Wave Farms Integration in a 100% renewable isolated small power system -frequency stability and grid compliance analysis.

M. Blanco, G. Navarro, J. Najera, M. Lafoz, J.I. Sarasua, H. García, G. Martínez-Lucas, J.I. Pérez-Díaz, I. Villalba

Abstract— **The increase in the penetration of variable renewable energies (RE) is having a negative impact on the frequency of electrical grids due to effects such as the reduction of inertia when RE is connected by power electronics systems. In addition, the deterioration of the electrical frequency causes that the frequency containment mechanisms to act more frequently, which increases the wear and tear on the conventional generation plants that supply them. Within variable renewable energies is wave energy, which adds to the variability (or lack of manageability) of other renewable energies (e.g. wind, solar) an oscillatory component that translates into an oscillating power injected in the electrical grid. This power oscillation produces oscillations in electrical frequency that can take an electrical system outside of normal operating limits. The effect of frequency oscillations is magnified in weak electrical grids such as the insular system in which the study of this article is proposed, the island of El Hierro. A specific tool is used to evaluate the electrical frequency of the system, also evaluating the wear and tear of conventional generation plants. The limits in the penetration of the wave generation are analyzed for this specific power system.**

Keywords— **wave farm grid integration electric frequency deviations wave power variability isolated electric power systems.**

I. Introduction

In general, variable renewable energy (RE) penetration in power systems has some inherent drawbacks, such as lack of manageability and resource variability [1]. Medium (in the range of minutes) and short term (in the range of seconds) variability has a negative impact on system reliability, causing a deterioration of system frequency quality in both interconnected and, moreover, isolated systems [1], [2]. Specifically, the variability of the wave energy resource is medium- and short-term. Therefore, although wave energy could be very suitable to be integrated in islands due to its location, the variable nature of wave energy could negatively impact the stability of the power grid [3].

The case study of the work focuses on the island of El Hierro (Canary Islands, Spain). It is an isolated electrical system with a very high penetration of renewable energy sources. The generation of the electrical system is composed of a wind farm, a pumped hydroelectric power plant and conventional generation by means of a diesel power plant.

In a previous analysis [4], the integration of energy storage systems based on flywheels was analysed. Based on this previous analysis, the manuscript studies the influence of the integration of the wave energy park in the electrical system of El Hierro, taking into account the Spanish Grid Code will be taken into account regarding frequency regulation mechanisms in isolated systems [5]. The degradation of the hydraulic pumping systems due to additional frequency regulation stresses and electrical frequency deterioration will be calculated and evaluated in relation to the penetration of wave energy into the system, with and without the battery energy storage plant. This will allow quantification of certain technical limits to wave energy penetration in isolated systems and to draw conclusions with reference to the size of such a power system.

In the section II, the model of the power system and its generation units is described (conventional power plants and reneable energy generation farms). In the sections III and IV, the results of the simulations are presented, separating the results of the impact of the inclusion of a storage system with batteries, from the impact of the integration of a wave generation system. Finally, in the section V, some conclusions are drawn

II. Model Description

The analysis is based on the mathematical model presented in [4]. The case study is an island electricity

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M.B., G.N., J.N., and M.L. are with CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas), Avda. complutense, 40, 28040, Madrid, Spain (corresponding autor email: marcos.blanco@ciemat). J.I.S., H.G., G.M-L, J.I.P-D are with UPM (Universidad Politécnica de Madrid), Paseo de Juan XXIII, 11, 28040 Madrid, Spain. IV is with ULPGC (Univerisdad de las Palmas de Gran Canaria) Campus Universitario de Tafira, 35017 Las Palmas de Gran Canaria, Palmas, Spain.

