UNIVERSIDAD POLITÉCNICA MADRID

ESCUELA TÉCNICA SUPERIOR DE
INGENIEROS DE CAMINOS CANALES Y
PUERTOS

**FREQUENCY CONTROL OF HYBRID
WIND-HYDRO POWER PLANTS
WITH LONG CONDUITS IN
ISOLATED POWER SYSTEMS**

Thesis submitted for the degree of Doctor in Civil Engineering Systems by

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LOS VOCALES

*A mis abuelas, quienes me han visto llegar hasta aquí,
y a mis abuelos, a quienes no les dio tiempo*

Success consists of going from failure to failure without loss of enthusiasm
El éxito es la capacidad de ir de fracaso en fracaso sin perder el entusiasmo

Winston Churchill

In learning you will teach, and in teaching you will learn
Aprende a enseñar, y enseñando aprenderás

Phil Collins

Haciendo memoria...

¡Vaya! Para un apartado que hay en español y “no técnico” y es el que más me cuesta empezar... y es que son muchas personas y hechos los que me han hecho llegar hasta aquí. Quizá debería empezar por recordar a mis profesores del Colegio Corazón Inmaculado de Madrid, pues ellos me enseñaron tanto conocimientos como valores. Echando la vista atrás (más atrás de lo que me gustaría), no se me olvidarán algunas frases y manías de María Jesús, profesora de matemáticas, que hoy en día ya como profe repito yo a mis alumnos... ¡si supieran lo que me quejaba entonces de ellas! Pero es que no es lo mismo estar a un lado que al otro en una clase.

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Abstract

The increase in the penetration of renewable energy is a reality in the vast majority of countries, both in Europe and in the rest of the world. This increase is not only occurring in continental power systems, but also on small islands that have high wind and/or solar potential. However, a high renewable energy penetration may compromise the stability of power systems, especially in the case of islands, which constitute isolated power systems. This is due to the inherent characteristics of renewable resources (uncertainty, intermittency and independence between availability and demand). These drawbacks are amplified by the power system inertia reduction caused by the fact that renewable generators are normally decoupled from the grid through a power electronics interface that do not add inertia to the system. It is well known that the long-term variability of renewable energy is well managed by pumped storage hydropower plants (PSHP). Thus, PSHP play an important role in the renewable resources integration, especially in isolated systems, because they can mitigate the energy fluctuations caused by the variations in the renewable resources availability.

There are small isolated power systems equipped with diesel units, wind farms and pumped storage power plants. The critical scene takes place when power demand is only supplied by renewable energy: PSHP in turbine mode and variable speed wind turbines (VSWTs) not aimed at providing frequency regulation. Therefore, the PSHP is aimed at contributing to frequency regulation without any other technologies. In this case, the hydropower plant must adapt its operating point to make generated power match demanded power. One of the objectives of this Thesis is to analyse the frequency control in isolated systems when it is only provided by hydro generators. Furthermore, power plants operating in this mode may be equipped with long conduits due to special topographic conditions.

As a case study, two islands belonging to the Canary archipelago have been selected: El Hierro and La Palma. The El Hierro power system is composed of several diesel generators and a hybrid wind-hydro power plant commissioned with the aim of reducing the consumption of fossil fuels. This hybrid power plant is composed of both a pumped storage hydroelectric plant with a 2577 meter length penstock and four 2.83 MW generation units coupled to Pelton turbines, as well as five 2.3 MW wind turbines.

The La Palma power system is composed of several thermal groups, photovoltaic units (4.6 MW) and wind turbines (7 MW). However, the island has several renewable energy expansion plans with the aim of reducing fossil fuels dependence. In fact, the construction of new wind farms is planned. Since renewable energy penetration increases needed energy storage systems, the construction of a PSHP is also scheduled. Therefore, this Thesis has assumed these expansion plans including a PSHP designed to cover the island power demand without using fossil fuels. The 50 MW hydropower plant could have a 1950 meter length tail-race tunnel to take advantage of a natural lagoon as an upper reservoir without a surge tank due to environmental constraints.

Frequency control becomes more complex when hydroelectric power plants are equipped with long conduits. In this case, the conduits' dynamics may significantly influence the power plant response making the governor tuning difficult, which is a problem that has not been deeply studied in the scientific literature.

Both isolated power systems (El Hierro and La Palma) have been mathematically modelled including the main components of which they are composed. Due to the conduits' length, water compressibility and the conduits' elasticity are taken into account since the associated pressure waves influence the system dynamic response.

To analyse the frequency control in these isolated systems, classical control techniques have been used. These techniques allow the establishment of a relationship between the dynamic response of the hydropower plant and the design parameters of the control system. In order to apply classical control techniques, the non-linear mathematical model proposed for each of the configurations is linearized around an equilibrium operating point. Thus, the dynamic matrix of the linearized system has been used to develop a modal analysis. Modal analysis allows the investigation of the consequences of different control strategies.

Through a strategic placement of the poles that represent the dynamic response of the hydroelectric power plant, the values for the controller's gains that improve the damping ratio of the oscillations, as well as the decoupling of the oscillation modes, are findable. This implies better behaviour of the power system in general, and of the generators in particular.

However, sometimes pumped-hydro storage systems need complementary technologies able to absorb or inject energy in the short-term to contain the frequency within the limits established by the transmission system operator. On a high wind potential island, energy fluctuations can also be mitigated if (VSWTs) are aimed at contributing to frequency regulation, although this contribution is not yet implemented in all power systems. For the El Hierro power system, the VSWT capacity to provide frequency regulation is considered. Therefore, wind–hydro joint frequency regulation has also been analysed for that power system in this Thesis.

The results obtained based on the linear model are applied to the non-linear model since the load-power regulation sometimes requires variations of the initial equilibrium conditions that exceed the small perturbation assumption. In fact, exhaustive searches of the hydro and wind governors' gains have been carried out in the non-linear model for the El Hierro power system showing results similar to those obtained from the linear model.

Based on the proposed obtained governors' gains, the hydropower plant and the VSWT dynamic response are analysed simulating, in the non-linear model, realistic events related to renewable energy fluctuations and power demand variations. Using different widely used system frequency and PSHP operating quality indicators, the system dynamic response, assuming the proposed recommendations, is compared with the one that would be produced using classic criteria settings, both for the hydropower plant governor and for the VSWT control loops. These classic criteria were proposed assuming hypotheses that do not include the phenomena described above such as conduits elasticity, fluid compressibility or the isolated systems requirements. In all the studied cases, a clear improvement of the system dynamic response, maintaining frequency within the limits established by the transmission system operator, and in the hydropower plant dynamics, is observed, thanks to the recommendations proposed in this Thesis.

Resumen

El incremento de la penetración de energías renovables es una realidad en la mayoría de países, tanto en Europa como en el resto del mundo. Dicho incremento no solo se está produciendo en los sistemas eléctricos continentales, sino también en pequeñas islas que cuentan con alto potencial eólico y/o solar. Sin embargo, una alta penetración de energías renovables puede comprometer la estabilidad de los sistemas eléctricos, especialmente en el caso de las islas, que constituyen sistemas eléctricos aislados. Esto es debido a las características inherentes a los recursos renovables (incertidumbre, intermitencia e independencia entre disponibilidad y demanda). Estos inconvenientes se amplifican por la reducción de inercia que sufren los sistemas eléctricos ya que la mayoría de tecnologías renovables están desacopladas de la red a través de electrónica de potencia. Está demostrado que la variabilidad de los recursos renovables es fácilmente gestionada por centrales hidroeléctricas reversibles. En este sentido, las centrales hidroeléctricas reversibles juegan un rol importante en la integración de energías, especialmente en sistemas aislados, puesto que pueden mitigar las fluctuaciones de energía causadas por variaciones en la disponibilidad del recurso renovable.

En los pequeños sistemas aislados, compuestos en ocasiones por generadores diésel, aerogeneradores y una central hidroeléctrica reversible, el escenario pésimo tiene lugar cuando la generación eléctrica proviene exclusivamente de recursos renovables: central hidroeléctrica en modo turbinación y aerogeneradores que no proporcionan regulación de frecuencia. Así, la regulación de frecuencia es únicamente llevada a cabo por la central hidroeléctrica reversible, adaptando ésta su punto de operación para generar la potencia demandada. El objetivo de esta Tesis es analizar el control de frecuencia en sistemas aislados cuando sólo es proporcionado por generadores hidroeléctricos. Algunas de estas centrales hidroeléctricas presentes en estos sistemas están equipadas con conducciones largas debido a las condiciones topográficas.

Se han considerado dos islas del archipiélago canario como caso de estudio: El Hierro y La Palma. El sistema eléctrico del Hierro está compuesto por varios grupos diésel y una central híbrida hidro-eólica puesta en marcha con el objetivo de reducir el consumo de combustibles fósiles en la isla. Esta central híbrida está formada por una central hidroeléctrica reversible con una tubería forzada de 2577 metros y cuatro grupos

generadores de 2.83 MW acoplados a turbinas Pelton, así como por 5 aerogeneradores de 2.3 MW cada uno.

El sistema eléctrico de la Palma está formado por varios grupos térmicos, paneles fotovoltaicos (4.6 MW) y aerogeneradores (7 MW). Sin embargo la isla cuenta con numerosos planes de ampliación de energías renovables con el objetivo de reducir la dependencia de combustibles fósiles. De hecho, está prevista la construcción de varios parques eólicos. Puesto que el incremento de la penetración de energías renovables necesita sistemas de almacenamiento de energía, también está programada la construcción de una central hidroeléctrica reversible. Por tanto, en esta Tesis se ha asumido estos planes de ampliación incluyendo una central hidroeléctrica reversible que ha sido diseñada para cubrir el pico de demanda de la isla sin necesidad de combustibles fósiles. La central, de 50 MW, podría tener una tubería de descarga de 1950 metros para aprovechar una laguna natural como depósito superior. No se ha diseñado chimenea de equilibrio debido a las restricciones medioambientales.

El control de frecuencia se torna más complicado cuando las centrales hidroeléctricas cuentan con conducciones largas. En este caso la dinámica de las conducciones puede influir notablemente en la respuesta de la central y dificultar la sintonía del controlador, problema poco tratado y con escasas soluciones propuestas en la bibliografía existente.

Ambos sistemas eléctricos (El Hierro y La Palma) han sido modelados matemáticamente incluyendo los principales componentes. Debido a la gran longitud de las conducciones, se han incluido la compresibilidad del agua y la elasticidad de las conducciones ya que las ondas de presión influyen la respuesta dinámica del sistema.

Para analizar el control de frecuencia en estos sistemas aislados se han empleado técnicas de control clásico. Estas técnicas permiten establecer relaciones entre la respuesta dinámica de la central hidroeléctrica y el diseño de los parámetros del sistema de control. Para aplicar las técnicas de control clásico, el modelo matemático no lineal propuesto para cada una de las configuraciones es linealizado en torno a una posición de equilibrio. Así, se ha utilizado la matriz dinámica del sistema linealizado para desarrollar un análisis modal. El análisis modal permite investigar las consecuencias de distintas estrategias de control.

Mediante la ubicación estratégica de los polos que representan la respuesta dinámica de la central hidroeléctrica y su regulador (y en su caso los lazos de control de los aerogeneradores), se pueden encontrar los valores para las ganancias del controlador que mejoren el amortiguamiento de las oscilaciones producidas así como el desacoplamiento de los modos de oscilación, lo que implica un mejor funcionamiento del sistema eléctrico en general y de los generadores en particular.

Sin embargo, en ocasiones los sistemas de almacenamiento por bombeo necesitan complementarse con tecnologías capaces de inyectar o absorber energía en el corto plazo para mantener la frecuencia del sistema dentro de los límites establecidos por el operador del sistema. En islas con alto potencial eólico, las fluctuaciones de energía pueden ser mitigadas si los aerogeneradores de velocidad variables proporcionan regulación de frecuencia, sin embargo dicha contribución no está implementada en todos los sistemas eléctricos. La capacidad de regulación de los aerogeneradores de velocidad variable se ha considerado en el sistema eléctrico de El Hierro. Así pues, se ha estudiado la regulación conjunta hidro-viento para este sistema eléctrico.

Los resultados obtenidos a partir de esta aproximación, necesaria para el cálculo de los polos, se aplican al modelo no lineal dado que la regulación frecuencia-potencia exige en ocasiones variaciones de las condiciones iniciales de equilibrio que exceden la pequeña perturbación. De hecho, en el modelo no lineal se han realizado búsquedas exhaustivas de las ganancias de los controladores de la central hidroeléctrica y los aerogeneradores, alcanzando resultados similares a los obtenidos con el modelo lineal.

A partir de las ganancias obtenidas, se analizan mediante simulaciones en el modelo no lineal la respuesta dinámica de una central hidroeléctrica y de un aerogenerador de velocidad variable ante variaciones en las consignas de demanda o fluctuaciones realistas de los recursos renovables. A través de diversos indicadores de calidad de la frecuencia del sistema y de operación de la planta frecuentemente empleados, se compara la respuesta obtenida asumiendo las recomendaciones propuestas con la que se produciría utilizando recomendaciones más clásicas, tanto para el regulador de la central hidroeléctrica como para los lazos de control del aerogenerador. Dichos criterios fueron enunciados bajo hipótesis que no contemplan los fenómenos antes descritos como la elasticidad de las tuberías, la compresibilidad del fluido o las exigencias de los sistemas aislados. En todos los casos supuestos se observa una clara mejoría de la respuesta

dinámica del sistema, manteniendo la frecuencia dentro de los límites establecidos por el operador del sistema, y de la central hidroeléctrica gracias a las recomendaciones propuestas en esta Tesis.

I. Introduction

This Introduction is organised as follows: A brief description of the present situation regarding renewable energies penetration, as well as renewable energy install capacity growth forecasts, are presented in section I.1. The particular case of renewable penetration on islands is analysed in section I.2, highlighting the specific case of the Canary Islands. In section I.3 the main characteristics of renewable resources are described, noting their drawbacks in isolated systems. After describing the negative effects, the different strategies that contribute to the integration of renewable energies in power systems are described in section I.4. These strategies are distinguished between those aimed at mitigating long-term negative effects and those focused on short-term effects. In section I.5, the general principles of frequency regulation in power systems are described.

Due to the objectives of this Thesis, frequency regulation provided by hydropower plants is described in detail in sections I.6, reviewing the most used hydroelectric power plant models, as well as the classic and modern control techniques to obtain the governor gains. Variable speed wind turbines (VSWTs) frequency regulation is also described in section I.7. Different control strategies that allow the satisfactory penetration of intermittent renewable energy in power systems are analysed, highlighting important characteristics in VSWT modelling.

Taking into account the state of the technique description, the motivation of this Thesis is presented in section I.8, while section I.9 summarizes the papers written because of this Thesis.

I.1 Present and future of Renewable Energy

The increase in the penetration of renewable energy is a reality in the vast majority of countries, both in Europe and in the rest of the world. The installed capacity of renewable energy for global and the top six countries is shown Figure 1. At the end of 2012, the global installed renewable power capacity reached 480 GW, while China remained the world leader with a 90 GW contribution followed by the USA and Germany with 86 and 71 GW installed capacities, respectively. Of the global capacity of 480 GW, the contribution of EU-27 is 210 GW and that of the BRICS countries, (Brazil, Russia, India, China and South Africa) 128 GW. According to the conclusions drawn by the European Council (European Council, 2014), at least 27% of the total energy consumed

by the member countries must be produced by renewable energies in 2030 (D'Adamo & Rosa, 2016).

Figure 1 Renewable power capacities in the world, EU-27, BRICS (Brazil, Russia, India, China and South Africa), and six countries at the end of year 2012 (Rehman, et al., 2015).

Global wind power installed capacity increased by 12.4% up to more than 318 GW in 2013 due to the greater participation of China and Canada, as shown in Figure 2.

Figure 2 Cumulative global wind power and solar photovoltaic installed capacity growth (Rehman, et al., 2015).

The World's cumulative photovoltaic (PV) installed capacity surpassed 100 GW at the end of 2012, achieving just over 102 GW, as depicted in Figure 2.

According to (Aziz, et al., 2017), wind is the most cost-competitive renewable source of electricity generation behind hydro, highlighting that 79 countries around the world generate energy from wind. Twenty four of those countries have already installed capacity larger than 1000 MW by 2013. In 2015, the ranking of European countries that produce wind energy was led by Germany, followed by Spain and the United Kingdom (U.S. Energy Information Administration, 2018). In accordance (WindEurope, 2017), 323 GW of cumulative wind energy capacity would be installed in the EU by 2030, 253 GW onshore and 70 GW offshore. That would be more than double the capacity installed at the end of 2016 (160 GW). It is expected that this capacity will generate 1272 TWh by 2020, which will become 2681 TWh in 2030, while the wind energy production in 2010 was 342 TWh (Ellabban, et al., 2014). Meanwhile, wind power installed will become 305 GW in the United States of America, while it is expected that it will reach 230 GW in China by 2030 (Shahan, 2011).

