (v_{min}) to a maximum ($v_{máx}$) with a nominal value (v_n). The specific values depend on the rotor's characteristics. Fig. 3 shows the curve of the C_f versus λ for a rotor with a fixed pitch angle. This is based on the experimental data obtained from

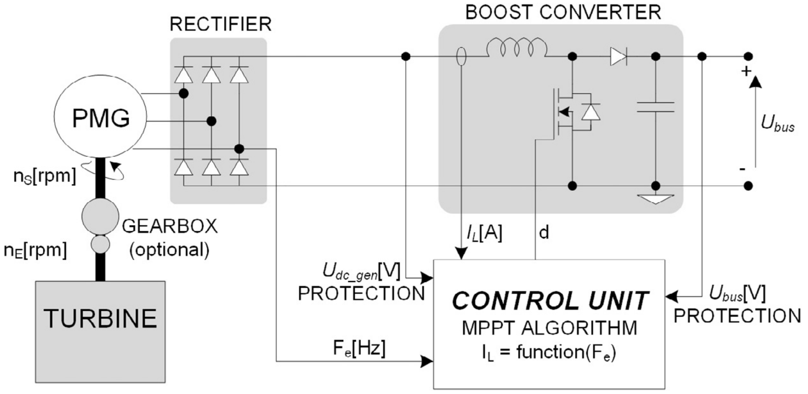

Fig. 1. Microturbine module design.