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Control of Oscillating Water Column-Based Wave Power Generation Plants for Grid Connection

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***Abstract*— There is a worldwide interest in the use of renewable resources for the generation of electrical power. Between all renewable energy sources, ocean energy is the one that still has the furthest to go to achieve commercial maturity. As the most promising ocean energy that can be harnessed in the Basque Country is wave energy, the NEREIDA MOWC project, promoted and led by Basque Energy Board, aims to prove the viability of this technology for future commercial plants. In this paper, an Oscillating Water Column-based wave power generation plant is modeled and controlled by means of a new control scheme that takes into account the influence of turbine damping and the main requirements imposed by new Grid Codes when a grid fault occurs on the transmission system.**

***Index Terms*— Doubly Fed Induction Generator; Low Voltage Ride Through; Crowbar; Wave Energy; Wells Turbine; Distributed Power Generation; Voltage-Source Converters; Flow Control; Oscillating Water Column.**

I. Introduction

The most important advantage of ocean energy is that it is a source of high energy density and the main disadvantage is the great difficulty in extracting the energy in such a hostile environment [1].

Ocean energy takes different forms, depending on how it has been stored: waves caused by the action of the wind on the surface of the sea, sea currents caused by the gravitational pull of the sun and the moon, differences in the density and salt content of the water and thermal gradient.

The most promising ocean energy which can be harnessed in the Basque Country is the wave energy [2]. In this context, the Mutriku Wave Energy Plant makes use of the new breakwater at the entrance of the port of Mutriku to harness wave power using Oscillating Water Column (OWC) technology. The plant, which has a capacity of 300 kW from 16 turbo-generator sets, is the first of its kind operating with multiple turbines in the world. It has been recently inaugurated and connected to the power grid [3].

This paper investigates the application of a new control scheme that takes into account the influence of turbine damping on OWC-based capture chamber efficiency and the main requirements imposed by new Grid Codes to renewable power generation plants [4]. The most rigorous requirements refer to Fault-Ride-Through (FRT) capability during voltage sags.

The rest of the paper is organized as follows: Section II provides the necessary background on OWC-based wave power generation. Section III is dedicated to wave power conversion. In Section IV, the technical connection requirements to power grids are presented. Section V is devoted to explain the proposed control scheme. In Section VI some demonstrative simulation examples are given in order to test the performance of the controller, and finally concluding remarks end the paper in Section VI.

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II. Modeling of the OWC-based Wave Power Generation Plant

A. Waves model

Wave energy is a time-varying oscillatory resource that the Linear or Airy Wave Theory describes as simple sinusoidal waves as shown in Fig. 1. This theory is generally accurate enough for many engineering purposes and specifically for control design purposes [5]. The most suitable approach in our case is to particularize it for transitional water ($0.25 \geq h/\lambda > 0.05$), where h is the water depth (m) and λ is the wavelength defined by:

$$\lambda = \frac{gT^2}{2\pi}\tanh(2\pi\, h/\lambda) \tag{1}$$

where g is the acceleration of gravity (m/s^2) and T is the wave period (s).

The regular waves can be written as following:

$$P_{wf} = \frac{\rho_w\ g\ A^2\ \lambda}{4\,T}\left[1+\frac{4\,\pi\,h/\lambda}{\sinh(4\,\pi\,h/\lambda)}\right] \tag{2}$$

where P_{wf} is the incident wave power (W) and A is the wave amplitude (m).

In the case of irregular waves, it must be taken into account the spectrum of the wave climate, consisting of the addition of all N components of the wave:

$$P_{wf} = \sum_{n=1}^{N}\frac{\rho_w\ g\ A_n^2\ \lambda_n}{4\ T_n}\left[1+\frac{4\pi h/\lambda_n}{\sinh(4\pi h/\lambda_n)}\right] \tag{3}$$

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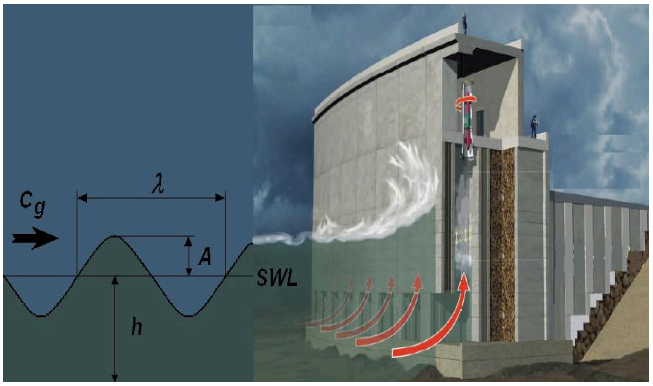