On the other hand, the ranking of European countries' producers of solar energy was led in 2015 by Germany, followed by Italy and Spain (U.S. Energy Information Administration, 2018). It is also expected that the solar world installed capacity will reach 192 GW by the year 2030. This growth of solar power installed causes a solar energy increase from the 32 TWh generated in 2010 to 332 TWh in 2020, reaching a forecast of 846 TWh in 2030 (Ellabban, et al., 2014).

Other renewable energies such as tidal energy, geothermal energy or biomass, are not yet sufficiently established to be compared to the penetration of wind or solar energy.

These increases achieved around the world constitute a good way to reduce the dependence on fossil fuels and greenhouse gas emissions generated by fossil fuel combustion (Denholm, et al., 2010). In addition to the advantages related to greenhouse gas emission reduction, renewable energy resources' costs are zero, having only operational and management costs associated. Thus, each energy unit generated by renewable energies, which replaces energy units generated by thermal power plants, saves costs for the electric power system (Weigt, 2009).

I.2 Renewable energy on islands

In the case of islands, which generally constitute isolated power systems, the renewable energy development is not only promoted by the environmental problems inherent to fossil fuels. The cost of transporting these fuels (such as gas, oil or coal) to the places of consumption, normally carried out by sea, is much greater than in the case of continental systems, so their replacement by renewable energy sources can have a very positive economic impact (Caralis & Zervos, 2007). In particular, solar and wind based generation systems have become sustainable and environmentally friendly options to supply power to isolated or off-grid locations (Singh, et al., 2016).

Depending on the effective diesel prices, experts estimate that cost reductions of up to 75% are possible by using renewable energy instead of diesel generators. The potential of renewable energy on smaller islands is estimated to be far beyond 30 GW (THEnergy, 2016). In fact, fossil fuels use reduction owing to the increasing use of renewable energies in small isolated systems has become the focus of interest of numerous researchers during the past few years.

These islands range from extremely small—such as the tiny Pacific nation of Tokelau, which moved to entirely solar power several years ago (Government of Tokelau, 2013)—to relatively large—Iceland relies almost entirely on hydropower and geothermal power, although these are less variable than wind and solar. Hawaii announced that it plans to transition its electric grid to 100% renewables by 2045. This is the most aggressive target in the U.S. and it means that the state will serve as a testbed for bringing large amounts of variable renewables onto the grid (EcoWatch, 2015 (a)). Kodiak Island in Alaska, the second largest island in the U.S., has just shifted to fully running its grid with wind and hydro power (EcoWatch, 2015 (b)).

As an example, the island of Crete, which is one of the Greek islands with high penetration of renewable energy, has hosted more than 50% of all renewable energy projects situated in Greece (Lin, et al., 2016). Wind power has been extensively used, and the installed capacity of wind power reached 166 MW in 2009 with a peak load of 650 MW. In 2012, the Greek government approved two new wind power projects with a capacity of more than 2000 MW. The island of Samso, Denmark, has invested heavily in local energy production, including wind, biomass, and solar power. The renewable production not only covers the electricity consumption, but compensates the energy utilized in the transportation sector generation (Conti, et al., 2010). The island of Reunion, a French overseas region located in the Indian Ocean, has high potentials of renewable energy resources such as solar, wind, geothermal, sea energy, biomass and hydropower. In Reunion, the wind utilization potential can reach 60 MW (Kuang, et al., 2016). Two renewable-related projects - PRERURE and GERRI - were launched in 2000 and 2008, respectively. They have indeed promoted investments to achieve an energy mix with 100% renewable energy sources by 2025 (Drouineau, et al., 2015).

In the Azores archipelago, the potential for renewables integration on Flores Island allows the consideration of the electrification of the transportation sector, playing in this case, a major role in reducing carbon emissions from the energy sector. This generation system is composed of diesel generators, two wind turbines and four hydro units (Vasconcelos, et al., 2015).

1.2.1 The Canary Islands case

The Canary Islands, located in the Atlantic Ocean, comprise seven islands: Tenerife, Fuerteventura, Gran Canaria, Lanzarote, La Palma, La Gomera and El Hierro, and additional islets. The electricity system of the Canary Islands is broken down into six electrically isolated subsystems, one per island except for Lanzarote and Fuerteventura, whose grids are joined by a submarine cable. The fact that the systems are isolated, which increases the difficulty of system optimization as a whole, to ensure the quality of the service, and the variability of the renewable energy production due to changing weather conditions, makes the development of the renewable energy market more difficult than in larger power systems. The electricity demand in The Canary Islands presents a clear annual cycle, with a higher power consumption during summer and at the beginning of autumn and with lower demand during spring. (González, et al., 2017). Table 1 lists the capacity of the different generating technologies installed on each Canary Island in 2015 (Gobierno de Canarias, 2016).

Table 1. Generating technology available in each Canary Island in 2015 (MW).

Energy resource	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Accumulated
Fossil fuels	1024.1	1111.6	232.3	187.0	105.3	22.6	14.9	2697.8
Renewable resources (RR)								
Wind	86.7	36.7	8.8	13.1	7.0	0.4	-	152.6
Photovoltaic	39.6	114.9	7.8	13.0	4.6	0.04	0.03	180.0
Hydroelectric	-	1.2	-	-	0.8	-	-	2.0
Hybrid wind-hydro	-	-	-	-	-	-	22.8	22.8
Biogas	-	1.6	2.1	-	-	-	-	3.7
RR accumulated	126.3	154.4	18.6	26.1	12.4	0.4	22.9	361.1
TOTAL	1150.4	1266.0	250.9	213.2	117.7	23.0	37.8	3059.0
RR over total	10.98%	12.20%	7.41%	12.24%	10.54%	1.74%	60.58%	11.80%

As shown in this Table 1, the current penetration rate is generally greater than 10%, which has motivated many researchers to focus their studies on these islands.

However, it is worth highlighting the case of the Island of El Hierro, in which more than 60% of the installed capacity is renewable. El Hierro was declared a biosphere reserve by UNESCO in 2000 (United Nations Educational, Scientific and Cultural Organization, 2014). The island aims to become 100% free from carbon dioxide emissions (Iglesias & Carballo, 2011). In order to contribute to the achievement of this objective, a hybrid wind–pumped storage hydropower plant at a rated power of 22.82 MW

(5 VSWTs at a rated power of 2.3 MW and a pumped storage hydropower plant (PSHP) at a rated power of 11.32 MW) was committed in June 2014 to minimizing the utilization of fossil fuels (Pezic & Cedrés, 2013).

Increases in the penetration of renewable energy have not only taken place on the El Hierro power system. Regarding La Palma Island, which has been declared a Biosphere Reserve by UNESCO since 2002 (United Nations Educational, Scientific and Cultural Organization, 2014), the objective is to reduce the consumption of fossil fuels and increase the use of renewable resources (Gobierno de Canarias, 2007). For this purpose, it is expected to increase the installed capacity of wind and solar farms and build a PSHP. One of the main objectives to achieve is producing energy exclusively from renewable sources.

However, VSWTs and photovoltaic systems are connected to the grid through power converters so they do not provide frequency regulation. In these cases, the rest of the generating units (usually diesel generators) must adapt alone their operating points after variations in power demanded. Thus, wind and solar energy can be considered as a negative load and diesel generators operate in isolation. However, generators based on fossil fuels tend to be substituted by renewable energy (such PSHP). This configuration makes frequency regulation a complex task that must be studied, justifying the interest of this Thesis.

I.3 Renewable energy characteristics

The benefits of renewable energy sources are well known and widely documented. Indeed renewable energy is generally well accepted by society, as shown by (Kaldellis, 2005) after conducting a study in Greece. However, the implementation of these non-manageable energy sources in power systems implies drawbacks inherent to their characteristics: system inertia reduction, intermittency, unpredictability and demand independence. As a real example, with the quick development of wind power technology, the penetration ratio of wind power in some areas of China has exceeded 20% (Zhu, et al., 2011), implying significant negative impacts on power grid dynamic stability, frequency and voltage regulation (Wu, 2013).

In general, the negative effects produced in the electrical grid are related to the loss of quality in the power supplied, having difficulties in maintaining frequency (Wang, et

al., 2016) and voltage (Georgilakis, 2008) within the limits required by Transmission System Operators (TSOs). Therefore, the difficulty of maintaining frequency within the established limits increases significantly. Actually, the scheduled load shedding activation may be needed (Sharma, et al., 2011) as an emergency measure when frequency is below certain values established by the TSO to avoid damages in the consumption loads. For these reason, this Thesis is focused on frequency regulation, not considering voltage control.

Renewable energy sources are naturally intermittent, with different degrees of intermittency. Among renewable resources, wind is a highly fluctuating meteorological parameter and changes hourly, daily, weekly, monthly, and annually. However, solar radiation is a better-known source of energy and it is less fluctuating, but only works during daylight hours. From the power quality point of view, solar energy provides relatively more reliable power and can be committed and managed with relatively small energy storage systems (Mahbub Alam, et al., 2014). This fluctuating nature of clean energy sources has an adverse effect on power production, becoming a challenge for regular and uninterrupted supply of power to the end user and for grid stability.

Regarding unpredictability, wind speed predictions have improved remarkably in recent years, according to the review of wind power forecasting models provided by (Wang, et al., 2011). Therefore, the main issue for the successful integration of these technologies is how to best manage the intermittency and stochastic nature associated with most of them (Canales, et al., 2015). As an example, (Blonbou, et al., 2011) applied a short-term wind energy prediction scheme developed by The University of French West-Indies and Guyana that uses artificial neural networks and adaptive learning procedures based on Bayesian approach and Gaussian approximation.

Regarding demand independence, wind and solar resources do not have any parallelism with the consumption pattern, neither in the short term nor in the long term (The Electric Power Research Institute, Inc, 2011). In fact, there may be a significant advantage in locating future wind parks on sites where wind speed patterns better match electricity demand patterns, rather than just choosing a site with the highest mean wind speed (Suomalainen, et al., 2013).

I.3.1 Renewable energy impact in power systems

Generally speaking, wind power generation uses either fixed speed (Types I and II) or VSWTs (Types III and IV). These four types are briefly described in a following section.

The vast majority of renewable power generation technologies (except conventional hydro power plants and Type I and II wind turbines) are decoupled from the grid through a power electronic converter. Hence, these generators cannot respond naturally to frequency drops although they have an inertia comparable to that of conventional generators (i.e. wind turbine generators have stored kinetic energy as they include rotating masses, but they do not sense the sudden drop in grid frequency because the converters react very fast and alternate the control signals) (Attya, et al., 2018).

(Lalor, et al., 2004) simulated the frequency response due to a disturbance on the all-Ireland system for a range of installed wind capacities under different system conditions, assessing the effects of increased wind generation on system frequency, and the security of the system following such disturbances. Authors remark that if wind provides no inertia, times of low system demand may be problematic. This study, published in 2004, was continued by (Lalor, et al., 2005), concluding that in order to allow increasing wind penetration, a change in reserve policy may be required. For example, increasing DFIG wind turbine usage may necessitate additional availability of non-spinning reserve to maintain system frequency above a given threshold. This is particularly important for small power systems where system inertia is low.

With high levels of wind energy penetration, especially with the large amount of VSWTs incorporated into the modern utility grid, the frequency response of power systems is more likely to be affected in the event of a frequency disturbance or fluctuating wind conditions. So, a variety of issues associated with technical, economic and regulatory aspects will arise following this scenario (Gao, et al., 2013).

Different examples related to renewable energy impacting on power systems can be found in the work developed by (Sharma, et al., 2011) in the Texan system in the United States. These authors analyse how the penetration of renewable sources affects the inertia of the system, especially during off-peak hours. From records of specific events, it is concluded that knowing the real inertia that the system has at every moment is necessary

in order to anticipate excessive frequency deviations associated with the disconnection of a generating unit or similar events. The system composed by the Eastern Interconnection of the US is studied by (Ingleson & Allen, 2010). The authors propose a methodology to evaluate the quality of the network after disturbances. Their study shows that the increment of renewable energy has worsened the quality of the network in recent years. Additionally, (Kou, et al., 2015) investigate the primary frequency response adequacy of that interconnected system with high-wind penetration in the year 2030. The other major interconnection zone in the United States, the Interconnection of the West, is analysed by (Miller, et al., 2011). Authors concluded that wind plants with inertial controls contribute some of their stored inertial energy to the grid. In fact, minimum frequency is improved with significant levels of wind generation. It is technically and economically possible, with controls commercially available today, to have better system frequency response with high levels of wind generation.

(Wang, et al., 2016) recognized that the influence of renewable energy penetration on the European continent has not been deeply evaluated. In this study, the European system is simplified and, through simulations, the sensitivity of certain parameters to the penetration of renewables (penetration rate, load sensitivity to frequency) is analysed.

In the Nordic power system, (Yang, et al., 2016) highlight the need to vary the conventional generating units' (hydroelectric power plants) governor settings due to the loss of system quality associated with wind energy development.

As a rule, the renewable energy impact on power systems mainly depends on their penetration rate and the system inertia (Albadi & El-Saadany, 2010). For this reason, the negative effects of renewable energy sources are amplified in isolated systems, thus its study must be developed as a particular case. The influence of the renewable energy penetration on power systems' dynamic behaviour has been measured and analysed from the perspective of quality loss in system frequency response in isolated systems.

The Irish power system is studied by (O'Sullivan, et al., 2014). These authors expect that 40% of the energy consumed on the island will come from renewable resources in the year 2020, mainly from wind. According to them, this renewable penetration rate implies that a detailed study of the maximum penetration of renewable energies, especially during off-peak hours, is needed. This study is also remarkable because the

authors show that a voltage drop can cause the consecutive disconnection of wind farms for their protection, with the consequent failure of the system in spite of previous dynamic studies. Furthermore, authors recognized that wind farms represent a potential source of governor droop and inertial response and doing a modeling effort, supported by ongoing demonstration trials is required to fully understand the implications of wide-scale implementation of such technology. (Iswadi, et al., 2015), in which real data of the Irish power system is considered, demonstrating the deterioration of the electrical power quality and foreseeing stability problems if the increase of renewable energy penetration is maintained with no progress in frequency control or wind forecast techniques. The impact of wind forecast errors in the Irish system is studied by (Dillon & O'Malley, 2017).

The power system of the Hawaiian Islands is analysed by (Hawaii State Energy Office, 2016), detailing the different generating units that work on the islands. Records of power and frequency of different moments with different penetration rates of renewable energy are shown, analysing how wind ramps affect the system and highlighting the importance of medium and long-term wind forecasts in order to operate the system safely and efficiently.

According to (Delille, et al., 2012), the increased penetration of wind and solar energy in the power systems of the French islands of Martinique and Reunion has generated serious problems of frequency deviations. In fact, establishing the load shedding as common operations for all these power systems. Therefore, the French government—by ministerial order—has limited the penetration of renewable sources in these power systems to 30%.

I.4 Strategies for renewable energy integration in power systems

Different methods exist in the literature, which mitigate the negative effects due to high rates of renewable energy penetration. These methods are not excluding, in fact, in many cases they are complementary. The best known and most used are briefly described below. The researches focused on the study of the strategies based on hydro power plants and/or VSWT capabilities will be developed in detail in specific sections below.

- a) **Improvement of wind intensity prediction models.** The impact that the improvement in short, medium and long-term wind forecast models implies for the economic results and the dynamics of the system, has been shown by

(Meibom, et al., 2011) among others. Also remarkable, is the work developed by (Tascikaraoglu & Uzunoglu, 2014), in which the author gives a detailed review of wind forecast models, highlighting a new technique developed in recent years based on the possibility of unifying several predictive methods, which reduces forecasting errors.

- b) **Smart grids development.** Smart grids are characterized by efficiently integrating behaviour and actions of all users connected to it, ensuring a sustainable and efficient energy system, with low energy losses and high quality and safety of energy supplied. Homes and businesses become small producers of electricity, not just consumers, at any given moment. Thus, the use of electric vehicles, water heaters (Monette, et al., 2016), among others, considered as "intelligent loads", helps to mitigate the variability of renewable energies. Therefore, (Zame, et al., 2018) propose the re-conceptualization of the traditional power grid model by increasing the bi-directional flow of information between upstream and downstream parties. Frequency can also be controlled from the demand side. In this case, the loads (known as "responsive loads") should adjust their operation to provide reserves for frequency regulation based on locally measured system frequency (Xu, et al., 2011). In recent years, researchers have been actively exploring the utilization of residential and commercial loads in frequency regulation without affecting customers' quality of life. (Shi, et al., 2018) review the theoretical basis and application background of the dynamic demand control, summarizing the technical features and advantage/disadvantages of three types of dynamic demand control algorithms, namely centralized control, decentralized control and hybrid control. Since a power system with high renewable energy penetration has many short-term frequency variations, with large mismatches (due to high wind penetration), the amount of responsive loads is expected to be large to provide enough reserves for frequency regulation. Furthermore, Under-Frequency Load Shedding is a common technique to maintain power system stability consisting of several load disconnections which can be applied if frequency is lower than certain values established by the transmission system operator (Karimi, et al., 2012).