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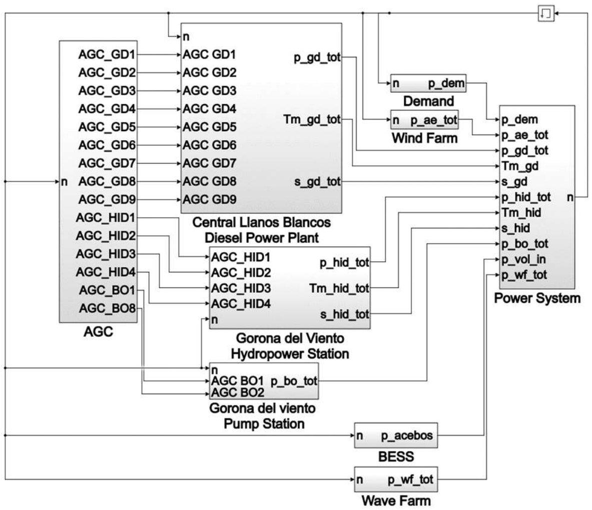

Fig. 1. Scheme of the MATLAB-Model of the *El Hierro* power system [4]

system of (approx.) 6MW of installed power consumed most of the year by 100% renewable energies: the island of *El Hierro* (Canary Islands, Spain) and the hydro and wind power plant *Gorona del Viento* [6], [7]. The model of the system is completed with the conventional power plant that traditionally supplied electricity to the island's system, and which is responsible for maintaining the supply at specific times.

The analysis in [4] proposed the inclusion in the model of a flywheel-based storage system to improve two aspects: the stability of the power grid, and reduce the wear and tear on the diesel and hydro-pump power plants (HPPP). In this paper, we try to analyse the impact that the inclusion in the mathematical model of a wave farm would have on the two aforementioned aspects. In addition, in this case, we start from a base case in which the supporting storage system would be a battery-based storage system.

In summary, the model represents the power system of the island of *El Hierro* and adds 2 fictitious systems: a wave farm (WvF) and a Battery based Energy Storage Plant (BESS).

1) *Electric Power System*

The power system model of the island of *El Hierro* is proposed as an aggregated inertial dynamic model that allows to evaluate the electrical frequency. The approach based on this aggregated inertial model was successfully used in the analysis Irish power system [8].

The way to ensure the stability of the power system in frequency is carried out, firstly, by means of the inertial response of the generation systems directly connected to the grid (the conventional diesel power plant – DPP - and the HPPP), secondly by means of a control system that implements the primary regulation (which is in charge of stabilizing the frequency in case of disturbances) and by means of the secondary regulation (which is in charge of restoring the frequency of the system to the reference level) [9]. The generators involved in secondary regulation are coordinated by automatic generation control (AGC).

The model was implemented in MATLAB Simulink, being highly configurable and can be adapted to other similar isolated power systems or modify/include other generation or storage systems, as is the case of the fictitious wave farm considered in this study. A scheme of the MATLAB blocks diagram of the model is presented in Fig. 1

The equation (1) evaluate the frequency deviations (Δf) taking into account that the power unbalance between the generation (diesel power plant: p_{DG}; wind farm: p_w; hydro pump power plant [hydro generation]: p_H; wave farm: p_{wv}), the power managed by the storage systems (Battery energy storage system: p_{BESS}) and the consumptions (hydro pump power plant [pumping]: p_p, and demand: p_d). The parameters that lead the dynamics of the frequency deviation are the inertial mechanical time (Tm) and the damping provided by sensitivity of the consumer load (D).

$$f\frac{df}{dt} = \frac{1}{T_m}(p_H + p_w + p_{wv} + p_{DG} \pm p_{BESS} - p_p - p_d - D \cdot \Delta f) \quad (1)$$

2) *Automatic Generation Control (AGC)*

The AGC is in charge of the secondary frequency regulation coordinating the participation of the generators (diesel power plant and hypro-pump power plant), and it was implemented according to [10]. The AGC activates automatically the frequency secondary regulation in the case of occurring an under-frequency deviation during at least 30 s and when the primary frequency regulation cannot to restore the deviation [9].

3) *Conventional Power Plant: Diesel Power Plant (DPP)*

The DPP model represents the *Llanos Blancos* power plant [11] and it is composed of 9 diesel groups and the model represents the dynamic response by means of a Laplace transfer functions [10] parametrised according the different power and technical characteristics of each unit.

4) *Renewable Power Plant 1: Wind Farm (WF)*

The WF is composed by 5 units of variable-speed wind turbines. Each wind turbines has been modelled according to [12]. The wind turbines model considers the following aspects:

- A pitch angle model to smooth the power generation by controlling the wind input torque.
- A generator model which includes a rotor inertial expression to evaluate the rotor speed variances.
- A wind speed time profile which is used as intut of the model (whereas the electric power generated is the output).

