Control Models for an Oscillating Water Column Device

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Abstract: - The primary focus of this manuscript is to advance wave energy converter (WEC) devices. Having this aim in mind, a power take off (PTO) system with novel rotational speed control strategies will be presented. The chosen take off system is an oscillating water column converter (OWC), a device that uses a Wells air turbine as the primary energy converter. The secondary of the device is a generator that has been chosen to be a Doubly Fed Induction Generator with novel control strategies. This set up aims to improve the performance by increasing the efficiency, as a result of an increment in the power captured, and providing quality power to the grid. The proposed control scheme is due to be implemented on the NEREIDA MOWC demonstration project, a breakwater wave plant located in the Basque location of Mutriku, using Wells turbines and induction generators. The difficulty lies in finding an efficient variable control speed operation able to smoothly convert the peak-to-average power ratio, even more when this ratio presents a broad bandwidth that relates to the diverse input wave periods. By controlling the slip of the generator, it is possible to determine the behaviour of the whole turbo-generator set so as to maximize the output power. At the same time, the Wells turbine contributes to the robustness of the system because it requires no additional parts to produce unidirectional rotation from the reversing oscillating flow, but its performance is hindered by the stalling behaviour. However, this stalling phenomenon is s non-uniform response that may be avoided by controlling the rotational speed. Therefore, the presented novel control and switching avoidance techniques, will greatly contribute towards an improved PTO for the wave energy sector.

Key-Words: - — Speed Control, Wave Energy, OWC, DFIG

1 Wave Energy

The EU has declared that action is “needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond”. Indeed, the ocean energy resources may contribute to the world future sustainable energy supply. The large amount of wave energy with a uniform geographical spread across the oceans could provide a significant contribution to energy independence and security. Renewable energy production may supply electricity, drinking water and other products at competitive prices, creating jobs and contributing to the decarbonization pathway of the current society.

The SET Plan Secretariat of the European Union has presented a declaration of intent on strategic Targets towards the Development of cost competitive ocean energy technologies. It states that wave energy technology should follow a pathway to reach maximum 5 years later than tidal energy the following LCoE targets: 20 ct€/kWh in 2025, 15 ct€/kWh in 2030 and 10 ct€/kWh in 2035. Currently, various types of devices have already been deployed that may be classified from the technology point of view as

Terminator devices extend perpendicular to the direction of the wave and capture or reflect the power of the wave. The oscillating water column is a form of terminator where water a capture chamber, trapping the air above. The wave action causes the captured water column to move up and down, forcing the air though to a turbine to generate power.

Fig.1. Mutriku wave plant

Attenuators are long multisegment floating structures oriented parallel to the direction of the waves. They ride the waves like a ship, extracting energy by using restraints at the bow and along the length of the device. The different heights of waves cause the flexing segments located along the device that are connected to converters to generate power as the waves move across.

Point absorbers are floating structures with components that move relative to each other due to wave action (e.g., a floating buoy inside a fixed cylinder). They use the relative heave motion caused by passing waves to drive energy converters.

Overtopping devices have reservoirs that are filled by incoming waves. The water is then released, and the energy of the falling water is used to turn hydro turbines to generate power.

Most these devices have in common that the power is fed down an umbilical cable to a junction box in the seabed, connecting it and other machines via a common subsea cable to shore. However, none of them has been currently able to solve the major technological challenges so as to become a cost effective energy wave convertor. These problems need to be urgently solved for Europe to be able to utilize ocean energy to cover 10% of the continental demand for electricity by 2050.

Although there is no obvious convergence towards a certain technology, oscillating water column devices are one of the most extended ways of the wave energy harnessing. For instance, the NEREIDA MOWC wave power plant promoted by the Basque Energy Board (EVE) and located in the Basque coast of Mutriku is based on OWC technology. It consists of 16 18.5kW turbines that provide a total power of 296kW [1]. See Fig 1. Since it was inaugurated in July 2011 it has produced 1 GWh, which represents an important milestone within wave energy industry. However, apart from unscheduled out-of-service states due to extreme power of waves that in certain circumstances even caused the damage of the control room. Therefore, an improvement controlling the performance of the system could highly increase the generated power.