- c) **Implementation of penalty systems for producers who fail to meet the grid requirements.** A penalty system has been introduced for generators that cause frequency disturbances in Bonneville Power Administration (Georgilakis, 2008).
- d) **Energy storage systems.** There are many authors who claim that storing energy in the short, medium and long term is a suitable way to allow the development of renewable energy, contributing to mitigating renewable resources' drawbacks. As an example, (Zhao, et al., 2015) (Aneke & Wang, 2016) (Parra, et al., 2017) have carried out exhaustive reviews of available energy storage technologies in the last few years remarking on, among other things, the importance of PSHPs, flywheels, batteries, or capacitors. In addition, according to (International Energy Agency, 2014), at least 140 GW of large-scale energy storage is currently installed in electrical power grids around the world. Pumped storage hydropower technology makes up 99% of this capacity and the other 1% comes from a mix of batteries, compressed air energy storage, flywheels and hydrogen storage. (Barnhart & Benson, 2013) explain that storage is an attractive load-balancing technology because it increases reliability and flexibility of the power grid (especially in locations with ambitious climate-change policies), while at the same time it helps decrease carbon emissions by reducing the transmission load and enabling spinning power plants to operate at optimum efficiency.

I.4.1 Storage systems in isolated power systems

In the case of isolated island grids, where conventional generating units and the limited size of the systems impose technical limitations, energy storage options are considered the most effective means of increasing renewable energies penetration (Katsaprakakis, et al., 2007). Due to the inherent characteristics of isolated systems, it is necessary to distinguish technologies that mitigate the negative effects of renewable energies in the long term and in the short term. However, several examples of short and long-term mixed strategies can be found.

1.4.1.1 Strategies in the long-term

Specifically, it has been shown in several publications that the long-term variability of renewable energy is well managed by combining wind and solar farms with PSHPs.

The system of a PSHP is, in general, composed of an upper and a lower reservoir, and a power station composed of one or several hydropower units, as show in Figure 3. However, there are PSHPs which have another configuration, as will be detailed below.

Figure 3 Typical scheme of a pumped storage hydropower plant (Chazarra, 2017)

PSHPs store energy in the form of water potential energy, which is pumped from the lower reservoir to the higher level reservoir. In this type of technology, low-cost electric power (electricity during off-peak time) is used to run the pumps to raise the water from the lower reservoir to the upper one. During the periods of high power demand, the stored water is released through hydro turbines to produce electric power. However, PSHP operation in isolated systems with high wind penetration is different. When renewable resource availability exceeds the power demand, PSHP must operate in pumping mode to store the excess of renewable energy. Conversely, when power supplied by renewable generators is below the total power demand, PSHP must operate in turbine mode to provide the total power demanded. In these systems, the profitability has its origin in the reduction of the thermal units used.

These plants require very specific site conditions to be feasible and viable, such as proper ground conformation, difference in elevation between the reservoirs and water availability. The configuration of a PSHP can be classified according to the type of units installed (Pérez-Díaz, et al., 2015). A *Binary unit*, which is composed of a pump-turbine and a motor-generator electrical machine. This type of unit was first introduced in the

1930s and has since become the dominant design for PSHPs throughout the world. The most typical configuration is composed of a pumped-turbine coupled to a synchronous electrical machine, directly connected to the grid. Figure 4 shows a scheme of a hybrid solar-wind-hydro system with a PSHP equipped with a binary unit.

Figure 4 A hybrid solar-wind-hydro system with pumped storage system equipped with a binary unit.

PSHPs equipped with a *ternary unit* are composed of a turbine, a pump and a motor-generator electrical machine coupled all in the same axis. Among others, ternary units are installed in cases in which Pelton turbines are needed because of the high head available

Finally, the storage system can be divided into two different subsystems, a turbine with a generator electrical machine and a pump with a motor electrical machine. Usually, these kinds of systems have a pump station equipped with a pump and a motor near to the power station equipped with a turbine and a generator electrical machine. Figure 5 shows a scheme of a hybrid solar-wind-hydro system with a PSHP with the independent pump and turbine systems.

Figure 5 A hybrid solar-wind-hydro system with PSHP with the pump and turbine systems divided.

(Kear & Chapman, 2013) conducted a survey and found that pumped hydro was seen by most as prohibitively costly, but was almost universally viewed as technically capable of providing renewable support and peak power adequacy. In the modern world, with

growing awareness among people, renewable sources of energy are being encouraged and used globally. The provision of pumped storage power plants in isolated grids, like those described above, seems to be a promising option to address both reduction in fossil fuels consumption and the continuously increasing power demand encountered in these areas (Rehman, et al., 2015).

(Brown, et al., 2008) proved that including pumped storage in a small island system can be an effective means of allowing larger penetration of intermittent renewable energy sources. The hybrid wind and pumped-storage systems constitute a realistic and feasible option to achieve high renewable penetrations, provided that their components are properly sized (Rehman, et al., 2015).

The main advantage of these hybrid power plants lies in the improvement of the dynamic safety of non-interconnected power systems through the introduction of hydro turbines (Daoutis & Dialynas, 2009). In fact, the combined use of wind energy with PHES is considered a good way of exploiting abundant wind potential. Therefore, the optimum sizing of pumped storage facilities in similar applications has been the objective of several studies. (Kapsali, et al., 2012) presented a detailed design of a pumped hydro-storage system for the recovery of wind farms' rejected energy on the non-interconnected Greek islands of Lesbos and Crete. In fact, rejected energy is one of the drawbacks of VSWTs participation in primary and secondary regulation.

It is worth mentioning the extensive work developed by Prof. Kaldellis on the Aegean Islands. Among others, an integrated techno-economic analysis of the viability of a hybrid wind-hydro power plant for medium-sized remote islands is presented in (Kaldellis, et al., 2001), determining the best size of the main components of that hybrid power plant. In (Kaldellis & Kavadias, 2001), the economic analysis is extended applying it to several typical Aegean Islands' cases, in order to define the most beneficial configuration of the proposed renewable power plant. In the case of the Faroe Islands, (Suul, et al., 2008) analysed the wind power integration combined with a variable speed PSHP. The research developed by (Vasconcelos, et al., 2015) was focused on Portuguese islands. On the island of Madeira, the benefits resulting from variable speed hydro pumping stations providing primary frequency regulating services were assessed.

(Ma, et al., 2014) analysed the consequences of introducing a pumped hydro storage in a hybrid solar-wind system on a remote island in Hong Kong. This pumped storage will substitute non-environmentally friendly batteries that contain lead and sulphuric acid. They affirm that this hybrid technology provides an energy storage solution employing the most traditional and mature storage technology.

In the Canary archipelago, (Bueno & Carta, 2006) proposed to install on the island of Gran Canaria, a hybrid wind-hydro pumped storage system because the results obtained applying an optimum-size economic model of such a system indicates that renewable energy penetration can be increased by 52.55 GWh/year at a competitive cost. (Ramirez-Diaz, et al., 2016) analysed the effects of the introduction of two energy storage systems on La Palma Island. These systems were pumped hydro storage and electric vehicles, concluding that the installation of an additional 25 MW from renewables, supported by 20 MW of pumped hydro storage and a fleet of 3361 electric vehicles would allow a 26% reduction in greenhouse gas emissions.

1.4.1.2 Strategies in the short term

In the short term, PSHPs need complementary technologies as proved in several articles due to the high reaction time caused by the water inertia in the conduits.

In the technical review carried out by (Zhao, et al., 2015), the authors drafted the PSHPs' frequency regulation capacity in the short term, allowing the penetration of renewable energies into isolated systems. Because of the fact that PSHP are not fast enough to inject the demanded power in the first seconds after a frequency disturbance, external systems capable of injecting or absorbing power over brief time periods to avoid inadmissible frequency variations are required. Flywheels, variable speed hydro-pump turbines, VSWTs or batteries can provide these fast contributions to frequency regulations.

Battery energy storage systems have already been implemented in isolated electrical grids to enhance the integration of renewable resources in economically feasible projects. Since the recent developments in electrical vehicles have decreased the kWh cost of lithium-ion batteries (Branco, et al., 2018), their applicability has increased. An example can be found on Graciosa Island in the Portuguese Azores archipelago, where batteries' energy storage systems, jointly with photovoltaic, wind power and thermal generators,

optimise the electrical power generation schedule to fit the load demanded by the inhabitants of this island. However, to compensate for power irregularities, batteries charge and discharge frequently, which degrades their lifetime significantly. (Li, et al., 2017) presented a new frequency control technique by integrating the superconducting magnetic energy storage with batteries, thus achieving the ability of not only performing a good frequency regulating function but also extending the battery service time. A case study of The Yong Shu Island in the South China Sea is developed by (Ye, et al., 2017). These authors evaluated the feasibility of building a renewable hybrid energy system to match the power demand, considering two energy storage technologies: hydrogen-fuel cell technology and the traditional battery technology.

Flywheels is one of the oldest storage energy devices. They are based in the kinetic energy stored in a high-speed rotational disk connected to the shaft of an electric machine. They can inject the stored energy into the network when needed. Flywheels have several benefits, they can be applied from very small micro-systems to huge power networks, as detailed by (Mousavi, et al., 2017) in their technical review. (Sebastián & Peña Alzola, 2012) present the simulation of an isolated wind power system consisting of a wind turbine generator, a consumer load, a synchronous machine and several flywheels. They show that the flywheels effectively smooth wind power and consumer load variations.

The basic idea underlying variable-speed technology in hydro turbines is to maintain high efficiency values in their whole working range. Turbine rotation velocity is modified in order to maintain optimal or near-to optimal efficiency values in a wide range of head and flow rates (Ardizzon, et al., 2014). As is described by (Nicolet, et al., 2011(a)), PSHPs equipped with variable speed pump-turbines offer a lot of advantages for a pump-turbine operating both in generating and pumping mode. Authors remark on their capacity to provide active power control in pumping mode, and the efficiency increase and wide range of operation in generating mode. From the point of view of frequency regulation, grid stability is improved, injecting instantaneous active power into the grid, similarly to flywheels. This is due to the existence of a power converter that allows the injection of the desired power into the network instantaneously, analogously to the wind turbines type III and IV.

Several researchers have focused on the analysis of PSHPs equipped with variable speed pump turbines. (Suul, et al., 2008) proposed a power plant equipped with variable

speed units to mitigate the variations in the short term in wind power generated by a wind farm located in an isolated system on the Faroe Islands. (Nicolet, et al., 2014) simulated the dynamic behaviour of an isolated system with a thermal unit, a wind turbine farm, photovoltaic units and a pumped storage hydroelectric plant equipped with variable speed. Authors analyse the contribution to the system response of the hydroelectric power plant due to variations in wind speed and solar radiation. Simulations presented, combined with operational cost simulations represent appropriate tools for the optimization of pumped storage power plants. Authors highlight that the constant development of power electronics and the associated cost reduction yield new opportunities such as synchronous machine with Full Power Frequency Converter, offering even more flexibility such as direct transition from turbine to pump and vice-versa.

As a negative aspect, at part load in pumping mode, reversible pump-turbine machines suffer from unstable behaviour related to a strong fluid-dynamical interaction between rotor and stator parts that causes the development of unsteady phenomena (Dorfler, et al., 2013). For that reason, (Martínez-Lucas, et al., 2017) propose a set of functions experimentally validated to model the pressure pulsations that appear in a pump-turbine operating at part load in pumping mode. These functions allow a preliminary evaluation of the impact that the propagation of these pressure pulsations have on the penstock fatigue.

Regarding the El Hierro power system, (Merino, et al., 2012) model this power system including a wind farm, a pumped storage hydroelectric power plant, and a diesel plant. This model has been used to analyse the transient stability of the system after severe disturbances. In order to achieve a reliable and efficient electrical system without using any fossil fuel energy, authors propose the use of hydraulic units connected to the grid as synchronous compensators, with a minimum water consumption. (Platero, et al., 2014) present a novel method of Pelton turbine operation with no water flow, as a way of providing fast power injection in the case of a sudden wind power decrease, or a wind-generator trip, improving the wind power penetration in the El Hierro power system.

VSWT (types III and IV) can help to mitigate the imbalances between production and demand in the first seconds until the hydroelectric plants can act. The

complementarity between PSHPs and VSWTs, on which this Thesis is based, will be described in the following sections.

I.5 Introduction to frequency control in power systems

Besides voltage, frequency is the main control variable in a power system. Frequency indicates the system's energy balance and it needs to be regulated for stable operation (Aziz, et al., 2017). When frequency is below its rated value, it means that power system generating units provide less power than system loads demand. In an analogous way, if power system frequency is higher than its rated value then generating units provide more power than system loads demand. Small load variations can destabilize the system, as indicated in (Vournas & Papaioannou, 1995). System frequency is usually controlled by controlling the active power injected into the electric grid by the system power plants. This control is essential for the grids' stable operation, ensuring continuous adaptation of generation to demand. Frequency below a certain prescribed level will deteriorate power quality and may eventually result in system outage. The mission of frequency regulation is to quickly respond to system frequency deviation by increasing or decreasing the power generation or load demand to bring frequency back to rated value (50 or 60 Hz).

Frequency regulation can be provided through two types of controls. On the one hand, Droop Speed Control refers to the prime mover governor speed control mode that allows multiple generators to be operated in parallel with each other to power electrical loads, or to "share" load. On the other hand, Isochronous Speed Control refers to the prime mover governor speed control mode that only controls the rotational speed of a generator.

Figure 6 represents a typical frequency regulation scenario based on Droop Speed Control after a power disturbance that starts deviating up to a minimum value named nadir point.

Figure 6 Regulation services after a frequency disturbance (Aziz, et al., 2017)

Frequency regulation based on Droop Speed Control, can be divided into three consecutive control actions (Shi, et al., 2018).

Primary Frequency Regulation, which refers to governor control that adjusts the active power of generating units to correct frequency variations within a few seconds. Normal power imbalance between generation and consumption is instantaneously covered through system synchronous generators' natural inertial response followed by these synchronous generators' governor response. Generators' inertia is considered the first level of frequency control reserve. Due to the inertia being proportional to the rotating masses of generators, a larger inertia means a lower deceleration, and so, a smaller frequency deviation. Conventional power plants, which remain connected to the grid even in the case of frequency deviations, accomplish active power-frequency control through the turbine governor's reaction to synchronous speed variations. Frequency nadir achieved just after a disturbance and the frequency settling time are highly dependent upon the generator's droop characteristic. A power plant with higher droop and slower governor response will lead to a lower nadir point during a contingency. As Figure 6 shows, primary frequency regulation introduces a permanent frequency error, which is corrected by secondary frequency regulation. In Spain's electric system, primary regulation services act up to 30 seconds after a frequency disturbance (Aziz, et al., 2017).

Secondary Frequency Regulation refers to automatic generation control (AGC) that adjusts the active power output of generating units to bring system frequency back to its rated value after a governor-based primary response. AGC is comparatively slower than primary control. The power plants participating in this service must maintain a reserve in

order to modify their operating point, restoring the frequency to its rated power in less than 15 minutes.

Tertiary Frequency Regulation means manual changes in the dispatching and commitment of generating units (reacting in more than 15 min). Tertiary frequency regulation is used to restore secondary reserves and to manage congestions in transmission networks. This control is applied to guarantee the timely provision of the adequate secondary control reserves and the economical distribution of the optimal secondary power control set-points to various generators. Both secondary and tertiary controls require increasing or decreasing power. Load shedding, peak-load generating units, like gas turbines or pumped storage units in turbine operating mode, provide tertiary control when demanded power increases, while pumped storage in pumping mode (also gas turbines) is used when demanded power decreases. In Spain's electric system, tertiary regulation services act between 15 minutes and 2 hours after a frequency disturbance.

Primary, secondary and tertiary regulation is not considered adequate in avoiding the negative economic effects associated with VSWT.

Isochronous Speed Control regulation can be used in isolated systems or power plants operating in isolation. When used, in small isolated systems, one generator is frequently operated in Isochronous Speed Control mode. Any other, usually smaller, generators connected to the grid are operated in Droop Speed Control mode. Various prime movers operating in Isochronous Speed Control mode would cause instability. Therefore, only one machine can operate in Isochronous Speed Control mode when multiple units are being operated in parallel. In this Thesis, hydropower plants operating in the El Hierro power system and the La Palma power system are assumed to be regulating frequency with an Isochronous Speed Control, constituting the critical scene.

According to (Shi, et al., 2018), Figure 7 summarizes the general scope of frequency regulation approaches, including both traditional and emerging. The control scenarios that are the scope of this Thesis are identified in red, highlighting wind turbine control as one the emerging ones.

Figure 7 Approaches for balancing the power generation and consumption.

I.6 Hydropower plants' contribution to frequency regulation

In order to analyse hydropower plants' contribution to frequency regulation, analysing existing models, and/or building a realistic model that takes into account all the phenomena involved in system operation, is essential to draw relevant conclusions, applicable to predicting the response of the power plant (Mansoor, et al., 2000).

