CONTROL OF OSCILLATING WATER COLUMN (OWC) WAVE ENERGY PLANTS

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Abstract

Wave energy composes a direct and easy way of harnessing power from the Ocean. Among the different techniques used, OWC devices stand as one of the most promising ones. NEREIDA MOWC demonstration project is a breakwater wave plant located in the Basque location of Mutriku, using Wells turbines and Doubly Fed Induction Generators (DFIGs). Since one of the main objectives when dealing with renewable energies is to make them economically viable to compete with fossil fuels and nuclear fission, all technological improvements are particularly welcome. In this context, this paper presents a control scheme for OWC wave power generation plants that allows to avoid the undesired stalling phenomenon present in Wells turbines. The proposed controller does appropriately adapt the rotational speed according to the pressure drop entry. The results show that the system avoids the stalling behaviour and that the active power of the generator fed into the grid is significantly higher in the controlled case than in the uncontrolled one.

Keywords: Ocean Energy, Wave Energy, OWC, Doubly-Fed Induction Generator, Wells Turbine, Stalling Behaviour.

1 INTRODUCTION

The aim of the NEREIDA MOWC project, promoted by the Basque Energy Board (Ente Vasco de Energía - EVE), is to demonstrate the feasibility of the OWC technology with Wells turbine power take-off into a newly constructed breakwater in Mutriku, in the north coast of Spain. It consist of 16 18.5kW turbines that provide a total power of 296kW [1,2]. See Fig 1. It was inaugurated in July 2011 and produced 200,000kWh during the first year while it was estimated a 600,000kWh production per year. Although the difference if mainly due to a storm that damaged the control room and kept the facility closed during the best wave months, an improvement in the power generation could highly benefit the system.

OWC is considered as one of the best techniques to convert wave energy into electricity. The bottom of the chamber is open to allow water to enter, so that the vertical oscillations of the waves on the outside induce vertical motions inside the chamber (see Fig. 2). As the internal water column oscillates, it displaces the air above...
causing a bi-directional flow through an aerodynamic turbine. Wells turbine, the most popular air turbine in wave energy applications, converts this bi-directional flow in a unidirectional rotational movement. Nevertheless, this kind of turbines are known to be particularly sensitive to airflow rate, since their efficiency drops drastically when the airflow rate exceeds a critical value depending on the turbine’s rotational speed. Thus, adequately matching the DFIG speed to the available wave energy level increases the turbine performance.

2 OWC PLANT MODELLING

In order to achieve a good plant description, a full modelling wave-to-plant must be performed. A number of regular wave theories have been developed to describe the water particle kinematics associated with ocean waves. Fortunately, the earliest description, attributed to Airy in 1845, is sufficiently accurate for many engineering purposes [3]. Linear wave theory describes ocean waves as simple sinusoidal waves. A wave resource is typically described in terms of power per meter of wave front [4].

\[ P_{\text{wavefront}} = \rho_w g H^2 L \left[ 1 + \frac{4 \pi h / L}{\sinh(4 \pi h / L)} \right] \text{(W/m)}. \]  (1)

where, \( \rho_w \) is the seawater density, \( g \) is the gravitational constant, \( H \) is the wave height, \( L \) is the wavelength, \( T \) is the wave period and \( h \) is the water depth.

Equation (2) expresses the power available from the airflow in the OWC’s chamber.

\[ P_{\text{in}} = (p + \rho V_s^2 / 2) V_s a. \]  (2)

where, \( P_{\text{in}} \) is the pneumatic incident power, \( p \) is the pressure at the turbine duct, \( \rho \) is the air density, \( V_s \) is the air-flow speed at the turbine and \( a \) is the area of turbine duct.

The equation for the system turbo-generator can be written as:

\[ J \frac{d\omega}{dt} = T_e - T_g. \]  (3)

The input to the Wells turbine is the pulsating pressure drop across the turbine rotor which is generated due to the airflow from the OWC chamber. The equations for the turbine are:

\[ dP = C_a K (1 / a) [V_x^2 + (r \omega)^2]. \]  (4)

\[ T_e = C_t K [V_x^2 + (r \omega)^2]. \]  (5)

\[ \phi = V_x (r \omega)^{-1}. \]  (6)

\[ Q = V_s a. \]  (7)

\[ K = \rho b h / 2. \]  (8)

where \( dP \) is the pressure drop across rotor, \( C_a \) is the power coefficient, \( k \) is one constant, \( V_x \) is the air-flow velocity, \( Q \) is the flow rate, \( r \) is the mean radius, \( \omega \) is the turbine angular velocity, \( C_t \) is the torque coefficient, \( \phi \) is the flow coefficient, \( \rho \) is the air density, \( b \) is the blade height, \( n \) is the number of blades and \( l \) is the blade chord length.