5) *Energy Storage System 1: Hydro-Pump Power Plant (HPPP)*

The HPPP is composed by a pumping station and a hydropower plant. The former store energy in a upper reservoir pumping water from a lower reservoir, while the

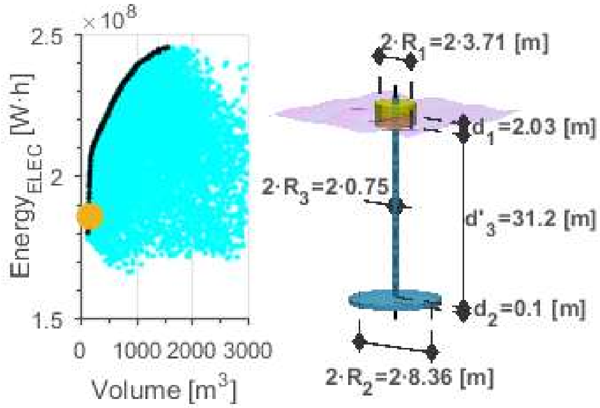

Fig. 2. WEC dimensions and PTO main characteristics have been selected by means design script based on Differential Evolution algorithms.[16]

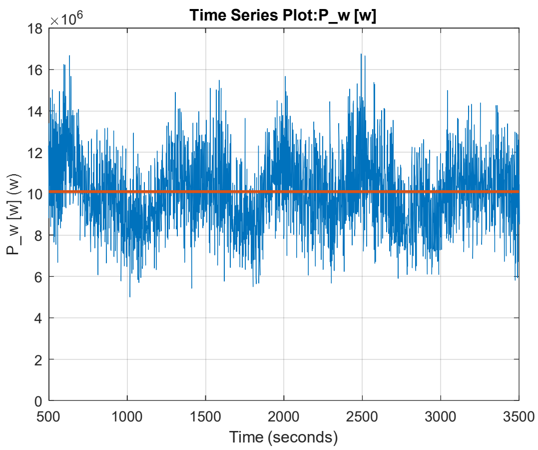

Fig. 3. Oscillatory WEC power generated time profile vs. average power generated value

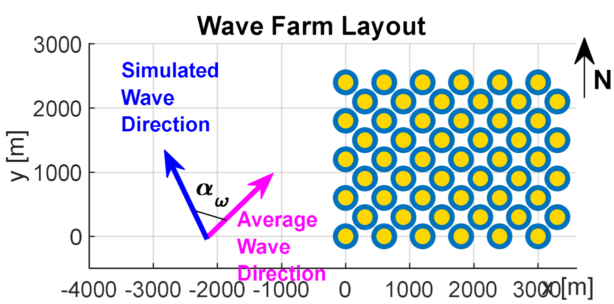

Fig. 4. Wave farm configuration takin into account the location wave energy resource and the reduction of the power oscillation [1].

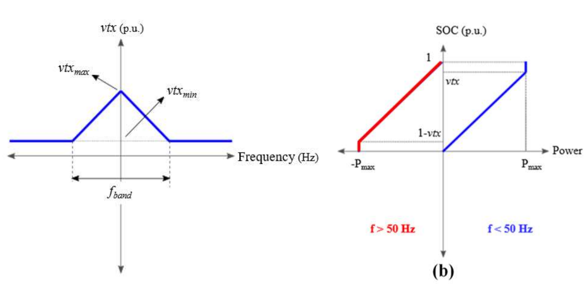

Fig. 5. Schemes of the BESS governor control scheme (GSC) NLPv. [4]

latter generate electricity from the potential energy of the upper water reservoir.

The pumping station consists of fixed-speed (6 ud.) and variable-speed (2 u.d.) pumps, which are modelled according [13] and taking into account hydraulic machines (whit its associated electric machine) and conduits and hydraulic machines was used, in addition to a simplified electric machine model, to represent the dynamic response of the pumping station.

The hydropower station consists of 4 Pelton turbines and in a similar way to the pumping station modelling, taking into account the turbines, electric generators and conduits as is described in [13].