Mathematical dynamic models of hydroelectric power plants represent a valuable tool for different applications. Both in the preliminary design phase of the power plant and during the operation design of the power plant, an appropriate model allows the establishment of certain parameters related to the power plant control strategies. (Mansoor, et al., 2000) summarize the main benefits of developing a correct hydropower plant model as follows:

- Construction of the model gives insight into the plant's characteristics and improves understanding of the physical phenomena involved.
- The simulation can be used to predict the response of the station during the design of new control systems and allows parameter sensitivity analyses to be performed.
- With the addition of an interface for display and input, the simulation can be used for operator training.

The purpose of the models is essential for determining the initial hypotheses and the conditions that allow a choice between the set of different types of models. Models must represent the real behaviour of the power plant, otherwise the advantages that models provide would be lost, and important-decision making errors would be incurred. These dynamic models includes the main component that compose a hydropower plant: conduits, turbine, speed governor, surge tank (when needed) and electric machine.

Depending on the scope of the study, these components can be modeled assuming different hypothesis, or even not being modeled.

Regarding the speed governor, the classical PI is the most common form of controller used in governors. In spite of the fact that the electronic PID controller exceeded the hydraulic-mechanical controller for many years, it is one of the most used currently to control hydroelectric power plants since PI controllers, without the derivative component, can be adjusted to behave like a hydraulic-mechanical controller (Kishor, et al., 2007). The structure of this controller is composed of two terms which treat the current control error (P) and past control error (I). Suitable criteria for governor gains setting have been thoroughly studied in previous decades.

In the following sections, a discussion between different models of conduits and different speed governor setting strategies will be address.

I.6.1 Dynamic models of conduits

As indicated by (Kishor, et al., 2007), there are several ways to classify hydroelectric power plant models, distinguishing between linear models and non-linear models. A partition is proposed for conduits models, assuming a rigid water column approach or models that include the elastic behaviour of water and conduits. At the same time, the plant can operate in isolation, covering its own load or connected to inter-connected power systems.

I.6.1.1 Rigid water column model

Conduits can be modelled using the rigid water column approach. This approach is based on assuming an inelastic penstock wall and incompressible water flow. Rigid water models are the most used in specialized literature in cases in which water hammer effect is neglected, as seen in (Ramey & Skooglund, 1970), (Luqing, et al., 1989), (Herron & Wozniak, 1991), (Malik, et al., 1991), (Kundur, 1994) or (Jones & Mansoor, 2004) among others.

Assuming this approach, (Hovey & Bateman, 1962) consider a model of a hydropower plant that only includes the dynamics of the penstock, the turbine and the speed governor, thus forming a third-order model. This same model has been satisfactorily used in (Chaudhry, 1970), (Jiménez & Chaudhry, 1987).

1.6.1.2 Elastic models

Most of the technical literature analysed in the detailed review carried out by (Kishor, et al., 2007) were based on simple first order conduits models. These authors remark that a first order model will have significant errors if used to model long penstocks. According to (Jiménez & Chaudhry, 1987), the conduit length may limit the applicability of the rigid-water-column models, making it necessary to consider the elastic phenomena from a certain value of the Allievi parameter. Therefore, a detailed hydraulic system model is required to take into consideration the water compressibility and penstock elasticity.

In order to include the elastic phenomena in models, there are several approaches in the scientific literature that replace the rigid water column model. Thus, (Chaudhry, 1987) proposes applying the well-known method of characteristics to solve the partial differential equations that govern the elastic behaviour. This method has been used in several studies, such as (Riasi & Tazraei, 2017). (Vournas, 1990), proposed both a first-order and a second-order transfer functions which approximates the exact hydraulic turbine transfer function based on hyperbolic tangents. (IEEE Working Group, 1992) also proposes a transfer function to include elastic phenomena in conduits. Transfer function approaches consider linear models.

The study developed by (Souza Jr, et al., 1999) proposes the so-called lumped parameters approach, in which it is considered that water energy losses, due to variations in water density, as well as those due to changes in diameter of the pipeline, are lumped at a single point of said section. This approach leads to a system of ordinary differential equations that can be represented as a series of consecutive, Γ -shaped elements where the conduit's properties (inertia, elasticity, and friction) are proportionally assigned to the segment's length. (Nicolet, et al., 2007) apply the lumped parameters approach to simulate the transient operation of an islanded power network subject to load rejections. Gorona del Viento PSHP is modeled by (Platero, et al., 2014) using a lumped parameters approach. A detailed description of the lumped parameters approach, which is applied in this Thesis, is provided in the methodology section.

The possible criticism of this method is how to know the number of sections to discretize the pipe. Sections must be sufficient so as not to lose accuracy, but without exceeding a number that complicates the resolution of the model. (Brezina, et al., 2011)

propose a range of sections in which to discretize the pipe according to the length of the pipe, the maximum admissible pressure and the speed of the pressure wave.

I.6.2 PI controller setting criteria

Control of hydroelectric systems is a task that occupies the research work of many authors. The same authors show a broad bibliographic review of the control of hydroelectric power plants following a scheme based on the historical evolution of control theory. Modern control is out of the scope of this Thesis.

In order to study the dynamic behaviour of a system, to develop modal analyses or to obtain simple rules, recommendations or expressions useful for PID governor tuning, Classical Control tools and techniques, (root locus plot, bode diagram,...) have been successfully applied. Modal analysis provides a powerful tool for studying the interaction between the oscillating modes that interfere with the dynamic behaviour of the system, differentiating the dominant variables of each oscillation mode.

The work developed by (Hovey & Bateman, 1962) is a basic reference for understanding the application of classical control theory to hydroelectric systems. Thus, the authors study the behaviour of the Kelsey plant, Canada, developing a method to determine the controller parameters that produce the best response from the plant. In this work, a linear model, which allows the analysis of small perturbations, is proposed. Having calculated the characteristic polynomial of the model state matrix, the stability criterion of Routh-Hurwitz is applied, obtaining the stability region.

(Chaudhry, 1970) extended the work developed by Hovey and Bateman, adding the consideration of the turbine permanent speed droop and the load self-regulation coefficient. The tuning criterion developed by Chaudhry was empirical, since after a multitude of simulations, the author selected the parameters that minimize the settling time of the power plant. (Thorne & Hill, 1975) investigate the stability region of a hydraulic turbine and the associated governor control, based on a proven model for the case of a single hydraulic unit connected to an equivalent system.

(Hagigara & Yokota, 1979) investigated the effect of derivative gain and other governor parameters on the stability boundaries of a hydraulic turbine generating unit supplying an isolated load. In fact, authors expanded the works of (Hovey & Bateman,

1962) and (Chaudhry, 1970) to show the stability boundaries of a hydraulic turbine generating unit having a P.I.D. governor. The optimum setting of the proportional, integral, and derivative gains is proposed from the Routh-Hurwitz criterion. The stability boundaries of a hydraulic turbine generating unit are studied as a function of governor proportional, integral, and derivative gains, machine and system speed regulations, turbine loading, interconnection, and system damping by (Phi, et al., 1981). Professor Wozniak develops a graph method which can be used to predict optimum proportional and integral speed controller gains by the pole cancellation method (Wozniak, 1990).

In the work developed by (Liu & Liu, 2007), a linearized mathematical model of a hydraulic conduit, taking into account the compressibility of the water and the elasticity of the conduit, was presented. This model was applied to the study of the oscillatory instability of a hydroelectric power plant in China with a 400 meter length penstock without a surge tank. The authors reported a modal analysis combining the hydraulic subsystem with the mechanic and the electric subsystems. They demonstrated that modal analysis is able to reveal the physical nature of the oscillation and the impacts of control parameters on stability, the association between certain oscillation modes and the selected variables. Using eigenvalues and participation factors of the linearized model state matrix, water elasticity and mechanic-water oscillation modes were identified, leading to an insight into the impacts of water conduit dynamics on the stability of hydraulic generating units. The penstock was modelled to include the elastic phenomena according to the recommendations proposed by (IEEE Working Group, 1992) assuming that the power plant operates in isolation. An eigenvalues analysis was applied by (Silva, et al., 2010) to a complete hydroelectric production site including hydraulic components (pump-turbine, penstock, gallery, reservoir etc.), to study and to analyse the interactions between the hydraulic, electric and regulation parts of the system. The authors recognize that the representation of the eigenvectors gives very useful information on the mode shapes of different components of the complete system. (Silva, et al., 2017) applied eigenvalues analyses to study the instabilities or undesirable disturbances at an existing hydropower plant, which may be caused by phenomena such as part load vortex rope pulsations in the draft tube of Francis turbines. They proved that Eigen analysis is a very useful tool, since it permitted the assessment of the global stability around the operating point for the part load condition. The conclusion of this analysis allow the avoidance of the risks of resonance between the draft tube and the electromechanical eigenmodes.

(Yang, et al., 2018) developed a fundamental study of hydraulic-mechanical-electrical coupling mechanism for small signal stability of hydropower plants, analysing the influencing mechanisms of water column elasticity, governor mechanical component, and water inertia, studied under different control modes of the turbine governor. The authors consider that a comprehensive study of the stability of the multi-variable hydropower systems is very important.

A bibliographic review of the tuning criteria applied to the PID controller for rigid water models and elastic models is summarized in the following sections.

1.6.2.1 PI setting criteria based on rigid water column models

As described by (Sarasúa Moreno, 2009) to control the water level in a run-of-river hydropower plant, the poles placement of the transfer function of the hydropower plant model is directly related to the response of the plant. The author established a relationship between both the frequency settling time and the oscillation period with the real and imaginary parts of the mentioned poles. Therefore, the power plant dynamic response can be predicted from the poles, that is, from the root locus of the linearized model. According to these relationships, the shorter the frequency settling time and the longer the period of the oscillations, the better the power plant response will be due to the limitation of the gate opening oscillations.

As it will be described below, other works base the PI controller tuning also on the root locus, and therefore, on the dynamic matrix of the system eigenvalues placement.

Governor parameters are critical, as shown by the analysis done by (Dandeno, et al., 1978) after the experience obtained at Ontario Hydro power plant with the operation of hydraulic units under islanding conditions. A governor-parameter sensitivity analysis was carried out in order to determine the overall governor setting requirements obtaining the eigenvalues and the damping ratio of each set of parameters. The Root locus method was used by (Hagigara & Yokota, 1979) for analysing the effect of governor parameters on the dynamic behaviour of a hydroelectric power system. The authors provide a general guide for optimum adjustment of derivative gain.

(Wozniak & Bitz, 1988) discussed the application of variable gains for the proportional and integral control (PI) applied in hydroelectric generators' speed

controllers. It is based on dynamically locating the poles of the governor transfer function in the appropriate places. It is therefore a matter of obtaining a programme able to adapt the governor gains according to the power plant operation point. The study was completed with the comparison of the plant response according to the proposed new method of variable gains with the response according to a PI control of fixed gains. Professor Wozniak concluded by affirming that the power plant dynamic response is improved, distinguishing that this improvement is more noticeable in the points far from the operation nominal point. Governor gains were obtained by (Wozniak, 1990) from four parameters: time constants of the water column, rotor inertia, self-regulation constants of the turbine and grid load using the pole cancellation method. This author recommended a fix damping ratio of 0.707 for the mechanical oscillating mode to minimize oscillations.

(Erickson & Wozniak, 1991) also applies a PI controller to analyse the maximum speed at which the nozzle opening can be moved in impulse turbines, that is, in Pelton turbines. A maximum in the variation rate of the nozzle gate was proposed, thus being able to avoid faster manoeuvres than the maximum obtained. For this purpose, the authors used a linearized model of the power plant including the penstock, the generator and the turbine. This result and those obtained by (Orelind, et al., 1989) were experimentally applied by (Collier & Wozniak, 1991), where the authors correct the existing PI control in the Bradley Lake hydroelectric power plant, equipped with Pelton turbines. These authors also studied for different power plant operation points, the influence of the controller's gains variation in the dynamic response of this plant. One of the conclusions reached was that, in this real case, the variation of the derivative gain of the PID control does not significantly influence the response of the plant.

Controller parameters were obtained from closed-loop poles and hydro turbine parameters by derived analytical formulas over a wide range of the hydro turbine operating points (Strah, et al., 2005). These authors presented several expressions for obtaining the controller's gains, as a function of the technical requirements that the designer considers such as frequency overshoot, period of oscillations or the frequency settling time.

A method of tuning the PID controller from the location of the poles of the closed loop transfer function is developed by (Abdolmaleki, et al., 2008). These authors presented the closed-loop transfer function of a hydropower plant, proposing the use of

the root locus to select the location of the poles which allows the best power plant response. They concluded by stating that the best hydropower plant response after a power disturbance occurs with the controller's gains, such that the real parts of the poles of the closed-loop transfer function are equal, a condition that is imposed in the tuning criterion proposed in this thesis. The use of the root locus technique as a basis for the tuning of a PI controller has also been used in run-of-river power plants by (Sarasúa, et al., 2007).

The above recommendations are based on conduit first order models which do not take into account the elasticity effect. Accordingly, the applicability of the PID tuning criteria described above, are limited in long conduits power plants, as demonstrated by (Sanathanan, 1987).

1.6.2.2 PI setting criteria based on elastic models

Although there are several contributions that model the dynamic response of hydropower plants when the influence of pressure waves cannot be neglected, as described above, very few attempts have been found in the literature dealing with the adjustment of PID governor. It is worth mentioning the work developed by (Murty & Hariharan, 1984) where the stability boundaries in terms of the PI gains are determined under the influence of the water column elasticity, extending the results obtained by the rigid water column approach. (Sanathanan, 1987) proposed a methodology based on a reference model to obtain a PID governor gains. In this model, the turbine-penstock is represented by a synthesized second order model.

(Kishor, et al., 2005) proposed reducing the order of turbine-penstock transfer function since the elasticity phenomena assumption generates an irrational term. For this, the author used the Padé approach method, the Maclaurin series and the H_∞ method. Finally, the authors argued that the H_∞ method is closer to a rigid column water model. (Sarasúa, et al., 2015) studied the dynamic response and governor tuning of a long penstock pumped-storage hydropower plant equipped with a pump-turbine and a DFIG connected to a small isolated power system with thermal generation, proposing two governor tuning criteria. One of these governor tunings are based on the recommendation of use a fixed damping ratio of 0.707 in the mechanical oscillating mode proposed by (Wozniak, 1990). The other governor tuning is based on a Pareto approach. In this case,

the response to a step decrease of 30MW in the load demand was simulated assuming different pairs controller gains.

PI control can be used in different systems. As an example, a model and a tuning criterion of a pumping station PI controller is studied by (Brezina, et al., 2011) using the transfer function pole placement method. Due to the length of the impulsion pipe, the authors included the effects that produce both the compressibility of the water and the elasticity of the pipe in the system for the controller tuning.

I.7 Variable speed wind turbines' contribution to frequency regulation

Wind generators can be equipped with fix or variable turbines. Furthermore, WG are categorized into four types (Iov, et al., 2008).

Fixed Speed Wind Turbines (WT Type I): This type of wind turbine uses an asynchronous squirrel-cage induction generator directly connected to the grid via a transformer. This means that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator design. This type of wind turbine needs a switch to prevent motoring operation during low wind speeds, and also suffers a major drawback of reactive power consumption since there is no reactive power control. Moreover, this type of wind turbine transfers the wind fluctuations to mechanical fluctuations and further converts these into electrical power fluctuations. These electrical power fluctuations can lead to an impact at the point of connection in the case of a weak grid. The operating range of rotor speed varies within a very small range, approximately 5% of the nominal rotor speed (Gupta, 2016).

Partial VSWT with Variable Rotor Resistance (WT Type II): This type of wind turbine uses a wound rotor induction generator (WRIG) directly connected to the grid. The rotor phase windings of the generator are connected in series with controlled resistances. In this way, the total rotor resistance can be regulated, and thus the slip and the output power can be controlled. Due to the limitation of the serial resistance sizes, the variable speed range is usually small, typically 0-10% above synchronous speed (Iov, et al., 2008).

VSWT with Partial-Scale Power Converter (WT Type III): This configuration, known as the doubly-fed induction generator (DFIG) concept, uses a variable speed controlled wind turbine. The stator phase windings of the doubly-fed induction generator are directly

connected to the grid, while the rotor phase windings are connected to a back-to-back converter via slip rings. The power converters could control the frequency and thus the rotor speed. The smaller rating of the power converters makes this concept attractive from an economical point of view. Furthermore, this type of wind turbine can also achieve the desired reactive power compensation.

VSWT with Full-Scale Power Converter (WT Type IV): This configuration usually uses a permanent magnet synchronous generator (PMSG) and a full-scale power converter. The stator phase windings are connected to the grid through a full-scale power converter. Some of the wind turbines of this type adopt a gearless concept, which means that instead of connecting a gearbox to the generator, a direct-driven, multi-pole generator is used without a gearbox.

The PMSG is fully decoupled from the grid; this is because the stator of this type of generator is connected to the power electronic converter in order to inject power into the grid. The DFIG is similar to the PMSG, except that DFIG is connected to the grid via a rotor circuit. The power electronic converter used in a VSWT enables the wind turbine to regulate the output power over a wide range of wind speeds (Revel, et al., 2014). However, this decoupling isolates the wind turbine from the frequency response after a disturbance.