The use of Wells turbines allows the fixed-pitch operation, which means that they present a robust performance due to the lack of airflow rectifying devices, since they always rotate in the same direction regardless of the air flow. However, the performance of the turbine varies over the range of rotational speeds of the turbo-generator. It means that, it exists a certain rotational speed where the performance of the turbine is maximum, increasing the mechanical power applied to the turbo-generator shaft, and thus, the generated power. Moreover, Wells turbines often experience an efficiency drop called stalling phenomenon, mainly at high speeds of the airflow through the turbine. In order to avoid the stalling phenomenon, a traditionally used butterfly type valve is mounted at the bottom so as to slow down the speed of the airflow and to isolate the chamber if necessary.

The rest of the paper is organized as follows; Chapter 2 describes the numerical equations for the PTO model. In Chapter 3 the design for the control model is described, both for the gird side converter as well as for the rotor size converter. Then, in Chapter 5 the control mode will be implemented for both high wave scenario as well as low wave scenario with the final aim to improve performance when switching between control modes. Finally, Conclusions will end the paper.

2 Power Take Off Model

OWC devices are mainly composed by a capture chamber, turbine and generator.

Fig. 2. Wells turbine for the Mutriku OWC wave power plant

The equations used for modeling the pressure drop across rotor and the mechanical torque produced by turbine are (see [2-3]):

$$dp = C_a K(1/a)[v_x^{\,2} + (r\omega_r)^2] \quad (1)$$

$$T_t = C_t K r[v_x^{\,2} + (r\omega_r)^2] \quad (2)$$

where C_a, C_t are the power and torque coefficients, r is the mean radius of the turbine (m), a is the swept area of the turbine (m^2) and ω_r the angular velocity.

$$K = \frac{\rho b l_1 n}{2}$$

where ρ represents the air density (kg/m^3), b is the blade span (m), l_1 is the blade chord (m) and n is the number of blades.

Attached to this turbine, an induction generator (usually DFIG) [4-6] is used to generate power from the turbine torque using different control schemes [7-18]. The dynamical equation that couples the turbine to the DFIG is given by the inertial toque as

$$J\frac{d\omega_m}{dt} = T_e - f\omega_m - T_t \quad (3)$$

where J is the total inertia of the system in (kg.m^2), f is the friction coefficient, T_t is given in eq. (2) and T_e denotes the DFIG electromagnetic torque defined in the *d-q* frame. For modeling purposes different approaches may be used [19-27]. The subscripts r, s shall in the following indicate either rotor or stator, respectively.

The rest of this section will be devoted to derive T_e. The voltage across the stator and the flux linkage in stator are defined as:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} + \omega_s \begin{bmatrix} -\psi_{qs} \\ \psi_{ds} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = \left(L_{ls} + \frac{3}{2}L_{lm} \right)\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{3}{2}L_{lm}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \quad (5)$$

and analogous equations are defined respectively for the rotor by swapping the subscript *s* to *r*, where R_s and R_r are the stator and the rotor resistances in (Ω), L_{ls} is the stator leakage inductance and L_{lm} the mutual inductance in (H), ω_s is the electric synchronous speed and ω_r is the rotor electrical speed, in (rad/s), and $\omega_r = s\omega_s$ where *s* is the slip, i_{ds} and i_{qs} are the d-q stator currents in (A).

In abc frame the electromagnetic torque can be expressed as a function of the power available on the shaft of the generator and the mechanical speed by

$$T_e = P_e/\omega_r = p\,P_t/\omega_r = P_t/\omega_m \quad (6)$$

where p denotes the stator pairs of poles. The generator electric power, P_e,

$$P_e = \left(v_{ds}i_{ds} + v_{qs}i_{qs}\right) + \left(v_{dr}i_{dr} + v_{qr}i_{qr}\right) \quad (7)$$

is partly used to magnetize the machine and partly wasted in ohmic losses, while the rest is the transmitted power so that substituting the voltages given by eq. (4), the power transmitted is determined by those terms of P_e that are independent of the resistances or the flux variation. Therefore, denoting the speed in the d-q frame as ω_{dq} the generated power by the DFIG is then

$$P_g = \frac{3}{2}\omega_{dq}\left(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}\right) + \frac{3}{2}\left(\omega_{dq} - \omega_r\right)\left(\psi_{dr}i_{qr} - \psi_{qr}i_{dr}\right) \quad (8)$$

the constant value 3/2 corresponds to the square root of the constant relating the electromagnetic torque to the energy value in the d-q axis via the Park Transform. This is to say

$$T_e = p i_{abcs}^T \frac{dL_{sr}}{d\theta_m} i_{abcr} = p\left(K_s^{-1} i_{dqs}\right)^T \frac{dL_{sr}}{d\theta_m} K_r^{-1} i_{dqr}$$
$$T_e = \frac{9}{4} p L_m \left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) \quad (9)$$