6) Renewable Power Plant 2 (fictitious): Wave Farm (WvF)

The WF model integrated in *El Hierro* power system model has been developed according [14].

For the sake of example, an hypothetical WF connected to the electric grid of *El Hierro* (Spain) is considered. The main characteristics are defined as follows:

- The WEC prime mover concept is a 2-boody point absorber of 160 kW (see Fig. 2) of maximum peak power, and the power take-off (PTO) is a linear generator of 160 kW of rated power.
- The WFs comprises 54 individual WECs distributed according 15 groups of devices (WECs) with a layout of 9 rows in a triangular pattern [3], [14].

a) Wave Energy converter design.

The WEC geometry has been obtained from the methodology presented in [15]. The problem of obtaining the WEC dimensions is faced as a mathematical optimization problem where: 1) the optimization algorithm is a differential evolutionary algorithm; 2) objective functions are minimizing the WEC volume and maximizing its electric energy extraction (multi-objective); 3) and the search space are the point-absorber dimensions. Fig. 2 shows the WEC geometry selected.

b) Wave Farm modelling

A single WEC dynamic model of the selected geometry of the WEC has been developed according [16]. From this model, the WF power output has been evaluated considering: 1) the space between each WEC is considered 600 m due to according to [17], [18] to minimize the fluid-dynamic interaction and permits the properly accommodation of the moorings; 2) the water free-surface elevation time-profile is obtained individually for each WEC position; 3) The waves are real (irregular) model according a JONSWAP spectrum: 4) the spatial distribution of the WECS has been selected to minimise the power output oscillation (see Fig. 3) [14] according the layout of the Fig. 4.

7) Energy Storage System 2 (fictitious): Battery based Energy Storage Plant (BESS)

A semiempirical ion-lithium battery model, developed and validated, has been used to develop the BESS model.

TABLE I INITIAL POWER DISTRIBUTION IN EACH REPRESENTATIVE GENERATION MIX FOR THE POWER SYSTEM

Generation mix		Demand	Pumps	VSWT	Pelton Turbines	Diesel units
1	D	-3.40	(-)	0.15	(-)	3.25
2	D+H	-4.50	(-)	0.78	0.82	2.90
3	D+P	-4.95	-4.00	4.05	(-)	4.90
4	H	-6.67	(-)	4.40	2.27	(-)
5	HSC	-5.25	-6.00	8.23	3.02	(-)

D = diesel, D+H = diesel plus hydraulic, D+P = diesel plus pumping, H = hydraulic, HSC = hydraulic short circuit

Values are in MW. A negative value is the power consumption from the grid, and a positive value is the power generation to the grid.

This model has been parametrized based on laboratory tests of commercial ion-lithium cells [19] (Battery: ANR26650M1 - A123; E0 = 3.3678 (V); Qmax = 2.3 (Ah)).

a) BESS GOVERNOR CONTROL SCHEME (GCS)

The GCS define the power set-point reference that the BESS should provide or absorb to the grid by means of the inputs power system frequency and state of charge (SOC) As output, the FESS governor provides the power set-point reference that the flywheels should provide or absorb to the grid.

The GCS used is the NONLINEAR PROPORTIONAL VARIANT (NLPV) algorithm proposed in [4]. The BESS set point is calculated dynamically evaluation first the vertex (*vtx*) value from the frequency deviation magnitude (see Fig. 5 - left), and then, evaluation the power set-point from the SOC value (see Fig. 5 - right). According to [4], the intelligent behaviour of NLPV has some clear advantages, such as the flexibility of the governor that significantly reduces the wear and tear on other installations and on the BESS itself.

III. RESULTS OF THE ANALYSIS OF EL HIERRO ELECTRIC GRID WITHOUT WAVE FARM – PRELIMINARY RESULTS

This section shows the results obtained before and after including the battery-based storage system, presenting the results of [4] and performing an analogous analysis.

The variables taken into account in the study have to do, on the one hand, with the quality of the system frequency, and on the other hand, with the loss of useful life of the diesel units of the DPP, the Pelton turbines of the HPPP, and the storage system BESS. Specifically, they are:

- (V1) the average deviation of the AVFD frequency [20];
- (V2) the number of seconds at the time that the electrical system has a frequency outside the limits of the Spanish grid code for isolated systems (+-250mHz [5]).
- (V3) the cycles per hour of the BESS [21];
- (V4.1/V4.2) and the wear (WaT) of the electromechanical diesel elements and the Pelton turbine nozzles [22], [23].