Fig. 1. Scheme of ocean wave and OWC

A. *OWC-based capture chamber*

The OWC is a device that converts the hydraulic energy of the waves into pneumatic energy. The principal component is the capture chamber, which is composed by a fixed structure with its bottom open to the sea. The wave motion alternately compresses and decompresses the air above the water level inside the chamber [3].

The hydrodynamic analysis is done in the time domain and the spring-like effect due to the compressibility of the air is taken into account. Hence, the equation which relates pressure variation to volume flow rate during the filling and discharge process is [6]:

$$\frac{dp}{dt} = q_i(t)\frac{\gamma\, p_a}{V_0} - q_o(t)\frac{\gamma\, p_a}{V_0} \tag{4}$$

where p is the pressure drop, γ is the specific heat ratio for the air, p_a is the atmospheric pressure, V_0 is the volume of air, $q_i(t)$ is the flow rate displaced due to the radiation and the diffraction and $q_o(t)$ is the flow rate across the turbine.

B. *WELLS turbine*

The Wells turbine is an axial-flow turbine that converts an oscillating flow into a unidirectional rotary motion for driving an electrical generator. That is, it always rotates in the same direction both for inbound and outbound air flow [7, 8].

The primary input for the design of a Wells turbine is the pneumatic power based upon the pressure drop and the volume flow rate. The equations used when modeling the turbine are given by [9, 10]:

$$P_t = Ca\left(\rho\, b\, l\, n/2\right)\left(1/a\right)[Vx^2 + \left(r\,\omega_t\right)^2] \tag{5}$$

$$T_t = Ct\left(\rho\, b\, l\, n/2\right) r\,[Vx^2 + \left(r\,\omega_t\right)^2] \tag{6}$$

$$\phi = V_x\ /\left(r\,\omega_t\right) \tag{7}$$

$$Q_o = Vx\, a \tag{8}$$

where a is the cross sectional area (m^2), b is the blade height (m), Ca is the power coefficient, Ct is the torque coefficient, P_t is the pressure drop across rotor (Pa), l is the blade chord length (m), n is the number of blades, Q_o is the flow rate (m^3/s), r is the mean radius (m), T_t is the torque produced by turbine (N.m), ϕ is the flow coefficient, Vx is the air flow velocity (m^2/s) and ω_t is the rotational angular velocity of the turbine (rad/s).

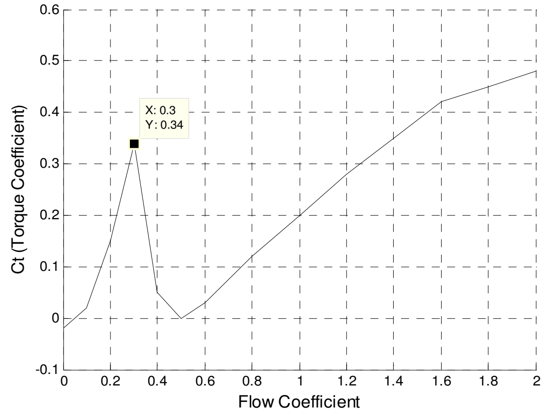

Fig. 2. Torque coefficient vs. flow coefficient

III. WAVE POWER CONVERSION

For given Wave Energy Converter (WEC), it is known that the amount of energy absorbed from waves depend on the damping of the power takeoff system, and, in this context, the WEC may be optimally damped [11]. The applied damping (N.s/m^5) is defined by:

$$D = P_t / Q_o \tag{9}$$

If the flow through the turbine is modulated, this is equivalent to govern the damping of the power takeoff mechanism [12].

