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On the electromechanical behavior of hydrokinetic turbines

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ABSTRACT

A stand-alone hydrokinetic energy conversion system (HECS), comprising a permanent magnet synchronous generator (PMSG), coupled to a horizontal axis hydrokinetic turbine through a mechanical transmission. The rotor performance is given by a characteristic curve of power as function of the rotation, given in non-dimensional quantities. The transmission is assumed to be of single stage with known mechanical efficiency. Park's transform is applied to obtain the PMSG model, which is connected to resistive and inductive loads. A new method for the rotor angular speed control underwater speed variations, consisting on changing a resistive load connected to the generator, is presented. We present an analytic expression for the value of the resistive load, which keeps the HECS in the optimal operational condition. In addition, the numerical model in used to perform an investigation on the influence of the rotor power curves on the generation system stability and conversion efficiency. The generation system is submitted to variations of terminal load and water speed in order to assess its response in several situations of practical interest. It is shown that rotors which sharp characteristic curves are most likely subjected to severe stopping in the case of stream speed variation or demand variation oscillation, when compared to rotors with more smooth power curves.

1. Introduction

Even in the initial stage around the world, hydrokinetic systems development provides an opportunity to distribute electricity in a sustainable way, by means the harnessing the potential of ocean waves, water canals, and tidal channels. In that sense, efforts for electromechanical emulation of these systems made in laboratories are increasing in the last years. For example, Benelghali et al. [5] have tested experimentally a small-scale marine stream turbine system in order to develop a sizing and a site evaluation tool to this type of installation. Zhou [46] has used experimental data obtained from laboratory testing of a hydrokinetic turbine to validate a maximum power point tracking (MPPT) control system. Likewise, the proposal of Neely et al. [35] was to emulate a hydrokinetic turbine using an induction motor to investigate the dynamic response of a Permanent Magnet Synchronous Generator (PMSG). On the other hand, the knowledge acquired related to operation, modeling and control of wind energy systems can be easily applied to hydrokinetic turbines development. Nevertheless, some important factors as lower tip speed ratios, fluid density and mechanical torque levels [45] must be considered, among others distinctive aspects of hydrokinetic turbines as the possible occurrence of cavitation and the necessity of reliable sealing systems [39].

Hydrokinetic converters can be connected directly to conventional grid or deliver power to isolated loads. In stand-alone wind energy conversion systems, gearless-drive PMSG-based and geared-drive squirrel cage induction generators (SCIG)-based systems represents a possible approach [2]. Moreover, a PMSG has high efficiency and reliability, since there is no need of external excitation Mahersi et al. [29].

Focused on efficiency of turbine conversion, the control methods proposed by different authors include the use of a purely electronic interface to directly change the electromagnetic torque through the modification of current that flows through the stator windings of the PMSG. For example, a well-known method is to control a rectifier by using a pulse width modulator, based on measurements of speed and rotor position. Considering this technique, Masmoudi et al. [30] applied a PI controller to PWM signals to regulate the PMSG currents. Later, Aissaoui et al. [1] proposed to use an adaptive Fuzzy-PI speed controller, giving a better performance. On the contrary, Hong et al. [19] implemented a similar idea in a conversion system without speed and position of the mechanical shaft monitoring. The other part of control systems deals with the stabilization of voltage at adequate levels to supply network or local loads.

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Nomenclature

β	blade pitch angle
$\boldsymbol{T}$	Park's transform
$\boldsymbol{v}_{abc}$, $\boldsymbol{v}_{dq0}$	terminal voltages per phase at dq frame (V)
η_{ct}	gearbox efficiency
λ	tip speed ratio
λ^*	optimal or critical tip speed ratio
ω_e	electrical rotational speed of generator (rad/s)
ω_h	generator rotational speed (rad/s)
ω_h^*	optimal generator rotational speed (rad/s)
ω_{tur}	turbine rotational speed (rad/s)
ω_{tur}^*	optimal turbine rotational speed (rad/s)
ρ	water density (kg/m^3)
Ψ_d, Ψ_q	flux linkage of stator windings in dq frame (Wb)
Ψ_{PM}	flux linkage of permanent magnets (Wb)
θ	mechanical angle of rotor (°)
C_p	rotor power coefficient of turbine
C_p^*	optimal rotor power coefficient
C_{p1}, C_{p2}, C_{p3}	characteristic curves of different turbines
f_g	gearbox multiplication factor
J_h	inertia of turbine on generator side (kg m^2)
J_{tur}	inertia of turbine (kg m^2)
J_1	gearbox first stage inertia (kg m^2)
J_2	gearbox second stage inertia (kg m^2)
i_d, i_q, i_q^*	currents in dq frame and ideal value of i_q (A)
L_d, L_q	inductances of stator windings in dq frame (H)
L_L	inductive load (H)
p	number of generator pole pairs
P	electrical active power (W)
P_{mec}	mechanical power extracted by turbine (W)
P_{mec}^*	optimal mechanical power (W)
Q	electrical reactive power (VAR)
r	rotor radius (m)
R_L	resistive load (Ω)
R_L^*	optimal resistive load (Ω)
$R_{L,C}$, $R_{L,UC}$	controlled and uncontrolled resistive loads (Ω)
R_s	stator windings resistance per phase (Ω)
t	time (s)
T_{em}	electromagnetic torque (N m)
T_{em}^*	optimal electromagnetic torque (N m)
v	water stream speed (m/s)
HECS	hydrokinetic energy conversion system
PMSG	permanent magnet synchronous generator
SCIG	squirrel cage induction generator