Both Type I and II represent the oldest type of wind turbines, while Types III and IV are the most commonly sold and installed topologies on the current market (Honrubia-Escribano, et al., 2018). Among other reasons, the price and size of power converters has decreased in recent years.

The National Renewable Energy laboratory and the Electric Power Research Institute in the United States have conducted a collaborative program starting in January 2011 (Ela & Brooks, 2011). The main purpose of this work was to analyse the state of the art and discuss the research needs of providing active power control from wind turbines and wind plants. Three ways to contribute to frequency regulation are described: inertia, primary and secondary.

Inertial Response: The inertial kinetic energy stored in the rotating masses of generator and wind turbines can be used to provide immediate energy to help reduce the rate of change of the frequency (RoCoF). VSWTs (Types III and IV) provide negligible

synchronous inertia as the fast control of power electronic converters maintains a practically constant output power, irrespective of changes in grid frequency. However, short-term inertial response from VSWTs can be achieved by modifying their control loops. Wind turbine inertial response has been introduced with different terms such as synthetic inertial response, inertial response, inertia emulation, short-term frequency regulation, and temporary frequency control. Some VSWTs' kinetic energy is transformed into electrical power through the inertial control and transferred to grid through converters.

Primary Frequency Response: Wind power can provide energy in this time frame to assist in reducing frequency deviation, raising the frequency nadir for a given loss of supply and stabilizing the system frequency at different time points following a disturbance. The primary frequency response stabilizes the frequency at a new value by increasing (or decreasing) power generation in proportion to the frequency variations. Admittedly, a non-optimal working point can be reached in the response curve of torque versus rotor speed of the turbine (de Almeida, et al., 2006) (Courtecuisse, et al., 2008).

Automatic Generation Control/Secondary Frequency Response: Wind power can provide this AGC function to stabilize frequency and reduce Area Control Error (ACE).

Primary and secondary regulation is out of the scope of this Thesis. In the following sections a brief description of VSWT dynamic models and VSWT inertial contribution to frequency regulation can be found.

I.7.1 Description of VSWT dynamic models

For the successful integration of wind energy into the grid, adequate models should be used to analyse the effects of wind power which depend on the wind speed (Gupta, 2016). According to (Jing, 2012) and taking into account the scope of this Thesis, the main components of which a VSWT model should be composed are the aeromechanical model, the rotor mechanical model and the control schemes for a wind turbine-generator system.

The aerodynamic model output represents the mechanical power provided to the wind turbine rotor. It is a complex non-linear function of pitch angle, rotor speed and wind speed (Honrubia-Escribano, et al., 2018). The relationship between the mechanical

power input and the wind speed passing through a turbine rotor plane can be expressed by the power coefficient of the turbine (Munteanu, et al., 2008). There are three most commonly used methods to simulate the power coefficient which is provided by the wind turbine manufacturer. The first two methods are given by (Sun, 2004), and (Yin, et al., 2007). The third method is the lookup table method, which is given by (Miller, et al., 2003) and used by (Bhatt, et al., 2011). In this method, the power coefficient values of the turbine are fitted with a fourth order polynomial as a function of the tip speed ratio and blade pitch angle.

The wind turbine rotor is the only mechanical element of the wind turbine components to be considered for dynamic modelling due to its influence on power fluctuations. For the rotor mechanical model, (Muyeen, et al., 2007) explained the reduced mass conversion method and compared a six-mass model with reduced mass models for transient stability analysis. It was concluded that the reduced order two-mass shaft model is the most appropriate for transient stability analysis. However, (Miller, et al., 2003) proposed a simple one-mass model to compute the rotor speed, which has been used by (Slootweg, et al., 2003), (Ekanayake, et al., 2003) and (Lei, et al., 2006) among others. In fact, some manufacturers recommend the use of the simple one-mass shaft model in cases where the power converter decouples the generator from the grid (Nanou, et al., 2011) (Zhao & Nair, 2011).

The main objectives of the control systems embedded in wind turbines are maximizing power production, mitigating dynamic and static mechanical loads and guaranteeing a continuous power supply to the grid, according to the utility requirements. The blade pitch angle and the generator torque are the major parameters to be controlled in wind turbines. Pitch angle control allows the control of the wind input torque, in order to enable a smooth power production and to reduce the mechanical loads. The conventional pitch angle control usually uses PI controllers (Muljadi & Butterfield, 2001). In fact, blade pitch angle control is usually composed of two PI controllers, one of them associated with rotor speed and the other with generator power (Honrubia-Escribano, et al., 2018). These synergistic actions have been widely used in the literature, even by manufacturers, to model pitch control (Miller, et al., 2003), (Hiskens, 2011).

The generator torque control allows the variation of the wind turbine rotor speed following a Maximum Power Point Tracking (MPPT) strategy, for extracting as much

power as possible from the wind flux (Novaes Menezes, et al., 2018). MPPT schemes can be grouped into current mode control and speed mode control, which depends on the setting of reference values. The reference values are the active power and electromagnetic torque for current mode control (Hamzaoui, et al., 2011) (Li, et al., 2006), and the rotational speed for the speed mode control (Pena, et al., 1996) (Datta & Ranganathan, 2003) (Hilal, et al., 2011).

I.7.2 Inertial frequency regulation

The basic idea behind most inertial response studies is to add an auxiliary signal, sensitive to frequency, to the reference power set point in VSWTs, momentarily increasing wind turbine output power. Practically, a 5–10% active power can be added in a time frame of 5–10 s through inertial control under the constraint of minimal rotor speed (Faiella, et al., 2013). In fact, the rotor slows down as kinetic energy is extracted and converted into electrical energy to deliver power support. The deceleration process stops when the rotor speed reaches a certain limit to avoid stalling the wind turbine. However, after the kinetic energy extraction, the VSWT should recover its previous rotor speed, i.e. it should accelerate. Therefore, during this acceleration the supplied power is lower than the available mechanical power (Attya, et al., 2018). As described below, different authors have modelled virtual inertia in order to allow VSWTs to provide frequency regulation.

Different studies analyse the effects of inertia emulation on VSWTs, as it is collected in the detailed reviews carried out by (Dreidy, et al., 2017) or by (Aziz, et al., 2017). A solution to the lack of DFIG wind turbine inertial response was proposed by (Ekanayake, et al., 2003) and used later by (Lalor, et al., 2005). These authors added a supplementary control loop to provide an inertial response similar to the response provided by a conventional synchronous generator. Following this idea and assuming that the inertial response of a generator is influenced by the sensitivity of the generator's electromagnetic torque to changes in the power system frequency, (Mullane & O'Malley, 2005) also deal with the inertial response of wind turbines, employing DFIG. They developed a fifth-order induction-generator model of a field-oriented controlled DFIG. The authors concluded that the controller structure and parameters should be provided in order to determine the inertial response of commercially available wind turbine generators. (Morren, et al., 2006(a)) proposed a method to let variable-speed wind turbines emulate

inertia and support primary frequency control, taking advantage of the kinetic energy stored in the rotating mass of the turbine blades. Normally, the controllers of variable-speed wind turbines try to keep the turbine at its optimal speed in order to produce maximum power. In this case, authors modified the VSWT control loop by adding an additional controller that adapts the torque set point as a function of the deviation of the grid frequency (supporting primary frequency control) and of the rate of the change of the grid frequency (inertia emulation). These authors conclude that a proportional control equal to the primary frequency control of large power plants shows the best results. In addition, if the inertial contribution is limited to the real inertial value of the machine, the relation between the extra power provided by the control loop and the RoCof, is the inertia constant. (Mauricio, et al., 2009) presented a method to improve the use of variable-speed wind energy conversion systems. They modified the inertial control scheme, adding a proportional loop which weights the frequency deviation. Additionally, these authors proposed different values for the gains of both inertial control loops and rotor speed governor, applicable to high inertial isolated systems. In this case, the inertial control loop gains are not constrained by the real value of the inertia constant. However, the main problem of the values proposed lies in the fact that small isolated systems are more sensitive to power disturbances than interconnected systems. In fact, in this Thesis, it has been proven that the values proposed are not adequate for El Hierro power system. (Gautam, et al., 2011) developed a control strategy to mitigate the impact of reduced inertia due to significant DFIG penetration in a large power system, designing a supplementary control for the DFIG power converters such that the effective inertia contributed by these wind generators to the system is increased. The input to the supplementary controller is the frequency deviation at the point of interconnection bus. Also, authors proposed adjusting pitch compensation and maximum active power order to the converter in order to improve inertial response during the transient with response to drop in grid frequency. (Ochoa & Martinez, 2017) implemented a virtual inertia controller version of the optimized power point tracking method for Type III wind turbines, where the maximum power point tracking curve is shifted to drive variations in the active power injection as a function of both the grid frequency deviation and its time derivative. Authors shown that the inertial contribution of the Type III-WT improves the frequency response of the power system, to a greater or lesser degree depending on the wind conditions. The application of the proposed control strategy under real wind conditions allows the smoothing of the Type III wind turbine output power, which results

in a reduction of the grid frequency fluctuations. These study is extended in (Ochoa & Martinez, 2018) by simulating the proposed strategies in the San Cristobal (Galapagos Islands-Ecuador) hybrid wind-diesel power system in which many power outages caused by frequency relays tripping were reported during the windiest season. The proposals benefits have been tested in a simulation environment by considering actual operating conditions based on measurement data recorded at the island. Synthetic inertia of a VSWT is also modelled by (Renuka & Reji, 2015). Furthermore, authors proposed a fuzzy logic based pitch angle control method to control rotor speed of wind turbine during high wind speed. This pitch controller can adapt to varying wind conditions quickly. However, authors do not discuss if blades can adapt its position as fast as controller try due to the maximum variation rate of blades servo. Authors highlight the important improvement in the minimum frequency (NADIR) in a hydro dominated power system during a load/generation mismatch.

Three activation schemes for synthetic inertia on VSWTs based on full converters were proposed by (Gonzalez-Longatt, 2015): (i) Continuously operating triggering, (ii) Under-frequency trigger and (iii) Maximum-Frequency gradient trigger. The author remarked that the value of the synthetic inertia must be carefully selected, beyond the physical value, because it has an important impact on the electromechanical dynamic of the synchronous generator and the system frequency response.

In a similar way, as in the case of hydroelectric power plants, classical control tools have been applied to studying the influence of wind energy on power systems. A design principle for wind turbine inertia emulators in an autonomous power system was proposed by (Papangelis & Vournas, 2014) based on the root locus plot. (Wilches-Bernal, et al., 2016) analysed how Type III wind turbine integration affects the system frequency response of a test power system. To this aim, root locus analyses based on small-signal models provide the insight in control parameter tuning to achieve a stable controller design is used.

However, VSWT inertial control has limitations. Providing repetitive inertial response leads to heat generation and stress on wind turbine components due to aero-mechanical, electrical and speed rating limits. The inertial control must respect electrical and mechanical loading limits of wind turbine generators. The inertial control must provide enough margin above stall, and is consequently limited when the initial rotor

speed is low. (Gonzalez-Longatt, et al., 2016) established a practical limit of synthetic inertia value based on different simulations. These simulations showed that there is a limit on the synthetic inertia controller related to the total physical inertia of the wind turbine. However, the author recognized that a review must be performed in order to define the real limit of the total kinetic energy that can be released from the wind turbine using the inertia control loop without provoking a massive rotational speed decrease and causing the wind turbine to stall.

I.8 Motivation and objectives of the Thesis

After a thorough review of frequency regulation in isolated systems, there are several questions that have not been answered by the scientific literature.

The influence that the elastic phenomena have on governor settings of PSHPs operating in isolated systems when power plants are equipped with long conduits, has not been sufficiently investigated. In these circumstances, the elastic phenomena cannot be neglected. A PSWP equipped with a long penstock was committed in El Hierro power system in 2014. This island has a 100% fossil fuel avoidance objective, thus the PSHP will operate without the diesel contribution. Therefore, power demand will be supplied only by PSHP and wind generators (100% renewable energy).

Many islands have a high wind potential that must be exploited to avoid both the emission of greenhouse gases and fuel transport costs. This implies that the transmission system operator of the isolated system must smooth out the drawbacks associated with the penetration of renewable energies in the system, such as frequency disturbances caused by renewable resource variations (wind and/or sun radiation) in the short term. Therefore, PSHPs that operate under these conditions must face not only the variations in power demand but also the power fluctuations that renewable resources can introduce to the system.

As VSWTs can provide frequency regulation, it is necessary to analyse both the contribution of VSWTs in wind-hydro dominated isolated systems, and the consequences of this contribution for hydroelectric power plants. In fact, it is necessary to analyse the joint frequency regulation of VSWTs and hydroelectric power plants.

For all these circumstances, the author considers that it is necessary to analyse the influence of the elastic phenomena effects of the long conduits, on the setting of the hydroelectric power plant's governor, when operating jointly with renewable energy generators, whose inertia are decoupled of the grid (i.e. photovoltaic and Type III and IV VSWTs). Additionally, tuning criteria for the gains of these controllers, distinguishing if it is a long penstock or a long tail-race tunnel, should be provided. Furthermore, if the capacity of VSWTs can be used (in fact, it is expected that it will be used), valid control strategies in isolated systems should be analysed and recommendations for the setting of the wind turbines' control loops gains should be provided, analysing the system variables which take part in each oscillating mode.

I.9 Summary of publications

The articles that are included in this Thesis have been published in JCR Journals. The scheme of these articles is shown in Figure 8, summarizing the objectives, the hypothesis assumed and the achieved conclusions. Further details of each article are presented in the following subsections.

Frequency Control of Hybrid Wind-Hydro Power Plants with Long Conduits in Isolated Power Systems				
Publication	Power-frequency control of hydropower plants with long penstocks in isolated systems with wind generation	Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel	Frequency Regulation of a Hybrid Wind - Hydro Power Plant in an Isolated Power System	Eigen Analysis of Wind-Hydro Joint Frequency Regulation in an Isolated Power System
Journal	Renewable Energy 83 (2015) 245-255	Renewable Energy 90 (2016) 362-376	Energies 2018 (11) 1-25	I. J. of Electrical Power and Energy Systems 103 (2018) 511-524
Hypothesis	<ul style="list-style-type: none"> ✓ Long penstock ✓ PSHP provides frequency regulation 	<ul style="list-style-type: none"> ✓ Long tail-race tunnel ✓ PSHP provides frequency regulation 	<ul style="list-style-type: none"> ✓ Long penstock ✓ PSHP and VSWT provides frequency regulation 	<ul style="list-style-type: none"> ✓ Long penstock ✓ PSHP and VSWT provides frequency regulation
Objectives	Elasticity effects and influence analysis Governor gains based on pole placement	Modal analysis Governor gains based on pole placement	VSWT strategies of frequency regulation Governor gains based on exhaustive searches	Modal analysis Governor gains based on the modal analysis
Conclusions	<ul style="list-style-type: none"> ✓ 2 tuning criteria ✓ They notably improve response quality 	<ul style="list-style-type: none"> ✓ 1 tuning criterion ✓ Covering the demand with 100% RREE without compromising the system 	<ul style="list-style-type: none"> ✓ 1 tuning methodology ✓ Improvements in frequency deviations 	<ul style="list-style-type: none"> ✓ 1 tuning criterion ✓ supplying demand and maintaining the system frequency within the limits

Figure 8 Scheme of the articles included in this Thesis

I.9.1 JCR Journal publications

The JCR Journal articles presented in this Thesis have already been published in the scientific and technical literature and in a paper that has been submitted and is currently under review. These papers are listed below:

Paper A

Title: Power-frequency control of hydropower plants with long penstocks in isolated systems with wind generation
 Authors: Guillermo Martínez-Lucas, José Ignacio Sarasúa, José Ángel Sánchez-Fernández and José Román Wilhelmi
 Journal: *Renewable Energy*, vol. 83, pp. 245-255
 DOI: <https://doi.org/10.1016/j.renene.2015.04.032>
 Impact factor: 3.404 (Q2) [2015]

Paper B

Title: Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel
 Authors: Guillermo Martínez-Lucas, José Ignacio Sarasúa, José Ángel Sánchez-Fernández and José Román Wilhelmi
 Journal: *Renewable Energy*, vol. 90, pp. 362-376.
 DOI: <https://doi.org/10.1016/j.renene.2016.01.015>
 Impact factor: 4.357 (Q1) [2016]

Paper C

Title: Frequency Regulation of a Hybrid Wind–Hydro Power Plant in an Isolated Power System
 Authors: Guillermo Martínez-Lucas, José Ignacio Sarasúa and José Ángel Sánchez-Fernández
 Journal: Special Issue *Wind Generators Modelling and Control* of the Journal *Energies*, 2018 11(1), pp. 1-25.
 DOI: <https://doi.org/10.3390/en11010239>
 Impact factor: 2.262 (Q2) [2016]

Paper D

Title: Eigen Analysis of Wind–Hydro Joint Frequency Regulation in an Isolated Power System
 Authors: Guillermo Martínez-Lucas, José Ignacio Sarasúa and José Ángel Sánchez-Fernández
 Journal: *International Journal of Electrical Power and Energy Systems*, vol. 103, pp. 511-524, 2018.
 DOI: <https://doi.org/10.1016/j.ijepes.2018.06.028>
 Impact factor: 3.289 (Q1) [2016]

II. Methodology

The methodology is divided into two sections. Section II.1 summarizes the structure of this thesis, explaining the reasons for the research process in order to achieve the expected results. Section II.2 describes the common methodology applied to each study. In some cases, the particularities of each study will be discussed.