Besides, the mechanical torque produced by the Wells turbine from the pneumatic air flow, according to (6) and (7), can be described as:

$$T_t = Ct\left(\rho\, b\, l\, n\, r^3/2\right)\left[1+\phi^2\right]\omega_t^{\,2} \tag{10}$$

where Ct is a function of flow coefficient, as can be observed in Fig. 2. The performance of the Wells turbine is limited by the onset of the stalling phenomenon on the turbine blades when the flow coefficient approaches 0.3. The Wells turbine efficiency drops drastically when the air flow rate exceeds this critical value, depending on the rotational speed [13].

From equation (10), it can be observed that torque coefficient, flow coefficient and turbine rotational speed are the main characteristics that determinate the maximum torque values.

So, if the Wells turbine is correctly dimensioned the turbine rotational speed can be varied to simultaneously maintain the optimal flow coefficient for efficient conversion of pneumatic power and match the required optimum damping to maximize the pneumatic power capture.

IV. GRID CONNECTION

In order to ensure stable operation of wave power generation systems, operational requirements are specified for such generators within the Grid Code documents in Spain [4]. The main requirements are established as: controllability of the active and reactive power and FRT capability during voltage drops in the transmission system [14].

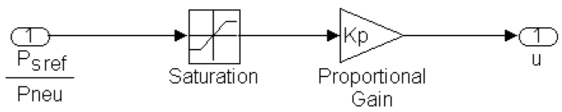

Fig. 3. Air flow control scheme

A. *Active power control*

Power stations are required to recover active power output within certain timescales in order to avoid dangerous changes in the frequency of supply.

In this paper, the active power is governed by the use of two different control strategies implemented to work together: the air flow control governs the throttle-valve that modulates the air flow across the turbine in order to avoid the undesired stalling behavior, while the rotational speed control increases the allowed slip of the induction generator coupled to the turbine, allowing to match the available wave energy level at each time instant [15].

The throttle-valve is driven by the actuator into the demanded position [16]. In this case, it is used a Proportional controller shown in Fig. 3, so the variable controlled is the value of the active power reference P_{sref} related with the captured pneumatic power, and the manipulated variable is the flow through the turbine.

The rotational speed control is performed by the Rotor Side Converter (RSC), whose control scheme is depicted in Fig. 4. This converter controls the active power P_s (and, thus, the speed of the DFIG). Its control law consists of setting the reference value of the active power generated by the generator equal to [15]:

$$P_{s\,ref} = K\,\omega_t^3 \qquad (11)$$

where the constant K depends on the characteristic values of the turbine. So, the control block of Fig. 4 basically acts as a feedforward controller that regulates the optimum running speed for the incident wave power.

B. *Reactive power control*

The reactive power control is used to maintain a constant stator voltage within the desired range when the DFIG is connected to power networks without reactive power compensation [17].

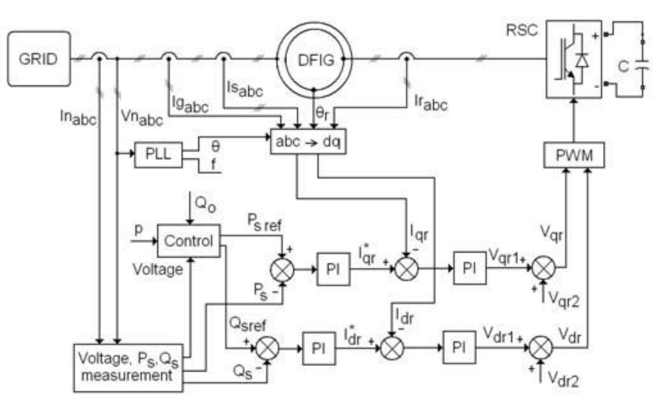

Fig. 4. Control scheme of the RSC

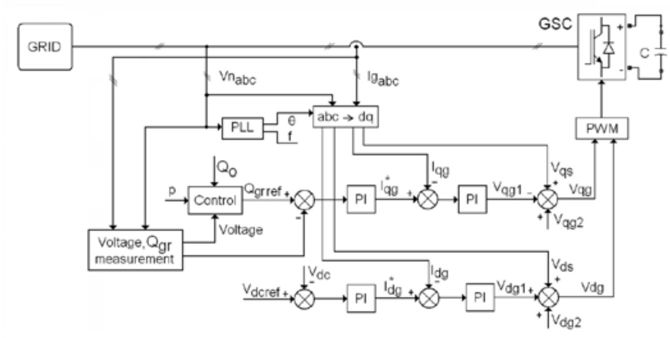

Fig. 5. Control scheme of the GSC

The reactive power control is performed by the Variable Frequency Converter (VFC), which is composed of a Grid Side Converter (GSC) connected to the grid, and a RSC connected to the wound rotor windings [18]. The RSC controls the reactive power Q_s exchanged between the stator and the grid and the GSC controls the reactive power Q_{gr} exchanged between the VFC and the grid. Fig. 5 shows the control scheme of the GSC [19, 20].