Another control method, proposed by Ramirez et al. [38] for an ocean stream turbine, uses a blade element momentum approach. The objective of this strategy is to estimate the hydrodynamic forces and resulting shaft torque about the axis of rotation, aiming to obtain the gain of torque controller for maximization of power coefficient.

Dealing with alternative methods of control of electrical machines for power delivering, Bastos et al. [4] proposed the insertion and variation of resistance in the rotor of induction generator, directly connected to the grid. In this case, the objective is to maintain system stability, resulting in an effective solution to quickly recover its nominal operation speed during short voltage drops.

Nevertheless, the success of any control strategy depends on the capacity of mathematical formulation to accurately represent the steady state and transient behavior. In that sense, the model proposed by Mesquita et al. [31] to fully describe a hydrokinetic system, is comprised of the hydrodynamic rotor design, coupled with the models of multiplier and generator. This model was numerically tested in a startup process, as well as over speed and dynamical conditions.

In this context, we present a mathematical model for the entire hydrokinetic conversion system, considering the influence of the rotor design, the dynamical behavior of the mechanical transmission and the electrodynamic response of the PSMG when combined resistive–inductive loads are considered. This model is used to demonstrate that an additional resistive load connected to generator can help to control rotor speed, aiming to increase the electrical generated power when operational conditions varies. Based on this model, we determine an algebraic expression to the ideal resistive load which leads the system to the maximum power coefficient for a given water stream speed.

One of the key aspects of the hydrokinetic technology is the mechanical power maximization. Following this goal, Guney [17] has proposed an improvement of the profile and shape of blades by using a mechanism of flip-wing or a fixed wing router. Differently, Lazauskas and Kirke [27] predicted that peak efficiency of a turbine with a passive pitch control might be 50% higher than an equivalent fixed pitch turbine, besides reducing the shaking and decreasing the starting torque. From this last concept, Davila-Vilchis and Mishra [12] concluded that efficiency or a hydrokinetic system can be also improved if more blades were used. Another way to increase the generated power is to use a hydraulic diffuser [43], in the so called shrouded-rotors turbines, which aims to increase the flow rate throughout the rotor section.

Most of the studies in the literature focus on techniques to relate the rotor geometry of the rotor characteristic curve. These curves typically associates the mechanical power (or torque) with the rotation speed, or, in terms of non-dimensional quantities, the *power coefficient*, C_p, and the *tip speed ratio*, λ, (both of these quantities will be properly defined later in this work). In that sense, the rotor characteristic curve is a $C_p = C_p(\lambda)$ function. In almost all works found in the literature, focus in on C_p maximization.

One of the most important contributions of the present work is an investigation on the influence of the rotor characteristic curves on the amount of delivered power and on the stability of the whole system. In this study, it is assumed a time varying upstream water velocity, simulating a water stream speed variation event. Among the possible sites suitable for HECS installation are rivers downstream dams of bigger hydroelectric facilities. Most of times, these sites are attractive for HECS assembling because of the availability of electrical power transmission structure, knowledge of the river topology and velocity, diminished amount of debris, and others. However, the majority of these facilities includes dam spillways to allow water height control. The acting of the floodgate may have an important influence on the speed downstream the dam, affecting the HECS performance [26]. Natural events, like upstream storms or tidal bores, as is north Brazilian rivers, may also affect the hydrology system causing river speed variations. Finally, if a HECS is considered to be installed in an ocean or tidal streams, water speed variations are even more frequents. We demonstrated that, in front of river speed and load variations, the dynamical response of hydrokinetic systems can be dramatically different depending on the shape of the turbine's power curve, even if the maximum C_p is the same. Actually, it is shown that some features of a $C_p(\lambda)$ curve can even favor the abrupt stop of the turbine.

The paper is organized in 5 main sections. Section 1 brings the introduction, contextualization of the work and establishment of the goals. In Section 2 the formulation is presented, where each