II.1 Thesis structure

The study of the control of hydroelectric power plants with long conduits in isolated systems with high wind penetration has been divided into four stages, corresponding to the four papers presented. Firstly, the study of the modelling and control of pumped storage hydroelectric power plants with long penstock supplying the power demand with a wind farm, was developed in Paper A. In this study, carried out in the El Hierro power system, it is assumed that wind turbines do not provide frequency regulation. Having analysed this system, and having proposed several tuning criteria for the hydro power plant governor, the case in which the hydroelectric plant is equipped with a long tail-race tunnel is analysed in Paper B. In this case, different tuning criteria are also proposed, analysing the validity of those proposed for the previous case. In this case, the frequency regulation capacity of the VSWTs is neither used, considering only the variability of the wind power. In both cases, VSWTs are not modelled, considering wind power as a negative load.

The capacity of variable-speed wind turbines of providing frequency regulation has been subsequently analysed. This analysis has been developed in two stages. In the first study, in Paper C, several VSWT control strategies are analysed to assess the VSWT's capability of providing frequency regulation. The nonlinearities of this model have not been linearized, making an exhaustive search of the gains of the controllers, both of the VSWTs and the hydroelectric power station, assuming different VSWT control strategies. Subsequently, in Paper D, the non-linear model has been simplified and linearized to carry out a modal analysis, with the aim of identifying the variables that intervene in each of the oscillating modes of the system.

II.2 Study's methodology

The methodology applied is based on the methodology used by (Sarasúa, et al., 2007). In that paper, the control of a run-of-river diversion hydro plant was considered,

using the classical control techniques. To achieve this aim, the model developed by the authors was linearized and its state matrix was obtained. After that, the influence of the PI governor gains was analysed from the root locus plot, proposing a simple rule to tune the controller gains. In order to evaluate the plant's response, different cases regarding initial river flow were considered, to simulate them in the non-linear model. This methodology has also been followed successfully in (Sarasúa, et al., 2014), where the authors study the stability of the water level control system of a run-of-river hydropower plant under normal operating conditions, using a small perturbation analysis. In this case, the results obtained in this study have been applied to the Ocaña II hydro plant (Cuenca, Ecuador) which is currently in its design phase.

This section is structured in an analogous way to the general methodology applied in the papers. The scheme of the following methodology in this Thesis is shown in Figure 9. Please note that this scheme do not represent an iterative process. Methodology used in Papers A, B and D are composed by 7 steps while methodology followed in paper C is composed by 5 steps. In the following sections, these processes will be described.

Figure 9 Methodology scheme

II.2.1 Non-linear modelling

A PSHP connected to an isolated system has been modelled in MATLAB with Simulink. In papers C and D in which VSWTs provide frequency regulation, they have also been modelled. PSHP will operate in generating mode during all simulations. The PSHP alternator is supposed to be very fast when compared with the other components of the model, therefore, the PSHP alternator's electric dynamics will be neglected. For the same reason, the VSWT converter's dynamics, also faster than the other components' dynamics, are neglected in the models. Water levels in both upper and lower reservoirs have been considered invariant.

II.2.1.1 Power system

A PSHP is connected to an isolated system comprising intermittent energy sources and loads. Inter-machine mechanical oscillations are neglected, so that the frequency is represented by a unique value. Therefore, the frequency dynamic is the result of the imbalance between the sum of the generators power and power demand. Frequency dynamic includes load frequency sensitivity. Mechanical inertia refers only to PSHP. When VSWT models are included, as wind generators are connected to the system through a frequency converter, their inertia is decoupled of the grid. In cases where the dynamics of the VSWT are not modelled, the wind power consists of a real wind power signal, in addition to real solar power signals. In no case has the dynamic of photovoltaic plants been modelled.

II.2.1.2 PSHP Conduits

The transient flow in conduits is described by expressions of conservation of mass and momentum (Chaudhry, 1987). When the conduit is short, for the purpose of the studies considered in this Thesis, it can be modelled assuming the rigid water column approach, including water inertia and head losses. In those cases in which the length of the pipe is large, the water and pipe material elasticity cannot be neglected. To solve these equations, considering the water and pipe material elasticity, different approaches can be found in the specialised literature, such as the method of characteristics (Riasi & Tazraei, 2017), or the transfer function proposed in (IEEE Working Group, 1992). In recent years, some authors (Nicolet, et al., 2007) (Platero, et al., 2014) have obtained good results with their hydro power plant models, using a lumped parameter approach.

In order to conduct analytical studies of the model, the use of the Characteristics Method and the transfer function are not appropriate and so, have been ruled out. Thus, the lumped parameters approach has been preferred. However, the transfer function proposed by (IEEE Working Group, 1992) has been used in some simulations. It has been verified that there are no significant differences in the response when compared with the lumped parameters approach.

II.2.1.3 PSHP Turbine

Turbine operation is described by two functions. In this Thesis, depending on the plant studied, a Pelton turbine or a Francis turbine has been modelled. The relation between the hydraulic and mechanic variables (q , z , h) is modeled through the static relation proposed by (IEEE Working Group, 1992). The relation between mechanic power and the hydraulic and mechanic variables is modeled through the relation proposed by (Cuesta & Vallarino, 2015) for Pelton turbines and by (IEEE Working Group, 1992) for Francis turbines.

II.2.1.4 PSHP Governor

The use of PI governors in hydropower plants is a common practice (Kishor, et al., 2007). The proposed PSHP governor model is partially based on (Mansoor, et al., 2000) (permanent speed droop is not considered). The main function of this governor is to control the unit speed by monitoring the frequency error signal, modifying the turbine nozzles or gate position (depending on whether they are Pelton or Francis turbines, respectively), and regulating the water flow through the penstock. The error signal is processed by a conventional PI controller. The limits in the positions of both the turbine nozzles and gate position and their rates of change are considered in the model, using a rate limiter and a saturation element.

II.2.1.5 Wind power model

The mechanic power extracted from the wind is modelled using a mathematical function obtained from the expression of the available wind kinetic energy (Bhatt, et al., 2011) where the usable fraction of kinetic energy is provided by a value representing the efficiency. This efficiency depends on wind speed, rotor speed and blade pitch angle. Usually, it is provided by a group of curves that relate these parameters.

II.2.1.6 VSWT rotor mechanical model

The VSWT model includes the rotor dynamics for the wind turbine rotor, according to (Eriksson, et al., 2016). Variations in rotor speed are caused by the imbalance between the torque provided by the wind turbine and the torque demanded by the power converter.

II.2.1.7 VSWT controllers

VSWTs include several controllers. Blade pitch angle control is a combination of a conventional pitch angle control and pitch compensation. The conventional pitch angle control implements a PI control that computes the difference between rotor and reference rotor speeds (Sun, et al., 2010). Furthermore, the pitch angle control considers the compensation through a different PI control that computes the difference between the mechanical wind power and maximum rated power for each wind speed (Ahmadyar & Verbic, 2015). Figure 10 shows the block diagram of the blade pitch angle control.

Figure 10. Block diagram of pitch control model.

An inertial control loop and inertial and proportional control loops are proposed, allowing the release of the stored fraction of kinetic energy in rotational masses to provide earlier frequency support, thus taking advantage of the rapid response capability of electronic power converters.

Owing to the existence of the wind energy conversion system, the inertial and proportional control loops add a power signal Δp_n to the power reference output, to be tracked by the converter (equation (1)) according to (Mauricio, et al., 2009)

$$\Delta p_n = \underbrace{K_{dn} \frac{d}{dt} (n_{ref} - n)}_{\text{Inertial control loop}} + \underbrace{K_{pn} (n_{ref} - n)}_{\text{Proportional control loop}} \quad (1)$$

Where K_{pn} weighs the frequency deviation, while K_{dn} is a constant weighing of the frequency variation rate to add a signal Δp_n to the power supplied by the converter. Because of VSWT contribution to frequency regulation through the inertial and proportional control loops, a wind turbine rotor speed control, which controls the rotational speed by regulating the electromagnetic torque, is required. This last control loop restores the VSWT rotor optimal speed after a frequency disturbance; otherwise, the VSWT will be destabilized. Therefore, a PI controller, which is based on (Mauricio, et al., 2009), obtains an extra power reference from the difference between the rotational speed and the optimal rotational speed. Figure 11 shows the block diagram of both inertial and rotor speed controller of the VSWT and the power converter.

Figure 11. Block diagram of VSWT controllers and power converter.

II.2.2 Model order reduction

According to (Kishor, et al., 2007), for control design purposes in plants with long penstock, it is convenient to use a reduced order model including elasticity effects. Following this recommendation, the order of the PSHP models (and VSWT model when modeled) has been reduced by obtaining fourth, fifth or sixth order models, depending on the power plant being studied (long penstock, long tail-race tunnel or wind-hydro power plant respectively).

For hydropower plants with long conduits, on which the effects of the elastic phenomena have been included, the simplest model is a II-shaped one segment model, having one series branch and two shunt branches. Therefore, for analytical purposes, the penstock is modelled following this recommendation, obtaining a second-order model.

For VSWTs, assuming small perturbations in the neighbourhood of an initial equilibrium operating point and a short-term framework, the mechanical power from the wind can be considered constant (Mauricio, et al., 2009) (Papangelis & Vournas, 2014). Furthermore, because of the slowness of blade pitch movements, these ones have been neglected and the pitch angle position has been considered static for analytical purposes.

II.2.3 Linearization

Some of the components described above are represented by nonlinear expressions and, therefore, are not suitable for analysing the system dynamics and the controller setting using classical control tools. Therefore, a linearized model is developed for small perturbation analysis in the neighbourhood of an initial equilibrium operating point. Please note that different initial equilibrium points have been studied. Taking into account the hypothesis assumed in the reduced order model, the VSWT model's results are linear (Strah, et al., 2005). In contrast, inertia and head losses in conduits and turbines are modelled with non-linear expressions. Therefore, these expressions are linearized around an equilibrium operating point.

The linearized relationship between flow, head and gate position in a hydraulic turbine can be written as a combination of the partial derivatives of the water flow with respect to the net head, speed, and gate position. The linearized expression for the relationship between the hydraulic power and the same variables is analogously obtained.

II.2.4 Governor settings definition

Methodology applied to tune the governor gains is based on classic control techniques, which currently are still used in several researches. An improvement in the system frequency, owing to VSWTs equipped with adequately controlled doubly fed induction machines, is shown in (Fernández, et al., 2007) through an eigenvalue analysis. In (Amjady & Reza Ansari, 2008), the authors analysed different aspects of small disturbance voltage stability from the eigenvalue's position, studying the influence between the dynamic characteristics of the system such as those of generators, controllers, and loads. In (Silva, et al., 2017), the authors presented a case study illustrating the effects of pressure pulsations due to vortex rope precession on the draft tube of Francis turbines, through a modal analysis combined with frequency-domain and time-domain simulations.

These classical tools are applied in the linearized reduced order model. The reduced n-order model is composed of n ($4 \leq n \leq 6$) state variables $\bar{x}$, which define the dynamic system. The general expression, which defines each linear equation (corresponding to each state variable) for the n-order model, is given by equation (2).

$$\frac{d\Delta\bar{x}_i}{dt} = \sum_{j=\bar{x}_1}^{j=\bar{x}_n} \frac{\partial \bar{x}_i}{\partial \bar{x}_j} \Delta x_j \quad (2)$$

Applying equation (2) to each i state value, the n equations, which represent the linearized reduced order model, are obtained. These equations can be written in matrix form ($\dot{\bar{x}} = A\bar{x}$), where A represents the state matrix of the system.

One of the classic analysis tools, which allows the analysis of the dynamics of the system from the position of the poles, is the root locus, which will be the main tool used in this Thesis. In fact, the eigenvalues ($\lambda_i = \alpha_i \pm j\beta_i$) are the main indicators of the dynamics and stability of the system.

Additionally, the participation factors are extracted from the normalized participation matrix, which is employed to measure the relative association between the i^{th} state variable and the j^{th} eigenvalue. The participation matrix is defined according to (Liu & Liu, 2007), as indicated in equation (3).

$$P = [V^{-1}]^t V \quad (3)$$

Where V is the matrix formed by the state matrix eigenvectors in columns (i.e. $V = [\bar{v}_1, \bar{v}_2 \dots \bar{v}_n]$).

The normalized participation matrix P^* is obtained by using the largest element of each column of the participation matrix P as the base value. The participation factors are each element p_{ij} of P^* , which are the measure of the participation of the state variable $\bar{x}_j$ in the oscillating mode associated with the eigenvalue λ_i . This technique allows the identification of the oscillation modes that interfere with the dynamic behaviour of the system

Moreover, the damping ratio (ξ_i) of the corresponding oscillation mode can be obtained from the state matrix, as expressed in equation (4) (Yang, et al., 2018).

$$\xi_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}} \quad (4)$$

In this Thesis, a root locus analysis of the linearized model is made. The position of the poles in the complex plane is closely related to analysed system response. System poles can be determined as the roots of the characteristic polynomial associated with the state matrix and their position depends on governor tuning. Thus, the controller gains should be selected so that the position of the poles causes a dynamic response whose characteristics are as close as possible to the specifications (rise time, overshoot, settling time, etc.) In fact, in previous years many works based on the root locus technique to adjust speed governors have been developed (Abdolmaleki, et al., 2008) (Strah, et al., 2005). Depending on the order of the model, different tuning criteria have been proposed, as is summarized in Table 2.

II.2.4.1 Proposed tuning criteria based on classical analysis techniques

Using classical control techniques, several tuning criteria are proposed according to the order of the model.

In Paper A, two tuning criteria are proposed for a fourth order model. In Double Real Pole (DRP) criteria, one of the conjugated poles is placed on the real axis, overdamping it associated oscillation. In addition, the real part of the complex pole is forced to have the same value. By increasing the pole real part (in absolute value), the controlled variable settling time is reduced, at the expense of an overshoot. It is worth to highlight that DRP has been taken from water level control where reducing the overshoot was not a priority. In Double Complex Pole (DCP), the two pairs of complex poles of the control loop are forced to have the same value. Therefore, both oscillating modes have the same damping ratio and no one oscillation prevails over the other one.

In Paper B, two tuning criteria are proposed for a fifth order model. (Wozniak, 1990) recommends using a fix damping ratio in the mechanic oscillation mode equal to 0.707 as a design criterion. Therefore, Fixed Damping Ratio criteria are based on this recommendation and expression provided by (Sarasúa, et al., 2015) are used. However, these expressions are formulated based on a fourth order model. Because of that, Fixed Damping Ratio Modified criteria combine a fix damping ratio of 0.707 and the maximization of the pole real part (in absolute value) for a fifth order model. In Paper D

criteria are proposed which are aimed at maximizing the smallest system damping ratio, which is one of the main indicators of the system stability (Yang, et al., 2018).

Table 2. Tuning criteria based on linearized models depending the order of the model

Criteria	Order of the model	Criterion target
DRP	4	$\lambda_i = \{a, a, a \pm jb\}$
DCP	4	$\lambda_i = \{a \pm jb, a \pm jb\}$
FDR	4/5	$\xi = 0.707$
FDRM	5	$\lambda_i = \{a, a \pm ja, b \pm jc\}$
$\max(\xi_{min})$	6	$\max(\xi_{min})$

The reasons for using these criteria are justified in the papers, as well as in the analysis of results section.

II.2.4.2 Governor setting based on exhaustive searches

In addition to the tuning criteria described previously, a methodology based on exhaustive searches is proposed for the adjustment of the PSHP and VSWT controller gains in the case in which VSWTs provide frequency regulation. These exhaustive searches have been carried out in the non-linear model, in order to take into account the nonlinearities in the governor settings. Because finding governor settings which provide the best values of different system quality indicators jointly is difficult, a compromising solution based on a coefficient that favoured increased NADIR values, and which penalised increased values for frequency and power settling times, has been proposed. This coefficient is expressed according to equation (5) T_n represents the frequency settling time while T_p represents the power settling time.

$$\varphi = \frac{NADIR}{T_n \cdot T_p} \quad (5)$$

II.2.5 Simulations

To check the suitability of controller tuning, Jones et al. (Jones, et al., 2004) suggested that it is enough to simulate a step, a ramp, and a random signal. Therefore, this methodology, assuming realistic events, has been followed in order to check all the governor settings. Every event described below has been simulated in the corresponding completely nonlinear model. However, these results cannot be compared to the current experimental data. It seems reasonable to expect a good agreement because a similar

model, used in (Mansoor, et al., 2000) for the Dinorwig power plant, achieved sufficiently accurate simulation results compared to field measurements.