C. *FRT capability*

When a grid fault occurs causing a voltage dip, the stator flux cannot follow the stator voltage variation, which provokes an increase of the current in the stator and rotor windings, that can damage the RSC and the rotor [21, 22].

Therefore, since the primarily objective of the implemented control is the uninterrupted operation feature of the WEC, the rotor is short-circuited by an Active Crowbar to protect the RSC from the rotor high currents [23, 24]. As shown in Fig. 6 the Crowbar is basically composed by a circuit mounted in parallel with the RSC. In this work an antiparallel IGBT transistor circuit has been chosen because it is fully controllable.

In this way, the control law only activates the crowbar in response to exceeding rotor current or DC-link voltage signals and just for the necessary time to prevent damages in the rotor converter, reconnecting it as soon as possible to avoid the loss of control of active and reactive power of the DFIG [25].

In order to control the acceleration of the turbo-generator group, the flow is typically modified accordingly with the power reference, regulating the throttle air valve.

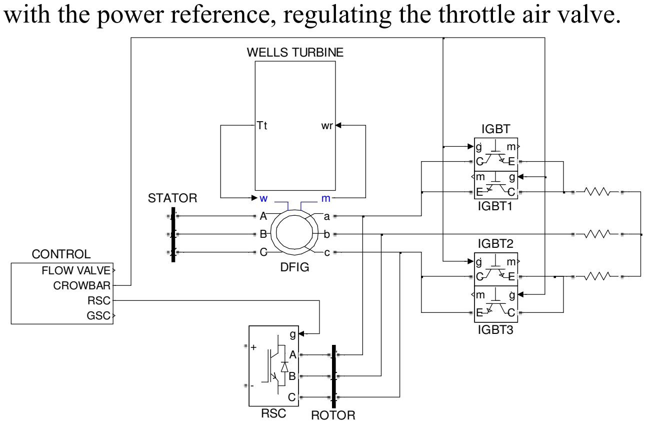

Fig. 6. Antiparallel IGBT transistor active crowbar

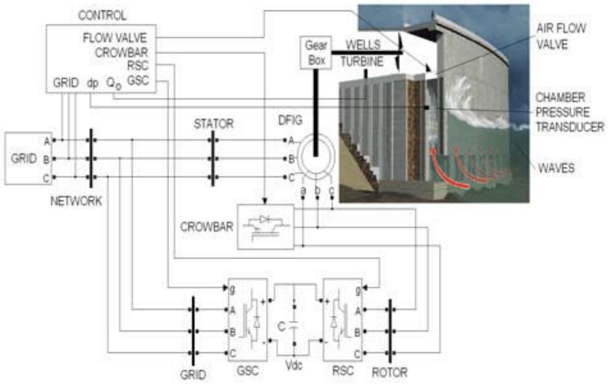

Fig. 7. Configuration scheme

V. Reference Signal Generator

The complete control scheme is depicted in Fig. 7, and its functioning is detailed in what follows. During the normal working regime of the WEC, the controller governs the throttle-valve that modulates the air flow across the turbine while adjusting the rotational speed to simultaneously maintain the optimal flow coefficient for efficient conversion of pneumatic power and match the required optimum damping to maximize the pneumatic power capture.

In this context, during the normal working regime the control block implemented does not activate the active crowbar, does not reduce the air flow, does not reduce the active power P_s through the RSC, does not generate reactive power Q_s through the RSC neither reactive power Q_{gr} through the GSC. Figure 8 show the detail of typical performance evolution curves corresponding to the different references.

However when a grid fault is detected, the control scheme implemented changes the reference of the crowbar to switch it on, the reference of the air flow control, the RSC reference of active power, the RSC reference of reactive power and the GSC reference of reactive power, as shown in Fig. 8, according to the pneumatic power and voltage reduction to improve the controllability of the active and reactive power and the FRT capability during the fault.