As is well-known, the main advantage of the d-q dynamic model of the machine is that all the sinusoidal variables in stationary frame appear as dc quantities referred to the synchronous rotating frame [5]. Hence, the equations for the generator are given by:

\[ v_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} + \omega_s \psi_{ds}. \]  (9)

\[ v_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} - \omega_s \psi_{qs}. \]  (10)

\[ v_{qr} = R_s i_{qr} + \frac{d}{dt} \psi_{qr} + (\omega_s - \omega_c) \psi_{dr}. \]  (11)

\[ v_{dr} = R_s i_{dr} + \frac{d}{dt} \psi_{dr} - (\omega_s - \omega_c) \psi_{qr}. \]  (12)

\[ T_e = \frac{3}{2} \left( \frac{P}{2} \right) (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}). \]  (13)

\[ P_s = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}). \]  (14)

\[ Q_s = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}). \]  (15)

and the flux linkage expressions in terms of the currents can be written as follows:

\[ \psi_{qs} = L_s i_{qs} + L_{ml} i_{qr} \ldots \psi_{dq} = L_d i_{dq} + L_{ml} i_{qr}. \]  (16)

\[ \psi_{ds} = L_s i_{ds} + L_{ml} i_{dr} \ldots \psi_{dr} = L_d i_{dr} + L_{ml} i_{ds}. \]  (17)

\[ L_s = L_{ds1} + L_{ms1} ; L_d = L_{qs1} + L_{ms1}. \]  (18)

where \( R_s, L_{ds1}, R_d, L_{qs1} \) are the stator resistance and leakage inductance, rotor resistance and leakage inductance respectively, \( L_s, L_d, L_{ms} \) are the total stator and rotor inductances and magnetic inductance respectively, \( v \) is the voltage, \( i \) is the current, \( \psi \) is the flux linkage, \( \omega_c \) is the stator supply frequency, \( P \) is the number of poles of the machine, \( \omega_s \) is the rotor electrical speed (\( \omega (P/2) \)), \( T_e \) is the electromagnetic torque and \( P_s, Q_s \) are the stator-side active and reactive powers respectively. The subscripts \( s \) and \( r \) denote stator and rotor values refereed to the rotor and the subscripts \( d \) and \( q \) denote the \( d-q \) axis components in the stationary reference frame.

The RSC is widely used to control the Wells turbine output power by means of speed control and the voltage measured at the grid terminals. A common feature of most DFIG-related papers is field oriented control (FOC), which enables decoupled control of active and reactive power. Aligning the \( d \)-axis of reference frame to be along the stator flux linkage (stator flux oriented control), we have:

\[ \psi_{qs} = 0 \ldots \psi_{ds} = \psi_s. \]  (19)

Using the equations, (16), (17) and (19) we have:

\[ i_{qs} = \frac{L_{mq} i_{qr}}{L_q}. \]  (20)

\[ \psi_s = \psi_{ds} = L_s i_{ds} + L_m i_{dr} = L_m i_{ms}. \]  (21)

where \( i_{ms} \) is the stator magnetizing current. Using equations (20) and (21), the equation (13) will result in:

\[ T_e = -\frac{3}{2} \left( \frac{P}{2} \right) \frac{L_s^2}{L_q} i_{ms} i_{qr}. \]  (22)

Besides, using the equations (20) and (21) in (9) and (10) we have:

\[ v_{qs} = R_s i_{qs} + \omega_s \psi_s. \]  (23)

\[ v_{ds} = R_s i_{ds} + L_m \frac{d}{dt} i_{ms} - \omega_c \psi_{qs}. \]  (24)
Considering that the stator is connected to the network and the influence of stator resistance is small, the magnetizing current, \( i_m \), can be considered constant [5,6] and, therefore, the equations (23) and (24) can be rewritten:

\[
v_{qs} = R_s i_{qs} + \omega_s \psi_s \quad \text{and} \quad v_{ds} = R_s i_{ds}
\]

Neglecting stator resistance in the equation (25) will be simplified as follows:

\[
v_{qs} = \omega_s \psi_s \quad \text{and} \quad v_{ds} = 0
\]

Substituting the equation (26) in the equations (14) and (15) we have:

\[
P_s = \frac{3}{2} \frac{L_m \omega_s \psi_s}{L_s} i_{qr}
\]

\[
Q_s = \frac{3}{2} \frac{\omega_s \psi_s^2}{L_s} - \frac{3}{2} \frac{\omega_s \psi_s}{L_m} L_s i_{dr}
\]

And therefore, the above equations show that the active and reactive powers of the stator can be controlled independently by the \( i_{qr} \) and \( i_{dr} \) components respectively.

The torque and power developed by the turbine can be computed based on the behavior of the power coefficient and the torque coefficient with respect to the flow coefficient [7]. These are the characteristic curves of the turbine under study and their shape may be seen on figures 3 and 4.