Recalling eq. (8) and eq. (6), assuming the particular case where the reference frame rotates with the stator, $\omega_{dq} = \omega_r$. Thus, the expression for the power and electromagnetic torque are

$$P_g = \frac{3}{2}\omega_r\left(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}\right) \quad (10)$$

$$T_e = \frac{3}{2}p\left(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}\right) \quad (11)$$

3 Control Model Design

With the emergence of a Doubly-fed Induction Generator (DFIG) the variable rotational speed operation has been allowed [28-30]. Although the use of the DFIG has been successfully used to improve the performance of other systems, it represents a novel solution in the wave environment and especially in OWC devices.

In this section, a speed control scheme is presented so as to improve the performance of the system. In this sense, in the proposed control scheme an adequate rotational speed is estimated to maximize the efficiency of the turbine.

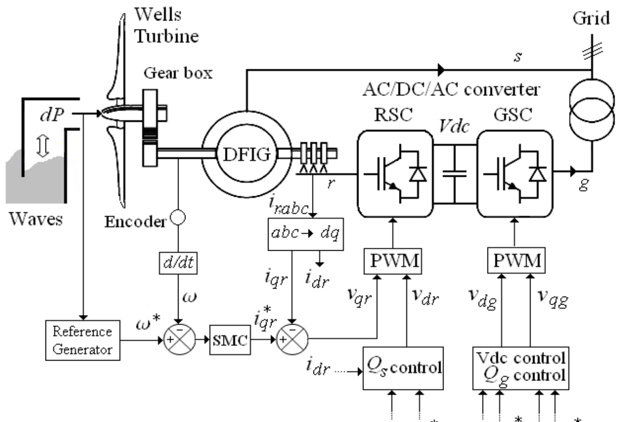

Fig. 3. Control design

The control scheme shown in Fig. 3 is used in the rotational speed controller to regulate the slip of the generator and to maximize the turbine torque. The rotor angular velocity is compared with the optimum reference rotational speed so as to determine the adequate rotor currents and the valve controls the input torque from the rotor determining the generator speed.

3.1 Rotor-side converter

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. The plant is given by the coupling equation, eq. (3), the flux linkage in stator, eq. (4), and an analogous system for the rotor. This dynamical system maybe further simplified. Let´s consider the expression for the currents given in flux linkage in stator eq. (5) and the analogous for the rotor

$$\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\end{bmatrix} = L_s\mathbf{I}\begin{bmatrix}i_{ds}\\ i_{qs}\end{bmatrix} + L_m\mathbf{I}\begin{bmatrix}i_{dr}\\ i_{qr}\end{bmatrix}$$
$$\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} = L_r\mathbf{I}\begin{bmatrix}i_{dr}\\ i_{qr}\end{bmatrix} + L_m\mathbf{I}\begin{bmatrix}i_{ds}\\ i_{qs}\end{bmatrix} \quad (12)$$

so that solving eq. (12) for the quadrature flux components one has:

$$\begin{aligned} i_{qr} &= \frac{1}{N}\left(L_m\psi_{qs} - L_s\psi_{qr}\right) \\ i_{qs} &= \frac{1}{N}\left(L_m\psi_{qr} - L_r\psi_{qs}\right) \end{aligned}, N = L_m^2 - L_r L_s \quad (13)$$

and analogous expressions may be found for the direct flux components in eq. (12).

Then, the flux dynamics described eq. (4), and its corresponding rotor equations, may now be expressed in terms of currents and voltages in the d-q axis as

$$\begin{bmatrix}v_{ds}\\ v_{qs}\end{bmatrix} = \frac{R_s}{N}\begin{bmatrix}L_m\psi_{dr} - L_r\psi_{ds}\\ L_m\psi_{qr} - L_r\psi_{qs}\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\end{bmatrix} + \omega_{dq}\begin{bmatrix}-\psi_{qs}\\ \psi_{ds}\end{bmatrix} \quad (14)$$

$$\begin{bmatrix}v_{dr}\\ v_{qr}\end{bmatrix} = \frac{R_r}{N}\begin{bmatrix}L_m\psi_{ds} - L_s\psi_{dr}\\ L_m\psi_{qs} - L_s\psi_{qr}\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}\psi_{dr}\\ \psi_{qr}\end{bmatrix} + \left(\omega_{dq} - \omega_r\right)\begin{bmatrix}-\psi_{qr}\\ \psi_{dr}\end{bmatrix} \quad (15)$$