Consequently it is necessary to apply a control to modify the references, taking into account the incoming sea power and the characteristics of the voltage dip in the grid.

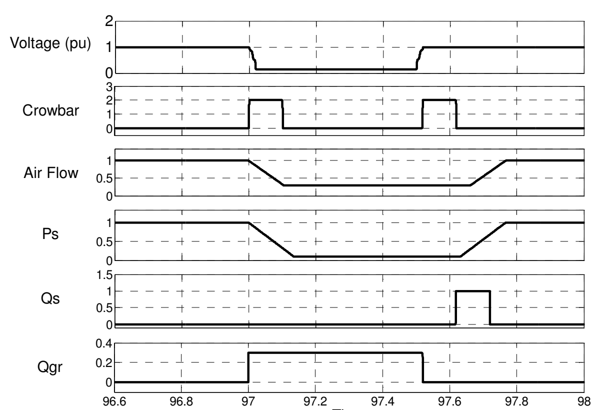

Fig. 8. Controller references

TABLE 1
Model Parameters

System	Turbine	Generator
J = 50 Kg.m^2	P $_{rated}$ = 45 KW	P $_{rated}$ = 37 KW
$\omega_g / \omega_t = 2$	n = 8	Vs $_{rated}$ = 400 V
Capture Chamber	r = 0.7285 m	F $_{rated}$ = 50 Hz
a = 6.2 m	a = 1.1763 m^2	nº of poles = 4
b = 11 m	b = 0.4 m	Rs = 0.0062 p.u.
V_0 = 1050 m^3	l = 0.38 m	Ls = 0.0447 p.u.
ρ_a = 1.2 Kg.m^{-3}	D = 1.714 m	Lm = 2.5482 p.u.
p_a = 101300 Pa	Hub/tip ratio = 2 / 1.2	Rr = 0.0115 p.u.
γ = 1'4		Lr = 0.0550 p.u.

VI. Simulation Results

The final objective of this work is to be applied to a real WEC called NEREIDA MOWC, into a newly constructed breakwater in the Basque location of Mutriku [3]. In this way, simulations have been carried out with wave fluctuation caused by a single frequency excitation of 0.086 Hz under different sea states (amplitudes from 0.5 to 2 meters).

The turbine-generator module jointly with the OWC module has been implemented using Matlab-Simulink software, parameterized as shown in Table 1.

In order to study the feature of the turbo-generator group for different sea states, it is necessary to consider that wave motion and wave energy absorption compose time-varying oscillatory phenomena and therefore it must be taken into account the average value of the pneumatic power and the average value of the torque generated by the turbine.

Numerous simulations have been carried out under different sea states and applied damping levels to quantify how the pneumatic power is captured in the capture chamber. The results may be observed in Fig. 9, which shows the average pneumatic power capture as a function of applied damping for different incident power levels. It is seen that as incident wave power increases then so does the required damping.

Fig. 10 illustrates turbine torque curves at different wave amplitudes as a function of turbine rotational speed and the superimposed maximum torque curve obtained from