### 3 STALLING BEHAVIOUR

From the equation (6), it may be observed that when the air-flow velocity increases, the flow coefficient also increases provoking the so-called stalling behavior in the turbine. This behavior is also clearly observable in Fig. 4 when \( \phi \) approaches 0.3. This value may change depending on the characteristic curve of each turbine.

In order to model the waves, it is necessary to take into account the spectrum of the wave climate, which indicates the amount of wave energy at different wave frequencies. Considering this data and the value \( T = 10s \) [8] for the standard input pressure drop in our case, the turbine input may be experimentally modelled as \(|7000\sin(0.1\pi t)|\) Pa, as it may be seen in Fig. 5. With this input, the variation of the flow coefficient for the uncontrolled system may be seen in Fig. 6. It can be observed that its value is higher than 0.3, which corresponds to the stalling behavior threshold value for our turbine. In this sense, figures 7 and 8 show the power extracted from the turbine and generator respectively. As indicated before, it may be clearly observed that the power to be extracted by the turbine and generator is limited by its stalling behavior.

![Fig. 3. Power Coefficient vs flow coefficient](image1)

![Fig. 4. Torque Coefficient vs flow coefficient](image2)

![Fig. 5. \(dP=|7000\sin(0.1\pi t)|\) Pa](image3)

![Fig. 6. Flow Coefficient vs time for \(dP=|7000\sin(0.1\pi t)|\) Pa](image4)
4 CONTROL STRATEGY

As it has been indicated, the undesired stalling behavior can be avoided if the turbine accelerates fast enough in response to the incoming airflow, which can be accomplished by increasing the permissible slip of the generator, allowing the system to reach higher speeds [9]. This speed control may be performed by using different kinds of controllers. Here will be presented the neural rotational speed control strategy depicted in Fig. 9, but it has been also successfully implemented by means of SMC and predictive controllers in the test bench of the group composed by a small wave tank (5m) and a 5.5kW DFIG (see Fig. 10) [10].

It may be seen from the aforementioned figure 9 that the DFIG stator windings are connected directly to the grid while the rotor windings are connected to the back to back converter. The converter is composed of a GSC connected to the grid, and a RSC connected to the wound rotor windings. The RSC controls the active power ($P_s$) and reactive power ($Q_s$) of the DFIG independently, while the GSC controls the DC voltage and grid side reactive power. In this work the RSC is expected to achieve the following objective: to regulate the DFIG rotor speed for maximum wave power generation without stalling behavior in the Wells turbine. In order to achieve independent control of the stator active power $P_s$ (by means of speed control) and reactive power $Q_s$ (by means of rotor current regulation), the instantaneous three-phase rotor currents $i_{r,a,b,c}$ are sampled and transformed to d-q components $i_{dr}$ and $i_{qr}$ in the stator-flux oriented reference frame. A detailed study about DFIG control devices by means of RSC and GSC has been conducted in [11, 12].
The purpose is to calculate the maximum pressure drop across the rotor of the turbine without stalling behavior. To do so, numerous simulations have been carried out in order to study the variation of the flow coefficient for different pressure drops and slip of the DFIG. Using these values, it is possible to derive an optimum range for the slip as a function of the pressure drop avoiding the stalling in the turbine. A summary of these values are shown in Table 1. In this work, various architectures of ANNs, considering three and four layers were tested. Also, different models were considered by varying the number of neurons of the hidden layers, aiming to achieve equilibrium between achieved accuracy and computational cost.

Figure 11 and Fig. 12 show the detailed of typical performance evolution curves corresponding to the training process of two representative net designs. It can be also observed that, although both ANNs adequately match the desired relationship between slip and $dP$, the accuracy of the networks highly depends on the complexity of the chosen design. Besides, the precision of the estimates also depend on the quality of the information used to train the network.

Following this procedure, an ANN with one hidden layer consisting of eight neurons has been chosen for our particular case since it presents an adequate performance to deal with the dynamics of the turbine generator module, and on the other hand, the use of more complex ANN designs does not report noticeable improvements.