The instant disturbances considered in all simulations have consisted of a positive power step in demand, which can be associated with a sudden disconnection of a wind turbine or a load connection. In this case, when VSWT does not provide frequency regulation, the hydropower plant must increase its generated power in order to compensate for the generation loss in the system and recover the frequency. When the VSWTs provide frequency regulation, they inject a fraction of the kinetic energy instantaneously while the hydropower plant changes its operating point.

The ramp disturbances represent a substantial variation in wind power generation, an event usually considered in isolated systems with high penetration of intermittent energies (wind and solar) (Nicolet, et al., 2009). Therefore, in cases in which frequency regulation is provided only by the PSHP, a linear increase in the wind generation has been considered while a wind speed ramp has been simulated when VSWTs provide frequency regulation.

Finally, as a random signal, fluctuations in intermittent energies have been considered. In cases in which VSWTs do not provide frequency regulation, a wind and solar power combination of signals representing different realistic scenarios has been assumed in simulations, while in cases in which VSWTs provide frequency regulation, a wind speed fluctuation has been simulated.

II.2.6 Results evaluation

Different parameters to evaluate the system quality assuming governor settings proposed in this Thesis have been employed. NADIR, the power settling time, or frequency settling time, are technical indicators which are used to quantify the system frequency quality. According to Seneviratne and Ozansoy (Seneviratne & Ozansoy, 2016), these frequency response indicators can be used in any network to assess the frequency response owing to a loss of a generator. However, more typical quality indicators have been used in this Thesis, which are listed in Table 3. Furthermore, in long discharge pipes, cavitation phenomena may appear downstream the turbine due to an excessive suction pressure caused by gate closing movements (Dorji & Ghomashchi,

2014). Therefore, the minimum water pressure downstream from the turbine has to be checked to guarantee the security of the pipeline due to cavitation problems.

Table 3. Response quality parameters

Controlled variable	Quality parameter	Expression		Definition / explication
H	Minimum water pressure downstream the turbine	$\min(H_{dt}) [m]$	(6)	To avoid this cavitation phenomena, the absolute pressure at that point should be greater than the vapor pressure (Warnick, 1984).
n	Frequency mean square error	$\frac{1}{t} \int_0^t (n - n_{ref})^2 dt [p.u.]$	(7)	It is a measure of the average of the squares deviations, that is, the difference between the instant frequency measure and nominal frequency.
	Medium frequency deviation	$\frac{1}{t} \int_0^t n - n_{ref} dt [Hz]$	(8)	It is a measure of the average of the absolute frequency deviations, that is, the difference between the instant frequency measure and nominal frequency.
	NADIR	$\min(n) [Hz]$	(9)	It is a measure of how low system frequency has come.
	Maximum frequency peak	$\max(n) [Hz]$	(10)	It is a measure of how high system frequency has come.
	T_n	$\min(t) \setminus n N_b \in (50 \pm 0.15 Hz) [s]$	(11)	It is defined as the time it takes for the frequency to lie within the normal limits established by the TSO for isolated systems (Red Electrica de España, 2012).
p	Power mean square error	$\frac{1}{t} \int_0^t p - p_{dem} dt [p.u.]$	(12)	It is a measure of the average of the squares of the deviations, that is, the difference between the instant generated power and demanded power.
	T_p	$\min(t) \setminus P \in (P_{dem} \pm 2\% \Delta P_{dem}) [s]$	(13)	It is defined as the time it takes for the power supplied by the generators to be within $\pm 2\%$ of the power demand value.

In addition, the simulations have been carried out assuming classical controller setting criteria or others proposed previously in order to check the quality improvement of the system dynamic response, thanks to the new proposed controller settings. Classic controller criteria for tuning hydropower governor used in this Thesis were proposed by (Paynter, 1955) and (Kundur, 1994), while the criterion for tuning VSWT controllers used in this Thesis was proposed by (Mauricio, et al., 2009) for high inertial isolated systems.

III. Publications

III.1 Paper A: Power-frequency control of hydropower plants with long penstocks in isolated systems with wind generation

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Abstract

In this paper the power-frequency control of hydropower plants with long penstocks is addressed. In such configuration the effects of pressure waves cannot be neglected and therefore commonly used criteria for adjustment of PID governors would not be appropriate. A second-order Π model of the turbine-penstock based on a lumped parameter approach is considered. A correction factor is introduced in order to approximate the model frequency response to the continuous case in the frequency interval of interest. Using this model, several criteria are analysed for adjusting the PI governor of a hydropower plant operating in an isolated system. Practical criteria for adjusting the PI governor are given. The results are applied to a real case of a small island where the objective is to achieve a generation 100 % renewable (wind and hydro). Frequency control is supposed to be provided exclusively by the hydropower plant. It is verified that the usual criterion for tuning the PI controller of isolated hydro plants gives poor results. However, with the new proposed adjustment, the time response is considerably improved.

Keywords: Wind-hydro systems, long penstock, governor tuning, pole placement method.

III.1.1 Introduction

In last years, the use of renewable energy sources to displace fossil fuels in small isolated systems has received considerable attention (Kaldellis, et al., 2001) (Kaldellis & Kavadas, 2001) (Iglesias & Carballo, 2011) (Merino, et al., 2012). Many islands have an excellent local wind potential so that economic and environmental costs of fuels may be avoided. Although these sources can contribute to some extent to power-frequency regulation, in many cases this service is provided mainly by conventional power plants. Hydropower plants can assume advantageously this task due to its renewable character.

Moreover pumped storage schemes compensate uncertainty in wind production. This type of solution is usually named “combined wind-hydro generation”.

The use of PID governors in hydropower plants is a common practice (Kishor, et al., 2007) and suitable criteria for gain adjustment have been thoroughly studied in last decades (Chaudhry, 1970) (Thorne & Hill, 1975) (Hagigara & Yokota, 1979) (Phi, et al., 1981) (Wozniak, 1990) (Kundur, 1994). However the hydropower plant configurations found in the systems mentioned above may include substantial differences with respect to general cases. Specifically, the length of the penstock can be considerably large due to special topographic conditions. This circumstance limits the applicability of the rigid-water-column models (Jiménez & Chaudhry, 1987) and the PID adjustment criteria based on this assumption (Sanathanan, 1987) (Choo, et al., 2007).

Although several contributions have been described to modelling the dynamic response of hydropower plants, when the influence of pressure waves cannot be neglected (IEEE Working Group, 1992) (Souza Jr, et al., 1999) (Nicolet, et al., 2007) (Naik, et al., 2012) very few attempts have been found in the literature dealing with the adjustment of gains of the PID governor in such cases. It is worth mentioning the work presented in (Murty & Hariharan, 1984) where the stability boundaries in terms of the PI gains are determined under the influence of the water column elasticity, extending the results obtained for rigid water column. In (Sanathanan, 1987) a methodology based on a reference model is proposed to obtain a PID governor gains; the turbine-penstock is represented by a synthesized second order model (Sanathanan, 1987). In (Nicolet, et al., 2007) the PID parameters determination is based on a high order plant model, where the turbine transfer function is identified by means of time-domain simulations.

The work of (Hagigara & Yokota, 1979) (Strah, et al., 2005) (Abdolmaleki, et al., 2008) (Sarasúa, et al., 2014) (Hušek, 2014) is aimed to obtain simple rules, recommendations or expressions useful for the PID governor tuning in the plant predesign phase, but they do not include water elasticity effects. For this purpose Classic Control tools and techniques, (root locus plot, bode diagram,...) have been successfully applied.

In this paper, a methodology is presented to achieve a similar objective taking into account water elasticity effects. For this purpose, a simplified linearized model is proposed to define some practical tuning criteria for a PI governor by pole placement

method (Strah, et al., 2005). The model is based in a lumped parameters approach (Souza Jr, et al., 1999) (Nicolet, et al., 2007) adjusted to match the penstock frequency response in the range of interest.

The controller performance is evaluated from the plant dynamic response obtained by simulation, using a detailed model which includes nonlinearities and distributed elasticity effects. The proposed PI adjustment criteria are tested in a real system implemented in a small island where the generation is provided by a wind farm and a hydropower plant (Iglesias & Carballo, 2011) (Platero, et al., 2014); the frequency is supposed to be controlled only by the hydropower plant.

Although modern wind generators could contribute to frequency regulation through pitch control, this contribution entails a cost: some wind energy will be lost (Vidyanandan & Senroy, 2013). So, in this paper no contribution to frequency regulation from the wind farm is assumed.

The paper is organized as follows. In section 2 the hydro plant dynamic model is described and a preliminary assessment of elasticity effects is done using three reference power plants. In section 3 the applicability of a reduced order model for stability analysis is discussed. In section 4 two tuning criteria are formulated using the reduced order model and their performance is analysed. In section 5 the obtained results are tested in a real hydropower plant: Gorona del Viento in El Hierro (Canary Islands). Finally, in section 6, main conclusions of the paper are duly drawn.

III.1.2 Modelling

Assuming that a hydroelectric plant operates in an isolated system, which includes wind generation and resistive loads, the block diagram of its dynamic model is shown in Figure A1.

Figure A1, Block diagram of the plant model

The equations associated with each block are detailed below. All variables, coefficients and parameters which appear in the expressions are described in the Appendix 1. In particular, p_d represents the net demand to be supplied by the hydro plant.

III.1.2.1 Penstock

In order to consider the elasticity of water and conduit, the expression (A1) is used (Choo, et al., 2007).

$$\frac{\Delta H(s)}{\Delta Q(s)} = -\frac{T_w \frac{a_w}{L} \left(1 - e^{-2\frac{L}{a_w}s}\right)}{\left(1 + e^{-2\frac{L}{a_w}s}\right)} \quad \text{where} \quad T_w = \frac{L}{gF} \frac{Q_b}{H_b} \quad (\text{A1})$$

For the sake of accuracy the head losses, local (k_{loc}) and continuous ($r/2$), are included as shown in Figure A2 (IEEE Working Group, 1992). The net head h , is obtained from the reservoir water level hc^0 , considering the friction losses and the pressure waves contribution.

Figure A2, Block diagram of penstock

III.1.2.2 Turbine

The equation (A2) (IEEE Working Group, 1992) gives the relationship between p.u. values of flow q , head h and nozzle opening z .

$$q = z\sqrt{h} \quad (\text{A2})$$

As is frequently the case in hydropower plants with long penstocks located in islands, Pelton turbines will be considered. The expression (A3) used for p.u. shaft torque corresponds to ideal rated conditions, where the absolute fluid speed is twice the runner peripheral speed (Cuesta & Vallarino, 2015).

$$c = q(2\sqrt{h} - n) \quad (\text{A3})$$

The modelled power plant may have two or more identical units, which are supposed to work at the same operating point; thus a single equivalent turbine has been considered.

III.1.2.3 Generation - load

Equation (A4) represents unit dynamics in the time range of interest, where only inertial effects are relevant (Wozniak, 1990) (Chaudhry, 1987).

$$c - c_d - k\Delta n = T_m \frac{dn}{dt} \quad (\text{A4})$$

As mentioned in the Introduction, the considered hydro power plant is connected to an isolated system with wind generation; then c_d represents the p.u. net load torque at reference frequency, $n_r = 1$ p.u. Input variable $p_d = c_d$ p.u. (see Figure 1) is modified as a result of a variation in the loads connected to the system or a change in the energy supplied by the wind farm. Inertia parameter T_m refers only to the hydro plant as wind generators are supposed to be connected to the system through frequency converters. The parameter k accounts for the load sensitivity to frequency, as wind generation does not contribute to frequency regulation.

III.1.2.4 PI controller

A conventional proportional-integral (PI) controller processes the frequency error signal: $(n_r - n) - \sigma\Delta z$. Equation (A5) gives the changes in the turbine nozzles due to the controller action.

$$\Delta z = \left[\frac{1}{\delta} + \frac{1}{\delta T_r} \int dt \right] [(n_r - n) - \sigma \Delta z]; \quad K_P = \frac{1}{\delta} \text{ and } K_I = \frac{1}{\delta T_r} \quad (\text{A5})$$

In the case considered, the frequency control is carried out only by the hydro plant; then, the permanent speed droop σ is set to zero and the frequency set-point n_r remains constant.

III.1.2.5 Example. Reference power plants

The importance of elasticity effects is assessed using three reference hydropower plants with different penstock lengths, the PI governor being tuned according to the recommendations given in (Kundur, 1994) for an isolated plant without considering the elasticity of water and conduit. The main characteristics of the reference power plants are summarized in the Table A1.

Table A1. Reference power plants characteristics

	Power plant 1	Power plant 2	Power plant 3
T_w	1.0 s	1.0 s	1.0 s
T_m	6.0 s	6.0 s	6.0 s
a_w	1000 m/s	1000 m/s	1000 m/s
L	250 m	1660 m	2500 m
$r/2+k_{loc}$	0.030 p.u.	0.030 p.u.	0.030 p.u.
ρ	2.0	0.3	0.2
δ	0.3833	0.3833	0.3833
T_r	5.0 s	5.0 s	5.0 s

As may be appreciated in the table, the three proposed reference plants differ substantially in the values of the Allievi parameter $\rho = a_w v/2gH$. In (Jiménez & Chaudhry, 1987) the influence of the Allievi parameter on the stability of a hydro plant is studied, concluding that elasticity effects are important for $\rho < 1$. In (Clifton, 1987) this limit is reduced to 0.75, warning that instability will appear when $\rho < 0.25$; in a numerical example analysed in this reference results that for $\rho \approx 0.4$ the inelastic model underestimates significantly the speed deviation.

Figure A3 represents the dynamic response of each power plant due to a 5% sudden reduction of the power demanded. The results obtained for each plant confirm the conclusions reported by the references cited above.

Figure A3, Reference Power plants 1, 2 and 3 dynamic response, $\Delta p_d = -0.05$ p.u.

III.1.3 Reduced order model

For control design purposes in plants with long penstock, it is convenient to use a reduced order model including elasticity effects (Kishor, et al., 2007).

III.1.3.1 Lumped parameters approach

In last years some numerical hydro plant models including elasticity effects (Souza Jr, et al., 1999) (Nicolet, et al., 2007) have represented the penstock by several consecutive elements where the conduit properties: inertia, elasticity and friction are assigned proportionally to the segment length.

The “configuration” and “orientation” of the elements are chosen according to the upstream and downstream boundary conditions. In the case shown in Figure A4 these boundary conditions are given by the head at both ends of the conduit.

Figure A4, Scheme of the penstock model

The penstock dynamics is defined in per unit values by the expressions (A6) and (A7).

$$\frac{dq_{t,i}}{dt} = \frac{n_t}{T_w} \left(h_{i-1} - h_i - \left(\frac{r}{2} + k_{loc} \right) q_{t,i} |q_{t,i}| \right) \quad (A6)$$

$$\frac{dh_i}{dt} = \frac{(n_t-1)}{T_l} (q_{t,i} - q_{t,i+1}) \quad \text{with} \quad T_l = \frac{T_e}{Z} \quad (A7)$$

where $T_e = L/a_w$ is defined as the water “elastic” time and $Z = T_a / T_e$ is the penstock surge impedance (p.u.) (Kaldellis, et al., 2001). In the scheme shown in Figure A4 there are n_t series branches and $n_t - 1$ shunt branches.

The number of segments obviously determines the order of the complete system. In Appendix 2 the step response of the subsystem penstock-turbine is obtained with lumped parameters models with one or ten segments and compared with that obtained with the continuous model. The results show that the number of elements must be high enough to cover the frequency range of the plant response.

One-segment model, II scheme

The simplest model is a II-shaped one segment model having one series branch and two shunt branches. Since the height at the upstream end of penstock can be considered as constant, a second order model will result. The expressions (A8) and (A9) represent penstocks dynamics in this case.

$$\frac{dq_t}{dt} = \frac{1}{T_w} \left(h_c - h - \left(\frac{r}{2} + k_{loc} \right) q_t |q_t| \right) \quad (A8)$$

$$\frac{dh}{dt} = \frac{2}{T_l} (q_t - q) \quad (A9)$$

In order to assess the applicability of this model, the frequency response of the penstock of reference power plant 2 has been determined using the continuous penstock model, the rigid water column penstock model (assuming $\tanh(sL/a_w) \approx sL/a_w$) and the one-segment model approximation (A8) and (A9). The results are shown in Figure A5; from this figure is clear that the rigid water column model can be used only when the response has a very low frequency range; even the frequency response of the one-segment model represented by equations (A8) and (A9) shows some significant deviations with respect to the continuous model (A1) in the range of frequencies observed in Figure A3. Therefore, as in (Sanathanan, 1987) (IEEE Power & Energy Society, 2014), some adjustments should be done in order to use the one-segment penstock model in stability analysis.

Adjusted one-segment model

Transforming the expressions (A8) and (A9) to the frequency domain and neglecting the friction terms, the resulting penstock transfer function can be written:

$$\frac{\Delta H(s)}{\Delta Q(s)} = - \frac{sT_w}{1 + s^2 \frac{T'_l T_w}{2}} \quad (\text{A10})$$

where a modified parameter $T'_l = \beta T_l$ has been considered, introducing the correction factor β . The physical meaning of this coefficient can be understood as if in (A9) the fraction of the conduit elasticity which corresponds to the downstream end of penstock were different than $1/2$.