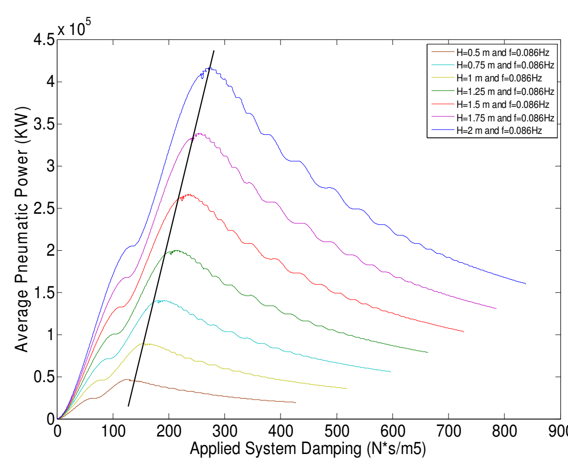

Fig. 9. Average pneumatic power vs. applied system damping

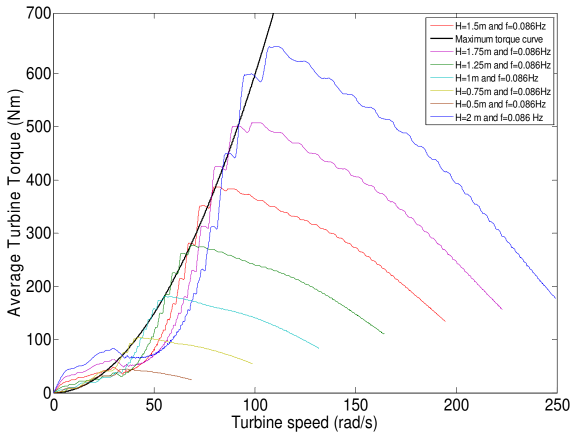

Fig. 10. Average turbine torque vs. turbine speed

equation (10). The average turbine torque for a given wave peaks to a maximum value corresponding to a single turbine rotational speed, which is the intersection point with the curve from equation (10).

Using these dates, it is derived the optimum range for the turbine speed as a function of the incident pneumatic power in the capture chamber.

In order to study the performance of the WEC, the next part of the study has been performed considering only two different sea conditions: the first case study considers waves with amplitude of 0.5 meters that does not produce the stalling behavior, while the second case considers waves with amplitude of 2 meters, which provokes the stalling behavior on the turbine.

During normal (fault-free) operation regime of the WEC, and applying the controller references shown in Fig. 8, the controller only reduces the air flow in the second case in order to avoid the undesired stalling behavior, as it may be observed in Fig. 11.

The active and reactive power generated by the induction generator at the stator terminals is shown in Fig. 12 for both cases. As shown in this figure, the generated active power in the first case is of 12.100 KW while in the second case is of 25.560 KW, depending on the reference of the controller. Analogously, the reactive power generated by the DFIG in both cases is of 0 VAr.

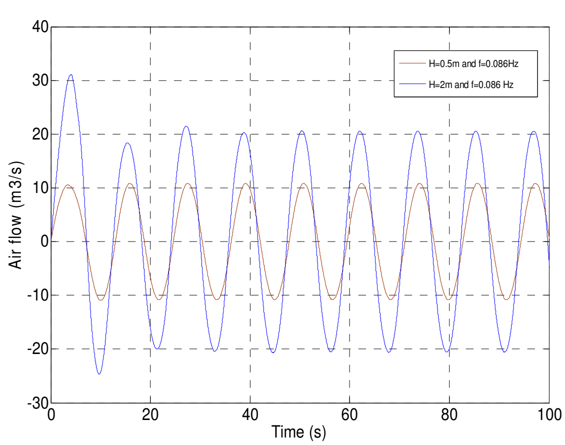

Fig. 11. Air flow during the normal working regime

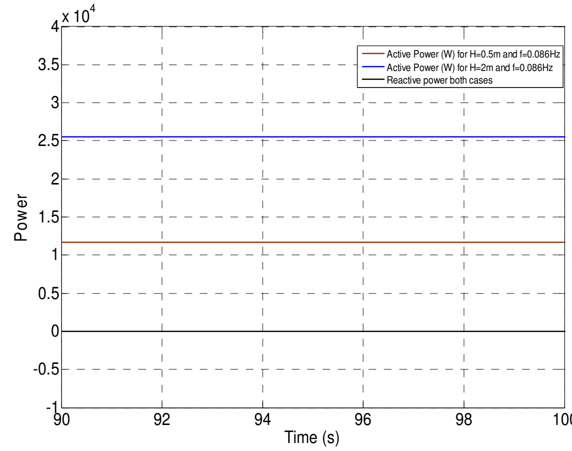

Fig. 12. Active and reactive power during the normal working regime

When a grid fault occurs with an 85% reduction of the grid voltage, applied at 97s and cleared at 97.5s, considering the controller references that can be observed in Fig. 8, the wave power plant rides through it without problems.

Fig. 13 shows the active and reactive power at the stator terminals. It can be observed that the active power drops rapidly down to zero when the fault is detected. At voltage recovery, the active power rises to its reference-power value. Analogously, the plant generates reactive power during the voltage sag and during the fault recovery, contributing to the attenuation of the voltage dip. Also, the reactive power consumption complies with new Grid Code requirements.

In the same way, it may be observed in Fig. 14 the effect of the fault over the rotor phase current. The active crowbar activation allows partial energy dissipation through the resistive load, keep currents within safe limits and prevent damages in the RSC.