1) Simulation scenarios - Electric representative cases selection

In an electricity system, the different scenarios that can occur in the generation mix are strongly conditioned by the penetration of non-manageable renewable energies (RE). In the case of the electricity system in question, this would be wind power, to which we would add wave power in the analysis of the following section (section IV). The RE have priority to participate in the generation of energy, so they define how much the other technologies participate in order to balance generation and demand.

On the other hand, non-manageable RE usually have a variable character depending on the energy source (wind or waves at any given moment), and this variable power injected into the grid causes problems of frequency deviations in the electrical grid.

In order to analyse the electrical system of El Hierro and the impact of variable ENs on the electrical frequency, 25 case studies or simulations have been defined that correspond to the combination of:

- 5 synthetic wind speed profiles based on the available historical data and a stochastic model [13];
- 5 generation mix selected based on data collected from the local electricity system operator (Red Eléctrica de España) and defines which units and technologies (with their respective powers) come into play in each case [24]. The 5 most representative mixes identified are, from lowest to highest wind penetration: diesel (D), diesel plus hydroelectric (D + H), diesel plus pumping (D + P), hydroelectric (H) and hydraulic short circuit (CCH). The hydraulic short circuit scenario corresponds to the joint operation of pumps and turbines, in a scenario in which the power absorbed by the pumps is higher than the power injected by the Pelton turbines. Table I presents the power of each representative case (mix).

In the El Hierro power system, to simulate frequency deviations caused by VSWTs, different synthetic wind speed profiles were developed based on available historical data and a stochastic model.

In combination with the synthetic wind speed profiles, 51 electricity generation mix scenarios were developed to represent normal system operating conditions when wind turbines were involved. Each generation mix is based on data collected from the local electricity system operator (Red Eléctrica de España) [58] and defines which units and technologies (with their respective powers) are committed for the system to operate normally.

These 51 scenarios combining different power system generation configurations can be classified according to the main technology present in addition to wind during power system operation, and also serve to name the groups. A total of five groups have been identified. They are, from lowest to highest wind penetration: diesel (D), diesel plus hydro (D+H), diesel plus pumped (D+P), hydro (H) and short circuit hydro (CCH). The hydraulic short-circuit scenario corresponds to the joint operation of pumps and turbines, in a scenario in which the power absorbed by the pumps is higher than the power injected by the Pelton turbines.

2) Impact of BESS integration in El Hierro electric Grid

The results presented are grouped according to the energy mix and the values obtained without and with a BESS system are compared. This allows us to analyse the improvement that the integration of the BESS system

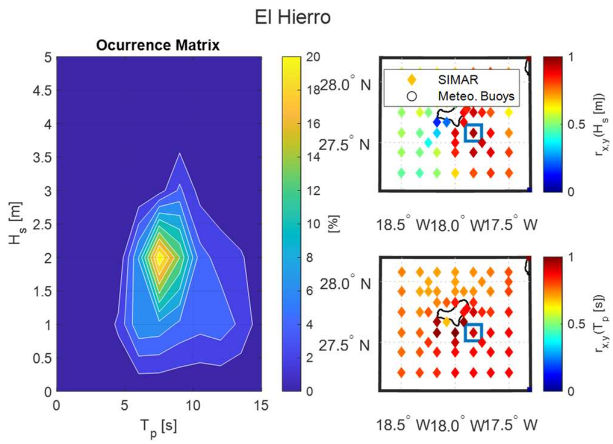

Fig. 6. Location of the WvF in coast of the El Hierro Island and occurrence diagram of the sea states.

