Ocean Engineering 163 (2018) 275–287

Contents lists available at ScienceDirect

Ocean Engineering

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

A real time sliding mode control for a wave energy converter based on a wells turbine

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ARTICLE INFO

Keywords:
Wave power
Wave energy converters
Sliding mode control
Real-time control
DFIG (doubly-fed induction generator)

ABSTRACT

Due to the nonlinear dynamics and uncertainties usually present in wave energy conversion systems, the efficiency of these devices can be enhanced employing a robust control algorithms. Wave energy converters are constructed using electric generators of variable velocity, like double feed induction generator (DFIG) since they may improve the system efficiency to generate power when compared to fixed speed generators. The main reason is that this generators with variable speed may adapt the speed of the turbine in order to maintain the optimal flow coefficient values which improves the efficiency of the Wells turbine. However, a suitable speed controller is required in these systems first in order to avoid the stalling phenomenon and second in order to track the optimal turbine reference velocity that optimizes the power generation.

In this paper a real time sliding mode control scheme for wave energy conversion systems that incorporate a Wells turbine and a DFIG is proposed. The Lyapunov stability theory is used to analyse the stability of this control scheme under parameter uncertainties and system disturbances. Next, the proposed control scheme is validated first by means of some simulation examples using the Matlab/Simulink software and second using a real-time experimental platform based on a dSPACE DS1103 control board.

1. Introduction

Renewable energy sources (i.e. wind and solar energy) have acquired an increasing interest in the last decade due to the harmful contamination effects caused by the traditional sources of energy. Recently, the international community has also paid special attention to wave energy, which could supply a considerable part of the electricity demand of some countries (Lopez et al., 2015; Reguero et al., 2015; Bailey et al., 2016; Torres et al., 2016).

When the wind blows on the surface of the ocean it causes the waves. In some locations, the wind blows consistently and with sufficient force to produce continuous waves along the shoreline. Since ocean waves contain tremendous energy potential, different wave power devices have been designed to extract their energy. Typically, these devices benefit from the surface motion of ocean waves or from pressure fluctuations below the surface (Ning et al., 2016; Son and Yeung, 2017; Tom et al., 2017). In this study, an oscillating water columns (OWC) device (Mahnamfar and Altunkaynak, 2017), (Rezanejad et al., 2017) is employed in order to extract the energy of the ocean waves into mechanical energy using a Wells turbine (Falcão and Henriques, 2016; Halder et al., 2016; Shehata et al., 2017). The mechanical energy harvested in OWC's is determined by wave height, wave speed, wavelength, and water density (Carballo and Iglesias, 2012), (López et al., 2016). However, the energy produced in these systems can be improved by means of the turbine rotational speed control because the turbine speed affects the hydrodynamic process of wave energy absorption (Henriques et al., 2016a, 2016b; Falcão et al., 2017).

The mechanism of the wave energy conversion systems follows an oscillating movement so the rotor velocity of the coupled electric generator is variable. These systems should incorporate an AC-AC converter in order to generate an electric power of constant voltage and frequency (Tsang and Chan, 2015). However in this configuration the converter should manage all the generated power and this fact present some lacks like the cost of the converters and the power lost in the conversion.

On the other hand the generation system could incorporate the doubly fed induction generator (DFIG) that is currently used by other power generation plants, for example the wind turbine systems, because it allows a variable turbine speed operation (Kahla et al., 2015), (Hamzaoui et al., 2016).

The stator of the DFIG is directly connected to the grid and the rotor of the DFIG is connected to the grid using a variable frequency converter (VFC). The advantage of this configuration is that in order to get

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https://doi.org/10.1016/j.oceaneng.2018.05.058
Received 23 July 2017; Received in revised form 26 May 2018; Accepted 28 May 2018

the total control of the generator, the VFC only have to manage a fraction of the nominal power, around 25%–30%. The VFC incorporates one voltage source located on the side of the grid called grid-side converter (GSC) and another voltage source located on the side of the rotor called rotor-side converter (RSC). These voltage source converters are connected back-to-back through a capacitor (Pena et al., 1996; Song et al., 2010; Barambones, 2012).

This kind of systems are habitually controlled using a vector control scheme and cascaded PI-current and power loops (Taveiros et al., 2015). However the nonlinear dynamics and the uncertainties presented in these systems suggest the use of a more robust controller in order to improve the system performance.

In this sense, one option is to consider the sliding mode control (SMC) because this kind of controller presents a good performance against unmodeled dynamics, insensitivity to parameter variations, and an excellent rejection to the external disturbances (Utkin, 1993). Moreover, the SMC has been used in order to control several types of induction machines in the last decade and good results has been obtained (Barambones and Alkorta, 2014; Soufi et al., 2016; Farhat et al., 2017).