Besides, the electromagnetic torque, eq. (11), and its corresponding electrical output power may now be expressed as

$$T_e = \frac{3}{2}\frac{p}{N}L_m\left(\psi_{ds}\psi_{qr} - \psi_{qs}\psi_{dr}\right) \quad (16)$$

$$P_e = \omega_r T_e \quad (17)$$

A common feature in most DFIG is field oriented control FOC, which enables the 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), it gives

$$\psi_{qs} = 0 \quad (18)$$

$$\psi_{ds} = \psi_s \quad (19)$$

Considering that the stator is connected to the network and the influence of stator resistance is small, the magnetising current, i_{ms}, can be considered constant and therefore the first equation of eq. (5) can now be rewritten as

$$\psi_s = \psi_{ds} = L_s i_{ds} + L_m i_{dr} = L_m i_{ms} \quad (20)$$

Under this assumption that the stator resistance is small and that the stator flux linkage is constant together with eq.(18), and the first equation in eq.(4) reads

$$v_{ds} = 0 \quad (21)$$

$$v_{qs} = \omega_{dq}\psi_s \quad (22)$$

substituting now eq. (18-21) into the first equation of eq. (14) yields an expression for the d-axis rotor flux

$$\psi_{dr} = L_r L_m^{-1}\psi_s \quad (23)$$

and the electromagnetic torque

$$T_e = \frac{3}{2}\frac{p}{L_m^2 - L_r L_s}L_m\psi_s\psi_{qr} \quad (24)$$

3.2 Air Valve

The turbine torque had been defined in eq. (2) to be dependent on the rotational speed, air velocity and C_t, the torque coefficient.

$$T_t = C_t K r[v_x{}^2 + (r\omega_r)^2],\ \phi = \frac{v_x}{r\omega_r} \quad (25)$$

This torque coefficient, C_t, is related to the flow coefficient, ϕ, by means of the characteristic curves of the turbine.

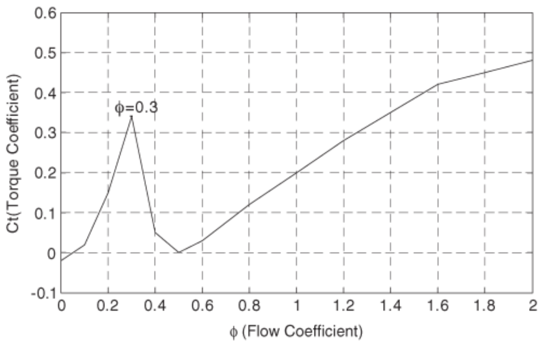

Fig. 4. Torque Coefficient vs. Flow Coefficient

It may be seen in Fig. 4 that the torque coefficient reaches its maximum value when $\phi = 0.3$ and ϕ may be directly computed as per eq. (25) where v_x is the air velocity (m/s) and considering when the air flux in the chamber to be incompressible it may be defined as

$$v_x = \frac{A_{OWC}}{A_{duct}}\frac{dh}{dt}$$

A_{OWC} is the chamber cross section area (m^2), A_{duct} is the duct cross section area (m^2) and *h(t)* is the wave height (m) inside the OWC [31-33].

4 Control Implementation

The equation that allows swinging between valve and rotational control is that given by (3) where disregarding the friction and assuming the turbine to be directly coupled to the generator reads

$$J\frac{d\omega_r}{dt}=T_e-T_t \tag{27}$$

The electromagnetic torque is given in eq. (24)

$$T_e=\frac{3}{2}\frac{p}{L_m^2-L_rL_s}L_m\psi_s\psi_{qr}$$

with the corresponding flux equations eq. (18), eq. (19), eq. (23) and the dynamic equation for the quadrature component of the rotor flux linkage

$$\frac{d\psi_{qr}}{dt}=-\frac{R_r}{N}\left(L_sL_rL_m^{-1}\psi_s\right)+v_{qr} \tag{28}$$

with $N=L_m^2-L_rL_s$.

