OWC Wave Power Plants Capture Chamber Modelling

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***Abstract* — The European Union is promoting the use of renewable energies as a path to fight global warming. Among them are diverse ocean energies and in particular, Oscillating Water Column (OWC)-based wave energy stands as one of the most promising technologies. An OWC device is basically composed by a capture chamber with a turbo-generator module attached to it. Although the study of the induction power module can be considered a well-known matter, the control-oriented modelling of the capture chamber composes still an open issue. In this work, an analytical model of the OWC chamber is developed and numerically implemented. The proposed model is then successfully tested and validated by means of experimental results for the particular case of Mutriku OWC wave power plant, affording excellent results.**

***Index Terms* — Modelling and Simulation, Wave Energy, OWC, Capture Chamber.**

Fig.1. Turbo-generator modules in Mutriku wave plant

I. OWC TECHNOLOGY DESCRIPTION

OWC-based converters are devices which basically turn the mechanical energy of the waves into electrical power by means of a capture chamber and a turbo-generator module (see Fig 1).

This capture chamber consists of a fixed structure whose lower part is opened to the sea and it always remains under the Still Water Level (SWL) [1]. In this way, sea waves generate an oscillatory air flow by pushing and pulling inner air, which compresses and decompresses it. This creates a pressure difference between both sides of the turbine that makes the turbine

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spin. This pressure drop dp can be defined by means of the following equation [2,3]:

$$dp = C_a \frac{\rho b l_1 n}{2} \frac{1}{a_1} (v_t^2 + (r \cdot \omega_t)^2) \qquad (1)$$

where:
ρ: Air density (kg/m^3)
b: Blade's height (m)
l_1: Blade's chord's length (m)
n: Blades number
a_1: Blade's section area (m^2)
r: Turbine's mean diameter (m)
ω_t: Turbine's angular speed (rad/s)

Despite of the airflow direction, the rotational movement of the turbine does not change due to the particular geometry of the turbine that is usually employed, the Wells turbine [4,5] (see Fig. 2).

Fig.2. Wells turbine in Mutriku wave plant

The symmetric blades of this kind of self-rectifying turbines allow the unidirectional rotation. However, this particularity also produces an undesired behavior: the Stalling effect, which makes the turbine stall when the airflow reaches a certain value.

The turbo-generator module composes the power take-off system (PTO) and consists of the turbine and an induction generator (usually DFIG) [6]. Its function is to transform the oscillatory pressure drop into electrical power. For this purpose, diverse control strategies may be applied [7-18]. The mechanical equation describing the dynamics of the turbo-generator block can be expressed as follows:

$$H\dot{\omega}_t + F\omega_t + T_e = T_t \qquad (2)$$

II. NEREIDA MOWC PROJECT

NEREIDA MOWC is a project carried out by the Basque Energy Board (EVE) in the town of Mutriku in the north of Spain. It is the first commercial MOWC-based power plant and consists of 16 turbo-generator modules and it was constructed to combine demonstrative commercial and research purposes (see Fig. 3).

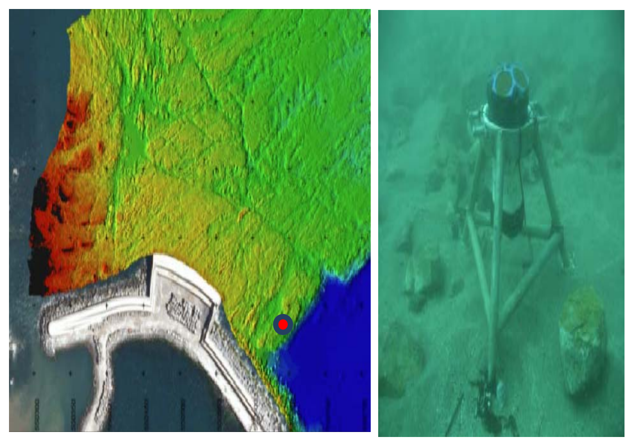

Fig.3. OWC power plant in Mutriku / RDI 600 with wave spectra recording

The aim of this work is to develop a control-oriented analytical model of the capture chamber of this type of OWC wave power plants and to prove the validity of the model obtained by means of in situ measured experimental data provided by the Mutriku OWC plant and wave surface data series collected at the Mutriku plant breakwater using an acoustic Doppler current profiler.

III. MODEL STATEMENT

In order to obtain an appropriate model many different system modelling approaches may be used [19-26]. In this case it is firstly required to obtain the value of the pressure drop from the features of the input waves. As it may be seen from (1), input waves directly affect the airflow speed.