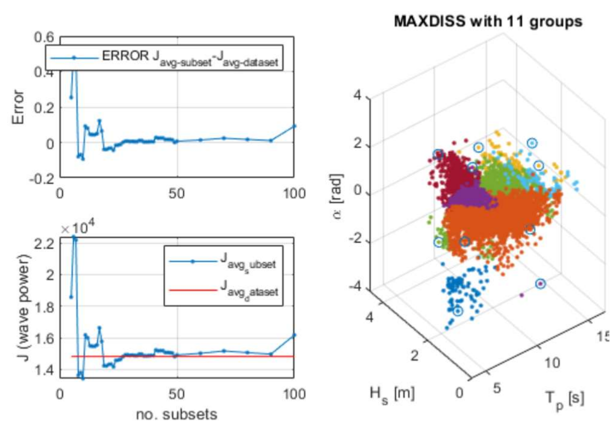

Fig. 7. MAXDIFF selection of the sea states of the WvF location.

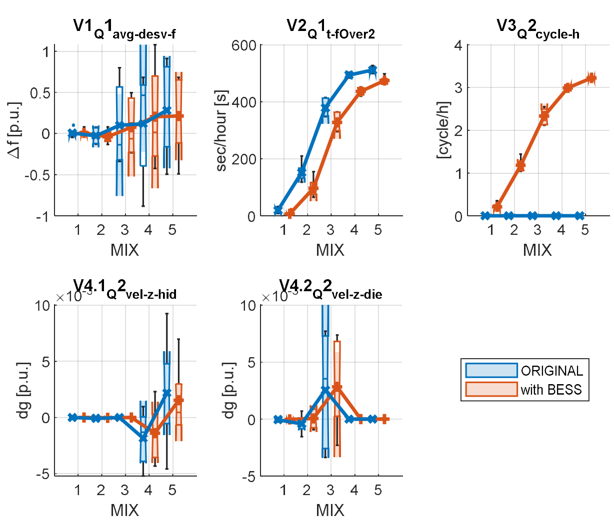

Fig. 8. Results of the analysis of the impact of the BESS integration in the El Hierro power system.

supposes to the system, both in reduction of frequency oscillations (and therefore in power grid quality) and in the reduction of wear in conventional generation systems (DPP and HPPP).

The BESS is integrated into the electricity grid as a support system for grid frequency regulation. A high penetration of variable RE makes primary and secondary regulation more demanding in order to keep the mains frequency stable, and this has a negative impact on the wear of conventional plants due to the set-point power changes necessary to stabilize the frequency derivatives.

Therefore, a priori, the inclusion of BESS in the frequency regulation mechanisms means that conventional generation plants have fewer variations in the power set-point and therefore positively affects to avoid their wear. In addition, BESS's fast response features improve grid power quality, lowering the amplitude of frequency oscillations.

The Fig. 8 represents the 5 wind cases of each of the generation mixes in 5 box and whisker diagrams (box plot [25]). Specifically, the figure shows how the inclusion of BESS improves power quality by reducing the time in which the frequency is out of range. The overfrequency values are higher, as would be expected, the greater the penetration of wind energy (WF) and, therefore, the lower the inertia of the system (conventional generation systems directly connected to the electricity grid. On the other hand, a slight reduction in wear and tear of conventional generation systems (DPP, HPPP) is achieved.

IV. IMPACT ANALYSIS OF THE INTEGRATION OF WAVE ENERGY IN EL HIERRO ELECTRIC GRID

After analysing the improvement that the inclusion of a storage system to support frequency regulation entails, this section analyses the impact on the electrical system of El Hierro and its generation plants of a wave generation plant (WvF). It is worth mentioning that the oscillation introduced by the WvF is of a higher frequency (around 0.05-0.25 Hz) than the power variations that the WF introduces into the system. Added to this is the fact that the amplitude of these variations is much greater, being able to have relationships between the average power and the injected peak power of up to 10 times (e.g. see Fig. 3).

1) *Simulation scenarios – Wave energy representative cases selection.*

In this section, the 25 cases described in section 3 (the combination of 5 generation mix with 5 wind profiles) become 275 (by adding 11 wave cases to the combinatorial). It starts from the hourly wave data for one year (2022) of the location shown in Fig. 6. on the coast of the island of El Hierro obtained from the Spanish institution "Puertos del Estado" [26]. From the 8760 cases, 11 are selected using the MAXDIFF tool described in [27], taking into account both the height, their period and their direction of the waves. This algorithm makes it possible to select the 11 most representative cases so that the annual energy content is maintained while cases that also represent the extremes of the scatter diagram are