The control objective is to maximize the amount of energy that is transformed from the wave to the wire. The system dynamics as given in eq. (27), may be controlled either by the electromagnetic torque, using the rotor voltage quadrature component v_{qr} that modifies the rotational speed as seen in eq. (28), or by the air flux valve that regulates the air velocity so as to maximize the turbine torque by means of the flow coefficient as given by eq. (25). The convenience of the different control mode implementation depends on the wave climate.

4.1 Low energy wave scenario

At low energy resource, the turbine is requested to transform as much as possible of the potential energy into mechanical energy. Initially the aim is to maximize the turbine torque for a given rotational speed. This is to say, the following proportional control drives the flow coefficient to the desired value that maximizes the torque coefficient C_t.

$$\frac{d\phi}{dt}=k_{\phi\max}\left(0.3-\phi\right) \tag{29}$$

In turn, according to eq. (26) and eq. (25), this flow coefficient value determines the valve position that leads to the desired the duct cross section area at a given rotational speed.

Besides determining the maximum turbine torque, a second control law is given so as to maximize the electromagnetic torque. This occurs when the quadrature component of the rotor flux linkage has the maximum value, as maybe read in eq. (24). This is to say, using eq. (28) for

$$v_{qr}=\frac{R_r}{N}\left(L_sL_rL_m^{-1}\psi_s\right) \tag{30}$$

the rotational speed is such that the power output to the grid is maximized. Therefore, a second control in series with the first control may be used to approximate the quadrature component of the rotor voltage to the desired value

$$\frac{d\omega}{dt}=k_{v_{qr}p}\left(v_d-v_{qr}\right)+k_{v_{qr}i}\int\left(v_d-v_{qr}\right),\; v_d=\frac{R_r}{N}\left(L_sL_rL_m^{-1}\psi_s\right) \tag{31}$$

4.2 High energy wave scenario

At high energy resource, the turbine can produce higher torque than demanded by the generator. This means that the generator may produce maximum power when the turbine is driven close to the flow coefficient $\phi=0.3$. This is to say, the following proportional control drives the flow coefficient to the desired value that maximizes the torque coefficient C_t

$$\frac{d\theta}{dt}=k_{\phi\max}\left(0.3-\phi\right) \tag{32}$$

where θ denotes the air valve angle.

In this scenario, the rotational speed is such that the power output to the grid is maximized so that eq. (30) holds and there is no need to consider the maximum power tracking control given by eq. (31). However, disturbances in the system may drift v_{qr} away from the desired value so that before switching from one control mode to another this check could be made to avoid mechanical overloading and undesirable transients.

5. Conclusions

A variable rotational speed control can be developed for OWC devices by means of the use of the DFIG. In this sense, the efficiency of the Wells turbine can be improved, increasing the generated power. Furthermore, by controlling adequately the rotational speed of the turbo-generator set, the stalling phenomenon might be avoided. Therefore, the use of the air valve might not be necessary, reducing the installation costs and improving the reliability and the response time of the wave power plant.

The use of Wells turbines allows the fixed-pitch operation, which means that they present a robust performance due to the lack of airflow rectifying devices, since they always rotate in the same direction regardless of the air flow. However, the performance of the turbine varies over the range of rotational speeds of the turbo-generator. It means that, it exists a certain rotational speed where the performance of the turbine is maximum, increasing the mechanical power applied to the turbo-generator shaft, and thus, the power generated. Moreover, Wells turbines often experience an efficiency drop called stalling phenomenon, mainly at high speeds of the airflow through the turbine. In order to avoid the stalling phenomenon, a traditionally used butterfly type valve is mounted at the bottom so as to slow down the speed of the airflow and to isolate the chamber if necessary.

Acknowledgments

Authors are also very grateful for the partial financial contribution to the UPV/EHU, through Project PPG17/33, and by the MINECO through the Research Project DPI2015-70075-R (MINECO/FEDER, UE). Authors would like to Acknoledge the collaboration of the Basque Energy Board (EVE) through Agreement UPV/EHU EVE 23/6/2011, the Spanish National Fusion Laboratory (EURATOM -CIEMAT) through Agreement UPV/EHU CIEMAT08/190 and EUSKAMPUS - Campus of international Excellence. They would also like to thank Yago Torre-Enciso and Olatz Ajuria from EVE for their collaboration and help.

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