Therefore, both waves and airflow speed must be related.

To do so, it is necessary to consider the wave dynamics, defined by different theories depending on the characteristics of the wave at hand. According by Airy linear theory, a wind wave can be described as an ideal sinusoidal wave [27]. The expression describing the surface of this kind of waves may be written as:

$$y(x,t) = a \cdot \sin\left[\frac{2\pi}{\lambda}(ct - x)\right] \quad (3)$$

Also, the volume of water in the chamber may be computed taking into account the volume of air contained in the OWC:

$$V(t) = V_c - V_w(t), \quad (4)$$

V_C and V_W representing capture chamber and water volumes, respectively.

This water volume may also be calculated by integrating the variation of the water level along the OWC area, so that:

$$V(t) = V_c + \frac{wH}{k}\sin\frac{kl}{2}\sin\omega t, \quad (5)$$

where l denotes the length of the chamber.

Therefore, the instantaneous air flow may be expressed as:

$$Q_a(t) = wHc \cdot \sin\frac{kl}{2}\cos\omega t \quad (6)$$

Now, considering the geometry of the chamber, it is possible to obtain the air flow velocity needed in (1):

$$v_t(t) = \frac{8awc}{\pi D^2} \cdot \sin\frac{\pi l}{cT}\cos\frac{2\pi}{T}t, \quad (7)$$

where D denotes the diameter of the duct.

Nevertheless, as it may be observed from (1), the rotational speed related is also needed. This speed depends on the torque applied by turbo-generator module that must be obtained from (2).

$$T_t = C_t K r[v_t^2 + (r\omega_t)^2], \quad (8)$$

where the Torque Coefficient (C_t) is related to the Flow Coefficient (ϕ) by means of the characteristic curves of the turbine [28]:

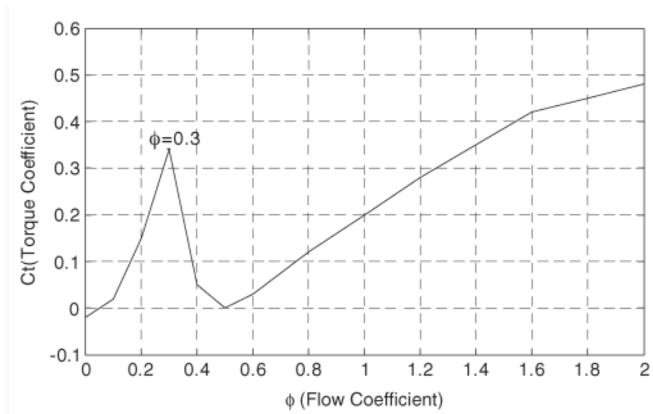

Fig.10. Torque Coefficient vs. Flow Coefficient

And ϕ may be directly computed as:

$$\phi = \frac{v_t}{r \cdot \omega_t} \quad (9)$$

Summing up the above relationships in (1), an expression of the pressure drop through the turbine as a function of the wave entry may be obtained as follows:

$$dp = f\left(\frac{v_t}{r \cdot \omega_t}\right) \cdot \frac{\rho b l_1 n}{2}\frac{1}{a_1}\left(\left(\frac{8awc}{\pi D^2} \cdot \sin\frac{\pi l}{cT}\right)^2 \cos^2\frac{2\pi}{T}t + (r \cdot \omega_t)^2\right) \quad (10)$$

where f(·) represents the turbine characteristic curve at hand.

IV. MODEL IMPLEMENTATION AND VALIDATION

Taking all the information above into account, a dynamical model of the behavior of the capture chamber can be implemented as shown in Fig. 4:

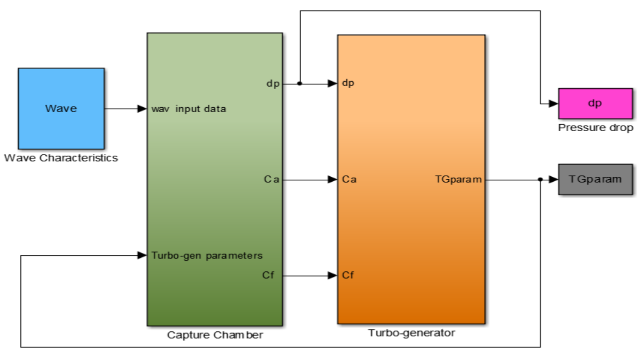

Fig.4. Implemented model

Then, considering making use of different sets of in situ measured wave input data for the particular case of Mutriku wave plant, the proposed model can be validated comparing its output with the measured experimental data of the real system (see Fig. 5).