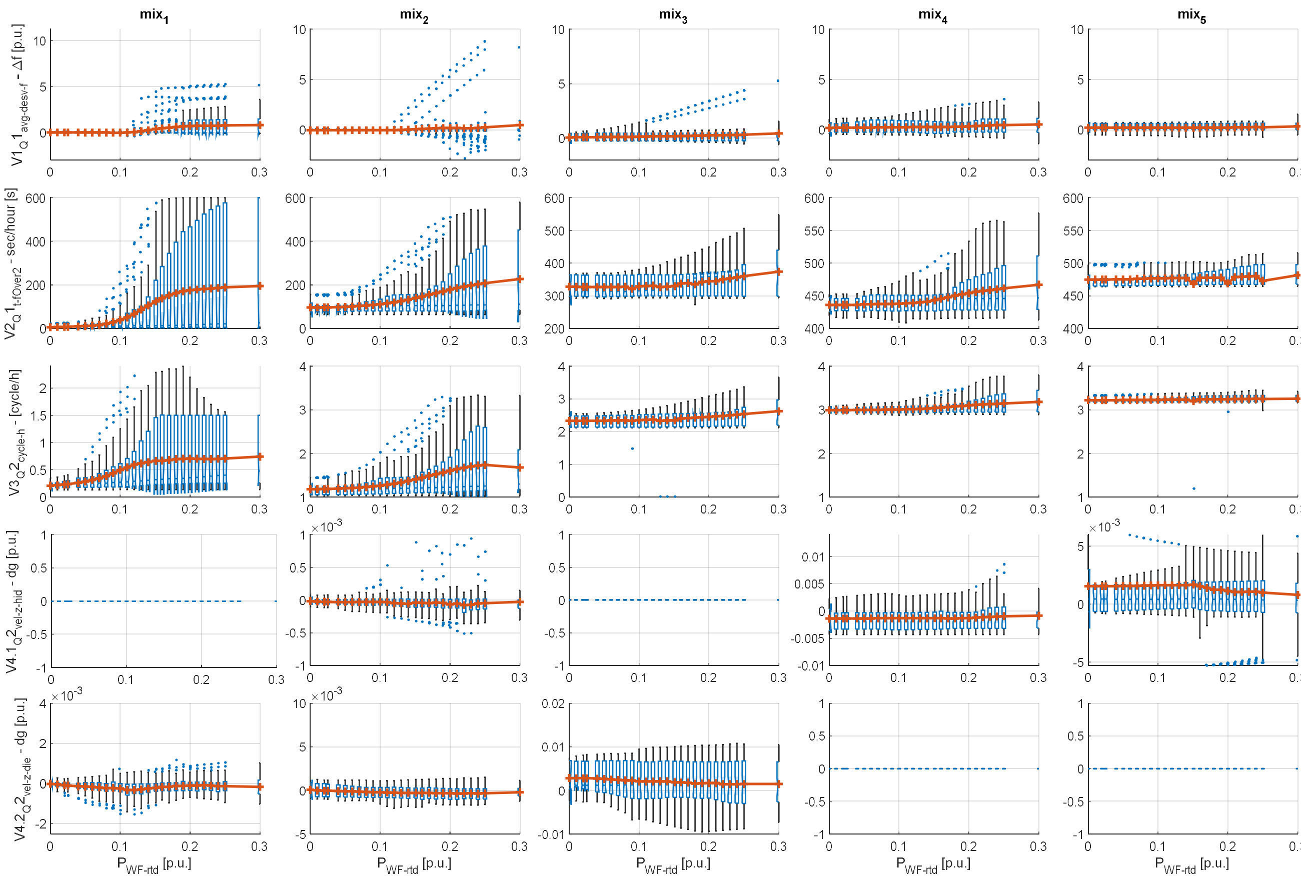

Fig. 9. Results of the analysis of the impact of the WvF integration in the El Hierro power system.

evaluated. The results are shown in Fig. 7 and the wave data is presented in Table II.

From the time profiles of the 11 wave cases, by using the WvF model described in section II.6), the 11 power profiles generated by the WF can be obtained. An example of WvF oscillating power profile has been shown in Fig. 3.