VII. Conclusions

This paper has investigated the application of a new control scheme of OWC-based wave power generation plants equipped with DFIGs for grid connection.

This novel controller has taken into account the

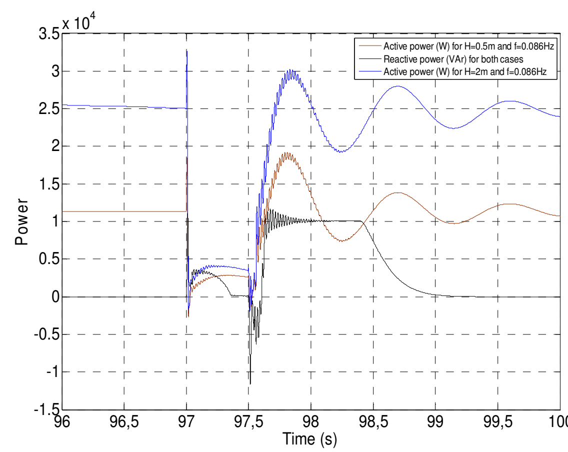

Fig. 13. Active and reactive power with a grid fault

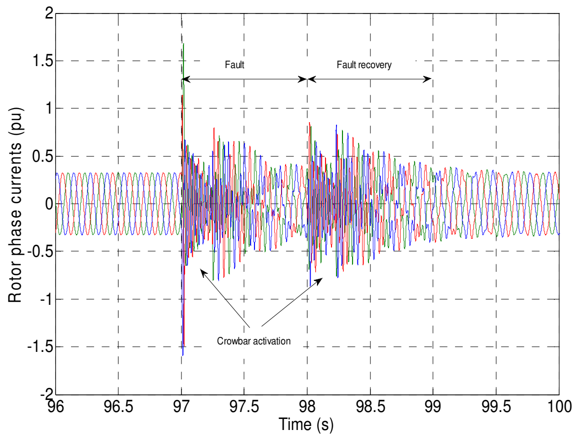

Fig. 14. Rotor phase currents (p.u.)

influence of turbine damping on OWC-based capture chamber efficiency and the main requirements to be met by renewable plants.

During the normal working regime of the wave plant, the turbine speed is encouraged to operate in a particular range based on the incoming power, to simultaneously maintain the optimal flow coefficient for efficient conversion and match the required optimum damping to maximize the pneumatic power capture.

However, when a grid fault occurs on the transmission system causing a voltage dip, the objective of the controller is to ensure the continuity of supply, complying with the technical requirements that new grid codes have developed: the control of active and reactive power and the uninterrupted operation feature.

It has been shown that the uninterrupted operation achieved complies with the Spanish operating procedure 12.3, increasing the reactive power production during the voltage dip and during the fault recovery.

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REFERENCES

[1] H. Polinder and M. Scuotto, "Wave energy converters and their impact on power systems," in Proc. International Conference on Future Power Systems, Amsterdam, The Netherlands, 2005, pp. 62–70, 2005.

[2] G. Iglesias and R. Carballo. "Wave energy and nearshore hot spots: The case of the SE Bay of Biscay". Renewable Energy, vol. 35, no. 11, pp. 2490-2500, 2010.

[3] Y. Torre-Enciso. "Mutriku Wave Power Plant: From Conception to Reality", European Federation of Regional Energy and Environment Agencies (FEDERANE) [Online]. Dec. 2009. Available: http://www.fedarene.org/documents/projects/Nereida/Document/01_Mutriku-OWC_plant.pdf

[4] BOE 254/2006 P.O. 12.3 Response Requirements of Wind Power Generation to Network Voltage Dips.

[5] A. Chadwick, J. Morfett and M. Borthwick. Hydraulics in civil and environmental engineering. London: Taylor & Francis group: 2004.

[6] A. Brito-Melo, L.M.C. Gato and A.J.N.A. Sarmento, "Analysis of Wells turbine design parameters by numerical simulation of the OWC performance," Ocean Engineering, vol. 29, pp. 1463–1477, 2002

[7] S. Muthukumar, "Design of a stand alone Wave Energy Plant," Proc of the Fifteenth International Offshore and Polar Engineering Conference, Seoul, Korea, 2005.