This work presents a real time SMC scheme in order to improve the power generation of a DFIG implemented in a OWC wave power plants. The proposed control scheme regulates the turbine speed in order to track the desired speed that maximize the power extraction from the Wells turbine because it optimizes the Wells turbine efficiency. This optimization of the Wells turbine efficiency is obtained selecting the flow coefficient value that maximizes the power generation. Moreover, this optimization of the Wells turbine efficiency, that maximizes the power generation, also avoids the stalling phenomenon because the proposed control scheme maintains the flow coefficient at the best efficiency point (bep) below the stalling point. There are several works in the literature that regulates the turbine speed in order to avoid the stalling behaviour (Alberdi et al., 2009; Garrido et al., 2012, 2013). However in these works the turbine speed is not regulated in order to follow a reference speed that follows the variation of the airflow speed in order to obtain the best flow coefficient that maintains the system in the bep despite variations of the airflow speed.

The turbine speed is controlled by means of the rotor current of the DFIG using the sliding mode control theory. Regulating the turbine velocity, the proposed control scheme optimizes the flow coefficients in order to obtain the maximum power extraction in the wave power generation plant under system uncertainties and wave power variations.

In order to confirm that the designed controller meets the proposed goals. First, this controller for a DFIG used in a wave power generation plant is validated using the Matlab/Simulink software. In these simulations several operating conditions are tested and satisfactory results are obtained.

Next, the real performance of the proposed control scheme is also validated over a real experimental platform based in a DFIG. The main componentes of this control platform are the dSPACE DS1103 Controller Board, the commercial induction machine Leroy Somer of 7.5 kW and the synchronous AC servo motor 190U2 Unimotor of 10.6 kW. The stator of the DFIG is directly connected to the grid and the rotor of the DFIG is also connected to the grid through the VFC. The shaft of the DFIG and the shaft of the synchronous AC servo motor are mechanically connected so the AC servo motor emulates the torque profiles that the Wells turbine generates as response to the oscillations of the free surface in the OWC chamber. In this experimental platform several real tests, employing different operating conditions, are carried out and the obtained results are satisfying.

This paper is organized as follows: in Section 2 is presented a theoretical modeling of the OWC wave power plant that incorporates a Wells turbine. In Section 3 the design of the proposed sliding mode controller that optimizes the power generation and avoids the stalling phenomenon is presented. Section 4 presents the simulation and the experimental results developed in the experimental platform that is also described in this section. Finally, some concluding remarks are presented in Section 5.

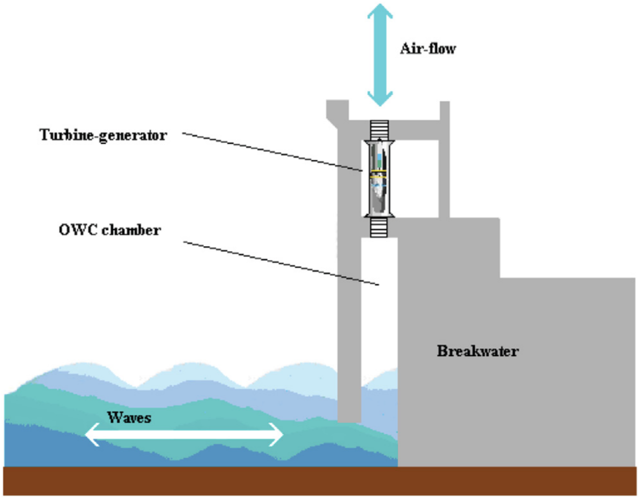

Fig. 1. OWC wave power system.

2. Modeling of the OWC plant

The hydrodynamic energy of the waves can be transformed to an oscillating air flow using the OWC device shown in Fig. 1.

The OWC system is composed of a fixed or floating hollow structure, open to the sea below the water surface, that traps air above the inner free-surface. Wave action alternately compresses and decompresses the trapped air which is forced to flow through a turbine that generates the rotational energy (Henriques et al., 2016b). This turbine is connected to a generator by means of a gear box in order to produce the electrical energy (Jayashankar et al., 2000). It should be noted that the airflow in the chamber is bidirectional depending if the wave is hitting or it is reflected. In this sense, to produce a continuous unidirectional rotation of the electrical generator, the Wells turbine can be used in order to generate the rotational energy. The Wells turbine is a low-pressure air turbine that, independent of the direction of the air flow, rotates continuously in one direction. Prof. Alan Arthur Wells of Queen's University Belfast designed this turbine in the late 1970s.

The power from the OWC available to a turbine is:

$$P_{in} = \Delta p \cdot v_x a \tag{1}$$

where v_x (m/s) is the airflow speed, Δp (Pa) is the pressure drop across the turbine, ρ (kg/m^3) is the air density and a (m^2) is the area of the section of the turbine.

In the OWC system considered in this work, the turbogenerator module is composed by a Wells turbine mechanically connected to an air-cooled DFIG by means of a gearbox in order to increase the rotational speed and accordingly to reduce the mechanical torque.

The rotor circuit of the DFIG is connected to the grid through a VFC and the active power flow between the rotor circuit and the grid must be controlled, both in magnitude and in direction, in order to produce electrical active power to the utility grid at constant frequency and voltage. Moreover, in this machine the rotor speed value can operate in an extended range from subsynchronous speed to supersynchronous rotational speed.

The VFC is composed of two four quadrant IGBT PWM converters usually called grid side converter (on the side of the grid) and rotor side converter (on the side of the rotor). These converters are back to back connected by means of a DC link capacitor.

It should be noted that in this configuration the power electronic converters only need to handle a small portion of the nominal power