2) Impact on wear and tear of existing power plants and on frequency deviations of the grid

The Fig. 9 represents the results of the 5 wind cases of each of the generation mixes and for several cases of WvF nominal power in 25 box and whisker diagrams. The values of the WvF nominal power has been analyzed in the range of 0-0.3 p.u, taking into account the base power lf the El Hierro System is 6 MW. In addition, Fig. 10 shows the relationship of the variables V1-B5, the mixes and the nominal power of the WvF, but in this case, the average values for each 5 wind cases are shown.

From the information of Fig. 9 and Fig. 10 it can be seen how the frequency has a deterioration in energy mix 1 (DPP and WF), and this has less impact in mixes 2-5, where HPPP also participates. This deterioration increases as the power increases by the WvF. The timing of the deterioration of the rate causes the wear of the BESS to increase, since it participates in rate regulation, but it keeps the wear of the DPP and HPP systems stable, since it seems that the increase in the need for primary and secondary regulation is mainly covered by BESS.

From the results of Fig. 10 it is possible to draw conclusions about certain technical limits for the penetration of wave energy in isolated systems and to draw conclusions with reference to the size of the El Hierro electrical system. In particular, there is a clear run-out in the frequency decay (V1 and V2) from the WvF nominal power value of 0.11 p.u. (660 kW) , being especially accused in the generation 1 mix. The results show that with a power generated above 10% of the total installed power, the system suffers a rapid deterioration of the electrical frequency, leading the system to non-permitted operating scenarios. In situations such as those proposed above said value, the electrical system could take protective actions such as shedding loads or generation.

V. Conclusion

In the article, a model of an isolated (insular) and relatively weak electrical grid (6 MW of installed power) has been presented. The model is especially suitable for the analysis of frequency deviations that occur in the electrical grid. This electrical grid have storage systems by hydro-pumping and a kinetic energy storage systems, and an installed wind power capacity capable of supplying 100% of the demand. In this scenario, the inclusion of a wave generation system is proposed, evaluating the system's ability to work with the power oscillations introduced and maintain the frequency excursions within the ranges defined by the grid code.

TABLE II INITIAL POWER DISTRIBUTION IN EACH REPRESENTATIVE GENERATION MIX FOR THE POWER SYSTEM

Case Number	Hs [m]	Tp [s]	Dir [rad]	Occ. [%]
1	4.20	0.60	1.1155	0.1712
2	14.30	4.60	-0.2967	0.0047
3	12.50	1.00	-2.7417	0.0002
4	6.90	3.00	-1.3978	0.0055
5	14.30	2.20	1.7961	0.0118
6	7.70	3.40	1.7961	0.1015
7	4.40	1.00	-2.1483	0.0095
8	10.60	0.60	0.2603	0.3386
9	16.70	3.00	-0.2967	0.0102
10	6.70	1.40	3.0528	0.1000
11	11.80	2.40	-0.3506	0.2468

Hs = Significant wave height (metters), Tp = peak wave period [s], Dir = main wave direction [rad], Occ = Annual occurrence.

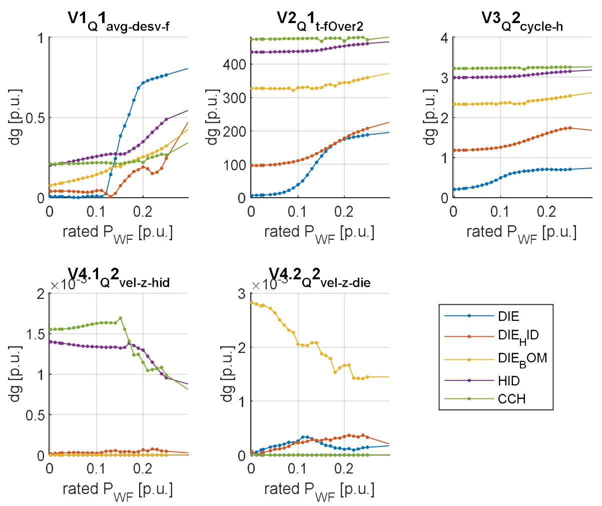

Fig. 10. Percentage of the year with the electrical frequency out of the grid code limits against the percentage of penetration of the wave energy generation.

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