[8] S.L. Dixon, Fluid mechanics and thermodynamics of turbomachinery, Elsevier Butterworth–Heinmann, 2005.

[9] T. Setoguchi and M.Takao, "Current status of self rectifying air turbines for wave energy conversion," Energy Conversion and Management, vol.47, no.15/16, pp. 2382–2396, Sep.2006.

[10] S. Anand, V. Jayashankar, S. Nagata, K. Toyota, M. Takao, and T. Setoguchi, "Turbines for wave energy plants," Proc of the 8th International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows, Lyon, July 2007.

[11] A.F.O. Falcao, "Control of an oscillating-water-column wave power plant for maximum energy production," Applied Ocean Research, vol. 24, no. 2, pp. 73-82, 2002.

[12] A.F.O. Falcao and R.J.A. Rodrigues, "Stochastic modelling of OWC wave power plant performance," Applied Ocean Research, vol. 24, pp. 59–71, 2002.

[13] M. Amundarain, M. Alberdi, A.J. Garrido and I. Garrido, "Modeling and simulation of wave energy generation plants: Output power control", IEEE Transactions on Industrial Electronics, vol. 58, no. 1, pp. 105-117, Jan. 2011.

[14] T. Thiringer, A. Petersson, and T. Petru, "Grid disturbance response of wind turbines equipped with induction generator and doubly-fed induction generator," Power engineering society annual meeting, Toronto, Canada. July, 2003.

[15] M. Alberdi, M. Amundarain, A.J. Garrido, I. Garrido and M. De la Sen, "Complementary Control of Oscillating Water Column-Based Wave Energy Conversion Plants to Improve the Instantaneous Power Output", IEEE Transactions on Energy Conversion, vol. 26, no. 4, pp. 1021–1032, Dec. 2011.

[16] F. Neumann, A. Brito-Melo, E. Didier and A. Sarmento, "Pico OWC recovery project: recent activities and performance data," in 7th European Wave and Tidal Energy Conference Series (EWTEC), Porto, Portugal, Sept. 2007.

[17] I. Martinez De Alegría, J. Andreu, J.L. Martín, P. Ibañez, J.L. Villate and H. Camblong, "Connection requirements for wind farms: A survey on technical requierements and regulation", Renewable and Sustainable Energy Reviews, vol. 11, no. 8, pp. 1858-1872, 2007.

[18] W. Qiao, G.K. Venayagamoorthy, and R.G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped With Doubly Fed Induction Generators," IEEE Trans. Ind. Appl., vol. 45, no. 1, Jan./Feb. 2009.

[19] B.C. Rabelo, W. Hofmann, J. Lucas da Silva, R. Gaiba de Oliveira, and S. Rocha Silva, "Reactive Power Control Design in Doubly Fed Induction Generators for Wind Turbines," IEEE Transactions on Industrial Electronics, vol. 56, no. 10, Oct. 2009.

[20] M. Alberdi, M. Amundarain, A.J. Garrido, I. Garrido and F.J. Sainz, "Control for voltage dips Ride-Through of Oscillating Water Column-based wave power generation plant equipped with Doubly-Fed Induction Generator", 19th Mediterranean Conference on Control & Automation (MED), pp. 371-377, Jun. 2011.

[21] E. Robles, J.L. Villate, S. Ceballos, I. Gabiola and I. Zubia, "Power electronics solutions for grid connection of wind farms", European Wind Energy Conference & Exhibition, 2007.

[22] J. López, E. Gubía, E. Olea, J. Ruiz, and L. Marroyo, "Ride Through of Wind Turbines With Doubly Fed Induction Generator Under Symmetrical Voltage Dips," IEEE Transactions on Industrial Electronics, vol. 56, no. 10, pp. 4246-4254, Oct. 2009.

[23] J. Niiranen, "Voltage dip ride through of a doubly-fed generator equipped with an active crowbar," Nordic Wind Power Conference, Mar. 2004.

[24] J. Niiranen, "Second Generation Active Crowbar for DFIG," Proc. Nordic Wind Power Conference, May. 2006.

[25] M. Rodriguez, G. Abad, I. Sarasola and A. Gilabert, "Crowbar control algorithms for Doubly Fed Induction Generator during Voltage dips, 11th European Conference on Power Electronics and Applications, Dresden, Germany, 2005.