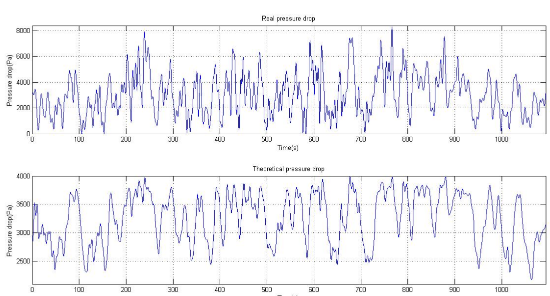

Fig.5. Pressure drop comparison on May 12th, 2 p.m.

As it may be observed, results show an excellent matching rate between the values predicted by the model and experimental measured data with a small bounded error in all cases.

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V. REFERENCES

[1] Y. Torre-Enciso, I. Ortubia, L. I. López de Aguileta and J. Marqués, “Mutriku wave power plant: From the thinking out the reality”, in *Proc. 8th Eur. Wave Tidal Energy Conf.,* 2009, pp. 319-329.

[2] Garrido, A.J., Garrido, I., Alberdi, M., Amundarain, M., Barambones, O., Romero, J.A. “Robust control of oscillating water column (OWC) devices: Power generation improvement”. OCEANS 2013 MTS/IEEE - San Diego: An Ocean in Common, art. no. 6740982. 2013.

[3] A. J. Garrido, I. Garrido, M. Amundarain, M. Alberdi and M. De la Sen, “Sliding-Mode Control of Wave Power Generation Plants” in IEEE Transactions on Industry Applications, vol. 48, no. 6, pp. 2372-2381, Nov. 2012. DOI: 10.1109/TIA.2012.2227096.

[4] L.Gato and V. Warfield, “Performance of a high-solidity Wells turbine for an OWC wave power plant”, in *Proc.Euro Wave Energy Symp.,* 1994, pp. 181-190.

[5] Amundarain Ormaza, M., Alberdi Goitia, M., Garrido Hernández, A.J., Garrido Hernández, I. “Neural control of the Wells turbine-generator module” 2009 IEEE Conference on Decision and Control, art. no. 5400638, pp. 7315-7320, 2009. DOI: 10.1109/CDC.2009.5400638.

[6] Marjani, A. El, F. Castro, M. A. Rodriguez and M. T. Parra, “Numerical modelling in wave energy conversion systems”, *Energy*, vol. 34, no. 8, pp. 1246-1253, 2008.

[7] Garrido, I., Garrido, A.J., Romero, J.A., Carrascal, E., Sevillano-Berasategui, G., Barambones, O. “Low effort LI nuclear fusion plasma control using model predictive control laws” in Mathematical Problems in Engineering, art. no. 527420, 2015. DOI: 10.1155/2015/527420.

[8] Garrido, I., Garrido, A.J., Sevillano, M.G., Romero, J.A. "Robust sliding mode control for tokamaks" in Mathematical Problems in Engineering, art. no. 341405, 2012. DOI: 10.1155/2012/341405.

[9] Garrido, A.J., De La Sen, M., Soto, J.C., Barambones, O., Garrido, I. "Suboptimal regulation of a class of bilinear interconnected systems with finite-time sliding planning horizons" in Mathematical Problems in Engineering, art. no. 817063, 2008. DOI: 10.1155/2008/817063.

[10] Jerzy Klamka, Adam Czornik, Michał Niezabitowski, Artur Babiarz "Controllability and minimum energy control of linear fractional discrete-time infinite-dimensional systems", Proceedings of the 11th IEEE International Conference on Control & Automation, 18-20.06.2014 r., Taichung, Taiwan, pp. 1210-1214.

[11] M. De la Sen, "Adaptive sampling for improving the adaptation transients in hybrid adaptive control". International Journal of Control, 41 (5), pp. 1189-1205, 1985. DOI: 10.1080/0020718508961191.

[12] Artur Babiarz, Adam Czornik, Jerzy, Klamka, Michał Niezabitowski, "Controllability of discrete-time linear switched systems with constrains on switching signal", Proceedings of the 7th Asian Conference on Intelligent Information and Database Systems (ACIIDS 2015), 23-25.03.2015 r., Indonesia, Part I, Lecture Notes in Artificial Intelligence, 9011, 304-312 (2015).