Table 1: Flow coeff. vs pressure drop and slip

| $dP=|P_0 \sin(0.1\pi t)|$ Pa | $\phi$ | $\text{slip}_{\text{AVER}}$ |
|-------------------------------|------|-----------------|
| 0–5500                        | 0 – 0.2987 | -0.0056    |
| 5500–5790                     | 0 – 0.2999 | -0.0234    |
| 5790–5975                     | 0 – 0.2995 | -0.0413    |
| 5975–6175                     | 0 – 0.2999 | -0.0600    |
| 6175–6375                     | 0 – 0.2995 | -0.0790    |
| 6375–6600                     | 0 – 0.2995 | -0.0986    |
| 6600–6850                     | 0 – 0.2999 | -0.1194    |
| 6850–7100                     | 0 – 0.2998 | -0.1406    |
| 7100–7375                     | 0 – 0.2998 | -0.1628    |
| 7375–7670                     | 0 – 0.2999 | -0.1860    |

Table 2: Turbine and Generator parameters

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n=8$</td>
<td>$P_o=7079$</td>
</tr>
<tr>
<td>$K=0.7079$</td>
<td>$R_s=0.0181$</td>
</tr>
<tr>
<td>$r=0.7285$</td>
<td>$L_i=0.13$</td>
</tr>
<tr>
<td>$a=1.1763$</td>
<td>$L_m=7.413$</td>
</tr>
<tr>
<td>$P_{atm}=760$</td>
<td>$R_{m}=107.303$</td>
</tr>
<tr>
<td>$T_{amb}=30$</td>
<td>$R_r=0.0334$</td>
</tr>
<tr>
<td>$b=0.4$</td>
<td>$L_{lr}=0.16$</td>
</tr>
</tbody>
</table>

5 RESULTS

In order to probe the performance and goodness of the proposed control scheme, a comparative study for both uncontrolled and controlled cases has been performed. Three different sea conditions have been considered; waves that do not cause the stalling behavior of the turbo-generator group, waves that cause the stalling behavior and irregular waves simulating a real sea state. The parameters of the turbine-generator module are shown in the Table 2.

The first case study considers waves producing pressure drop variations of $|7000 \sin(0.1\pi t)|$ Pa, which produces the stalling behavior in the uncontrolled system. Fig. 13 shows the variation of the flow coefficient for this case. As it may be observed, the flow coefficient reaches the stalling threshold value, as shown in Fig. 13(a). In contrast, the rotational speed control avoids this stalling behavior, as shown in Fig. 13(b). As it may be seen, now the flow coefficient does not exceed the stalling threshold value 0.3. The power generated by the turbine and induction generator is shown in Fig. 14 and Fig.15 respectively for the uncontrolled case (a) and rotational speed control (b). As shown in Fig 15(a), the average generated power in the uncontrolled case is 20.053Kw, while the power generated
in the controlled case using rotational speed control, increases up to 27.569Kw, as shown in Fig. 15(b). This represents an increment on the generated power due to its stabilization by totally eliminating the losses associated with stalling behavior.

The second case study considers a realistic scenario with irregular waves, which produces changes in the pressure drop input to the turbine as shown in Fig. 16. In this case the average power of the generator fed into the grid is significantly higher in the controlled cases than in the uncontrolled one as shown the Fig. 17. In the uncontrolled case, the turbine reaches repeatedly the stalling threshold value, generating an average power of 22.942Kw, as shown in Fig. 17(a). In contrast, the controlled average generated power, using rotational speed control, is increased up to 27.036Kw, as shown in Fig. 17(b).

Table 3 shows a summary of the average powers delivered by the generator for different pressure drop inputs for both uncontrolled case (a) and rotational speed control (b) cases.

<table>
<thead>
<tr>
<th>dP=</th>
<th>P₀ sin(0.1πt)</th>
<th>(Pa)</th>
<th>(a) Generator Power (Kw)</th>
<th>(b) Generator Power (Kw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>11.920</td>
<td>11.920</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>20.060</td>
<td>20.060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>25.202</td>
<td>25.570</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7000</td>
<td>20.053</td>
<td>27.569</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td>15.012</td>
<td>29.480</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irregular wave</td>
<td>22.942</td>
<td>27.036</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

A output power control strategy of an OWC-Wells turbine-generator module has been presented in order to improve the stalling behavior in the Wells turbine, the most popular air turbine in wave energy applications, which is particularly sensitive to the airflow rate due to its drastic efficiency drop when this airflow rate exceeds a critical value depending on the turbine’s rotational speed. The control system appropriately adapts the slip of the induction generator according to the pressure drop entry maximizing the generated power. To do so, the rotor side converter is used as control actuator to regulate the doubly fed induction generator rotor speed for obtaining the maximum wave power generation allowed by means of the controller without entering in stalling behaviour.

Acknowledgement

This work was supported in part by the University of the Basque Country (UPV/EHU) through Research Project GIU11/02 and the Research and Training Unit UFI11/07, by the Ministry of Science and Innovation (MICINN) with Research Project ENE2010-18345, by the Basque Government through S-PE13UN042 and by
the Euregion Aquitaine-Euskadi through Project 2013/GR1/11.
The authors would also like to thank the collaboration of the Basque Energy Board (Ente Vasco de Energia - EVE) through Agreement UPV/EHUEVE23/6/2011 and the Spanish National Fusion Laboratory (CIEMAT) UPV/EHU/CIEMAT08/190.

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