[13] Jerzy, Klamka, Adam Czornik, Michał Niezabitowski, Artur Babiarz, "Trajectory controllability of semilinear systems with delay", Proceedings of the 7th Asian Conference on Intelligent Information and Database Systems (ACIIDS 2015), 23-25.03.2015 r., Bali, Indonesia, Part I, Lecture Notes in Artificial Intelligence, 9011, 313-323 (2015).

[14] Barambones, O., Garrido, A.J., "An adaptive variable structure control law for sensorless induction motors" European Journal of Control, 13 (4), pp. 382-392. 2007. DOI: 10.3166/ejc.13.382-392.

[15] Goretti Sevillano, M., Garrido, I., Garrido, A.J., "Sliding-mode loop voltage control using ASTRA-Matlab integration in Tokamak reactors" (2012) International Journal of Innovative Computing, Information and Control, 8 (9), pp. 6473-6489.

[16] Garrido, I., Romero, J.A., Garrido, A.J., Lucchin, D., Carrascal, E., Sevillano-Berasategui, G. "Internal inductance predictive control for Tokamaks" (2014) World Automation Congress Proceedings, art. no. 6936072, pp. 628-633. DOI: 10.1109/WAC.2014.6936072

[17] Barambones, O., Garrido, A.J., Maseda, F.J., Alkorta, P., "An adaptive sliding mode control law for induction motors using field oriented control theory" Proceedings of the IEEE International Conference on Control Applications, art. no. 4776782, pp. 1008-1013. 2006. DOI: 10.1109/CACSD-CCA-ISIC.2006.4776782.

[18] Alkorta, P., Barambones, O., Garrido, A.J., Garrido, I. "SVPWM variable structure control of induction motor drives". IEEE International Symposium on Industrial Electronics, art. no. 4374768, pp. 1195-1200. 2007. DOI: 10.1109/ISIE.2007.4374768.

[19] Garrido, A.J., Garrido, I., Barambones, O., Alkorta, P., Maseda, F.J. "Simple linear models for plasma control in Tokamak Reactors" 2008 International Conference on Control, Automation and Systems, ICCAS 2008, art. no. 4694261, pp. 2429-2432. 2008. DOI: 10.1109/ICCAS.2008.4694261.

[20] Artur Babiarz, Jerzy Klamka, Radosław Zawiski, Michał Niezabitowski, "An Approach to Observability Analysis and Estimation of Human Arm Model", Proceedings of the 11th IEEE International Conference on Control & Automation, Taichung, Taiwan, pp. 947-952 (2014).

[21] Adam Czornik, Michał Niezabitowski, "Alternative formulae for lower general exponent of discrete linear time-varying systems", Journal of the Franklin Institute, 352, 399-419 (2015).

[22] De la Sen , M. , "On the robust adaptive stabilization of a class of nominally first-order hybrid systems", IEEE Transactions on Automatic Control, Vol. 44, No. 3, pp. 597-602, 1999.

[23] Aitor J. Garrido, Izaskun Garrido, Odysseas Chalatsakos, Ander Viñas, Ainhoa Villaverde, Vicente Queral and Jesús A. Romero, "Modelling and control of the UPV/EHU Stellarator", Proceedings of the IEEE 23rd Mediterranean Conference on Control and Automation (MED), June 16-19, 2015. Torremolinos, Spain (2015). DOI: 10.1109/MED.2015.7158785

[24] Garrido, I., Lee, B., Fladmark, G.E., Espedal, M.S., "Convergent iterative schemes for time parallelization" (2006), Mathematics of Computation, 75 (255), pp. 1403-1428. DOI: 10.1090/S0025-5718-06-01832-1

[25] Nistal, R., De La Sen, M., Alonso-Quesada, S., Ibeas, A., Garrido, A.J., "On the stability and equilibrium points of multistaged SI (n) R epidemic models" (2015), Discrete Dynamics in Nature and Society, 2015, art. no. 379576. DOI: 10.1155/2015/379576

[26] Sevillano, M.G., Garrido, I., Garrido, A.J., "Control-oriented Automatic System for Transport Analysis (ASTRA)-Matlab integration for Tokamaks" (2011) Energy, 36 (5), pp. 2812-2819. DOI: 10.1016/j.energy.2011.02.022.

[27] A. Chadwick, J. Morfett and M. Borthwick, *Hydraulics in Civil and Environmental Engineering.* London, U.K.: Spon Press, 2004.

[28] I. Garrido, A. J. Garrido, M. Alberdi, M. Amundarain and O. Barambones "Performance of an Ocean Energy Conversion System with DFIG Sensorless Control" in Mathematical Problems in Engineering, vol. 2013, no. 1, pp. 14, 2013. DOI: 10.1155/2013/260514.