The value of the correction coefficient β is obtained by equating the frequency corresponding to the poles of the one-segment transfer function (A10) with the first peak of the frequency response of continuous model (A1). This frequency, neglecting losses, is $(\pi a_w)/2L$, then

$$\frac{1}{\sqrt{\frac{T'_l T_w}{2}}} = \frac{\pi a_w}{2L} \quad (\text{A11})$$

This results in $\beta = 8/\pi^2$, which is a constant value independent of penstock parameters. The frequency response of the adjusted one-segment model is also represented in Figure A5 and shows a good concordance with the continuous model for frequencies up to the first peak. As the frequencies observed in Figure A3 are within this range, an accurate enough response can be expected using this model.

Figure A5, Frequency response of penstock models, reference power plant 2.

To verify the adequacy of the adjusted one-segment model, the response of the complete plant model after a sudden reduction of 50% of the power demanded is simulated using the reference plant 2 data. In Figure A6, the results obtained using the continuous model are compared with those obtained with the 10 segments and the

adjusted one-segment models. Simulation results demonstrate that higher frequency modes do not appear in the response of the complete power plant model. Moreover, the response obtained with the adjusted one-segment model is fairly close to that obtained with the continuous model; therefore, the penstock adjusted one-segment model is considered as adequate.

Figure A6, Reference power plant 2 response. $\Delta p_d = -0.5$ p.u.

III.1.3.2 Linearization

Some of the components described above are represented by nonlinear expressions and, so, not suitable for synthesizing the controller using linear methods. Therefore, a linearized model is developed for small perturbation analysis in the neighbourhood of an initial equilibrium operating point.

The equations that characterize the hydro power plant are (A2), (A3), (A4), (A5), (A8) and (A9); nonlinearities appear in the turbine equations (A2) and (A3), and in the inertial penstock equation (A8).

III.1.3.3 Turbine

The linearized model of a hydraulic turbine can be written as follows:

$$\Delta q = b_{11}\Delta h + b_{12}\Delta n + b_{13}\Delta z \quad \Delta c = b_{21}\Delta h + b_{22}\Delta n + b_{23}\Delta z \quad (A12)$$

The coefficients b_{1i} are the partial derivatives of the water flow (A2) with respect to net head, speed and nozzle position; the coefficients b_{2i} are the partial derivatives of the

torque (A3) with respect to the same variables. Both groups of coefficients are expressed in (A13).

$$\begin{aligned}
 b_{11} &= \left. \frac{\partial q}{\partial h} \right|_{(h,n,z)_0} = \frac{z_0}{2\sqrt{h_0}} & b_{21} &= \left. \frac{\partial c}{\partial h} \right|_{(h,n,z)_0} = 2z_0 - \frac{z_0 n_0}{2\sqrt{h_0}} \\
 b_{12} &= \left. \frac{\partial q}{\partial n} \right|_{(h,n,z)_0} = 0 & b_{22} &= \left. \frac{\partial c}{\partial n} \right|_{(h,n,z)_0} = -z_0 \sqrt{h_0} \\
 b_{13} &= \left. \frac{\partial q}{\partial z} \right|_{(h,n,z)_0} = \sqrt{h_0} & b_{23} &= \left. \frac{\partial c}{\partial z} \right|_{(h,n,z)_0} = 2h_0 - n_0 \sqrt{h_0}
 \end{aligned} \tag{A13}$$

III.1.3.4 Penstock

Linearizing the friction losses term in the penstock equation (A8) results in:

$$\frac{d\Delta q_t}{dt} = \frac{1}{T_w} \left(-\Delta h - 2 \left(\frac{r}{2} + k_{loc} \right) q_t^0 \Delta q_t \right) \tag{A14}$$

III.1.3.5 State space formulation

Finally, the plant model results in a 4th order linear invariant dynamic system. The state equations written in canonical form are:

$$\begin{aligned}
 \frac{dx(t)}{dt} &= \mathbf{A}x(t) + \mathbf{B}u(t) \quad \text{Where } \mathbf{A} \text{ and } \mathbf{B} \text{ matrixes are} & (A15) \\
 \mathbf{A} &= \begin{pmatrix} -\frac{2b_{11}}{T'_l} & \frac{2}{T'_l} & -\frac{2b_{13}}{T'_l} & 0 \\ -\frac{1}{T_w} & -2\frac{(\frac{r}{2}+k_{loc})q^0}{T_w} & 0 & 0 \\ -\frac{b_{21}}{\delta T_m} & 0 & -\frac{b_{23}}{\delta T_m} & -\frac{b_{22}-k+\frac{T_m}{T_r}}{\delta T_m} \\ \frac{b_{21}}{T_m} & 0 & \frac{b_{23}}{T_m} & \frac{b_{22}-k}{T_m} \end{pmatrix} & (A16) \\
 \mathbf{B} &= \begin{pmatrix} 0 \\ 0 \\ \frac{1}{\delta T_m} \\ -\frac{1}{T_m} \end{pmatrix} & \mathbf{x}(t) = \begin{pmatrix} \Delta h \\ \Delta q \\ \Delta z \\ \Delta n \end{pmatrix} \\
 & & \mathbf{u}(t) &= (\Delta c_d)
 \end{aligned}$$

III.1.4 Tuning Criteria

The methodology followed in the present paper is based in the pole placement technique (Sanathanan, 1987) (Vidyanandan & Senroy, 2013) (Chaudhry, 1987). Poles

position in the complex plane is closely related to the power plant response. System poles can be determined as the roots of the characteristic polynomial associated to the dynamic matrix A (A16) and their position depends of governor tuning. Thus, the PI gains should be selected so that the poles position gives rise to a dynamic response whose characteristics are as close as possible to the specifications (rise time, overshoot, settling time, etc.) (Sanathanan, 1987).

To obtain results that could be easily applied to different power plants without arduous mathematical calculations some simplifications are considered in matrix A :

- The power plant is supposed to work in rated conditions. The base values of the model correspond to the rated operation point. Therefore h^0 , q^0 and z^0 and are equal to 1.0.
- Friction losses are neglected
- The loads connected to the power plant are resistive and inertialess. This assumption is usual in the case of power plants connected to isolated systems (IEEE Power & Energy Society, 2014).

The resulting coefficients b_{ij} , k and $r/2 + k_{loc}$ are shown in Table A2

Table A2, Tuning assumed values

b_{11}	0.5	b_{12}	0.0	b_{13}	1.0
b_{21}	1.5	b_{22}	-1.0	b_{23}	1.0
$r/2+k_{loc}$	0.0	k	-1.0		

The characteristic polynomial is obtained from the dynamic matrix, (A16), using the parameters of Table A2; the result is expressed by equation (A17).

$$x^4 + \left(\frac{\delta T_m + T'_l}{\delta T_m T'_l} \right) x^3 + \left(\frac{-2T_w T_r + 1.5T_w T'_l + 2\delta T_m T_r}{T'_l T_r T_w \delta T_m} \right) x^2 + \left(\frac{-1.5T_w + 2T_r}{T'_l T_r T_w \delta T_m} \right) x + \frac{3}{T'_l T_r T_w \delta T_m} = 0 \quad (A17)$$

The pole's real part has a direct relation to the settle time. The tuning philosophy of (Cuesta & Vallarino, 2015) is based on avoiding the slow pole and equating the real part of the poles near the imaginary axis.

A similar strategy is followed in (Chaudhry, 1987) but applied to water level control. In this case there was other priority: reducing the wicket gates movements. So, one pair of eigenvalues was placed on the real axis. This approach minimizes the effort made by the servo which acts on the turbine wicket gates. The resulting excessive overshoot is not

a problem because the tolerance to water level variations is larger than to frequency variations.

In the next sections two tuning criteria are proposed:

- Double Real Pole (DRP). The four poles have the same real part but one pair of poles is on the real axis. This strategy is taken from (Chaudhry, 1987), where it is applied to water level control.
- Double Complex Pole (DCP). Two pairs of conjugate identical poles.

III.1.4.1 Double Real Pole Criterion (DRP)

The four close-loop poles are of the form $\{a, a, a \pm jb\}$ (Chaudhry, 1987). Therefore, the characteristic polynomial can be expressed as follows (A18).

$$(x - a)(x - a)(x - (a + jb))(x - (a - jb)) = 0 \quad (\text{A18})$$

The expression (A17) is identified to (A18) and the result is a fourth order equation system (A19). The four unknown variables are a , b , δ and T_r .

$$\begin{aligned} \frac{\delta T_m + T'_l}{\delta T_m T'_l} &= -4a & \frac{-2T_w T_r + 1.5T_w T'_l + 2\delta T_m T_r}{T'_l T_r T_w \delta T_m} &= 6a^2 + b^2 \\ \frac{-1.5T_w + 2T_r}{T'_l T_r T_w \delta T_m} &= -4a^3 - 2ab^2 & \frac{3}{T'_l T_r T_w \delta T_m} &= a^4 + a^2 b^2 \end{aligned} \quad (\text{A19})$$

The expressions that represent the solution of the nonlinear system are quite complex. So, in order to simplify the presentation of the results, a graphical solution is shown in Figure A7. Knowing the water time constant T_w and the elastic wave time L/a_w of the penstock it is possible to obtain the reset time T_r and the product of temporary droop and mechanical time $\delta \cdot T_m$. This tuning criterion is thought to be applied in the context of long penstocks, so Allievi parameter is lower than 0.5.

The Double Real Pole criterion is applied to the reference power plant 2 ($T_w = 1.0$ s, $L/a_w = 1.66$ s and $T_m = 6$ s). The resulting pair of gains is included in Table A3.

The same simulation done previously, sudden loss of 5% net demanded power in reference power plant 2 adjusted with a classic criterion (Kundur, 1994) (Figure A3), is done now again with the controller adjusted with DRP criterion. Simulation graphical results are shown in Figure A9. As it can be appreciated in this figure, the proposed adjustment improves the results obtained with classic recommendations. Table A4

contains response characteristics with the purpose of evaluating and comparing the quality of the responses. The settling time is considerably reduced by DRP but the overshoot and consequently the quadratic and absolute errors are higher. It is worth to highlight that DRP has been taken from water level control where reducing the overshoot was not a priority.

Figure A7, PI Tuning curves, Double Real Pole Criteria

III.1.4.2 Double Complex Pole Criteria (DCP)

DCP criterion maintains the philosophy of equal real part in each pole. Second condition is to equate absolute value of the four imaginary parts. In this way, one oscillation would not prevail over the other. The expected result is to continue reducing the settling time and to decrease the overshoot in the frequency response.

The four close-loop poles are of the form, $\{a \pm jb, a \pm jb\}$ and the characteristic polynomial expression is (A20).

$$(x - (a + jb))^2 (x - (a - jb))^2 = 0 \quad (\text{A20})$$

In this case the equation system, that is the result of identifying the two expressions of characteristic polynomial, (A17) and (A20), is:

$$\begin{aligned} \frac{\delta T_m + T'_l}{\delta T_m T'_l} &= -4a^3 & \frac{-2T_w T_r + 1.5T_w T'_l + 2\delta T_m T_r}{T'_l T_r T_w \delta T_m} &= 6a^2 + 2b^2 \\ \frac{-1.5T_w + 2T_r}{T'_l T_r T_a \delta T_m} &= -4a^3 - 4ab^2 & \frac{3}{T'_l T_r T_w \delta T_m} &= a^4 + 2a^2 b^2 + b^4 \end{aligned} \quad (\text{A21})$$

A parametric solution is presented in the Figure A8 and the particular values of PI gains, corresponding to the reference power plant 2, are shown in Table A3.

Figure A8, PI Tuning curves, Double Complex Pole Criteria

Simulations previously done in reference power plant 2, with classic and DRP criteria are completed now with the controller tuned using DCP criterion. Simulation graphical results are summarized in Figure A9 and Table A4 contains the main response characteristics.

Table A3. PI Gains for reference power plant 2.

	Double Real Pole	Double Complex Pole	Classic
δ	0.6942	0.5251	0.3833
T_r (s)	13.3064	3.7939	5.0000

In this case, the poles were not forced to be located over the real axis. Therefore, the response has more oscillations than the DRP response. Nevertheless, this oscillation is damped quicker and the settling time is the lowest. The frequency overshoot and the mean absolute error $\overline{\sum |\varepsilon_n|}$ are similar than classic's. Only the mean square error $\overline{\sum \varepsilon_n^2}$ is slightly higher than the error obtained with the classic criterion.

Table A4, Response quality parameters. Reference power plant 2. $\Delta p_d = -0.05$ p.u. Simulation time 200 s

Criteria	$\overline{\sum \varepsilon_n^2}$	$\overline{\sum \varepsilon_n }$	$\max \varepsilon_n $	$T_{2\%}$ (s)
Classic	$1.5360 \cdot 10^{-5}$	$1.3904 \cdot 10^{-3}$	0.02436	83.1
Double Real Pole	$6.1043 \cdot 10^{-5}$	$2.6632 \cdot 10^{-3}$	0.03402	37.1
Double Complex Pole	$1.9399 \cdot 10^{-5}$	$1.2167 \cdot 10^{-3}$	0.02714	35.0

Figure A9, Hydro plant dynamic response. DCP, DRP and Classic Criteria. $\Delta p_d = -0.05$ p.u. First 70 s.

III.1.5 Case Study

Recommendations extracted from this study are applied to the governor of Gorona del Viento Hydropower Plant. This plant is located in El Hierro, an island belonging to Canary Islands archipelago and declared a Biosphere Reserve by UNESCO. The island aims to become 100% carbon dioxide emissions free (Iglesias & Carballo, 2011). The energy demand is supplied by a wind farm and the hydro power plant mentioned above. The plant can operate also in pumping mode and so, the excess of available wind energy is stored in the upper reservoir.

In this context it can be assumed isolated operation hypothesis: variations of the net power demanded, due either to a variation in load demand or in the wind generation, are balanced only by the hydro power plant.

The hydro power plant data used in the model have been taken from (Platero, et al., 2014). They are summarized in Table A5.

Table A5, Gorona del Viento Power plant ratings		
Generating Unit	Rated Power	2.830 MW
	Rated flow	0.50 m ³ /s
	Number of units	4
	Rated speed	1000 r.p.m.
	Mechanical starting time (T_m)	6 s
	Gross Head	670 m
Penstock	Length	2577 m
	Diameter	1 m
	Darcy - Weisbach friction loss coefficient	0.015
	Wave speed (a_w)	1193 m/s
	Relation $\frac{L}{a_w}$	2.16 s

Presently Gorona del Viento power plant never works with all units operating simultaneously, because maximum power demanded in the island do not usually exceed 7 MW. In valley hours the demanded power is around 4 MW. Therefore, as an average case, it is assumed the power plant operates with two units at full load. Then, the rated and base flow are set in the value $1.0 \text{ m}^3/\text{s}$. This hypothesis affects the water losses in the penstock and the water starting time T_w . The Allievi parameter value is one-half of the value with all the units operating; so this assumption is more exigent for the tuning criteria. The numerical values of these parameters are shown in Table A6.

Table A6, 2 units operating

ΔH	4,75 m
T_w	0.5028 s
ρ	0.1164

Table A7 contains the numerical values of PI gains tuned according to the DRP, DCP and classic criteria. The eigenvalues obtained from the fourth order power plant model, tuned with classic criterion, are also shown in this table. One pair of poles has positive real part so the system response in this case will be unstable and no simulations will be carried out with this governor configuration.

Table A7. Gorona del Viento power plant PI tuned gains.

	Double Real Pole	Double Pole	Complex	Classic	Eigenvalues (Adjusted 1 segment model)
				Gains	
δ	1.4325	0.5713		0.1990	$0.0724 \pm 0.6059i$
T_r (s)	32.8405	2.0511		2.6390	$-0.5719 \pm 0.3429i$

One of the main requirements for this hydro power plant is maintaining the frequency within the power quality limits according to regulation (European Standards EN 50160, 2007). The ranges of frequency variations are for non-interconnected supply systems: $50 \text{ Hz} \pm 2 \%$ for 95 % and $50 \text{ Hz} \pm 15 \%$ for 100 % of a week. Two different simulations are carried out. On the one hand, an event that may occur frequently is modelled (normal operating conditions), and in the other hand an unlikely event is simulated (abnormal conditions). Both simulations are carried out with the power plant controller tuned with the two criteria presented in previous section.

III.1.5.1 Normal operating conditions

A common event in hydropower plants operating in isolated systems with high wind penetration is produced by wind fluctuations giving rise to variations in the wind generated power (Nicolet, et al., 2009). As an example, an increase in the wind speed is

supposed causing a linear increase of the power produced by wind turbines. The net power p_d decreases and the hydro power plant is asked to reduce its production in order to maintain the system frequency. The required power variation is -0.25 p.u in 60 seconds.

Simulations results are shown in Figure A10. It can be observed that the response with the controller tuned with DRP criterion is not strong enough, so the frequency overshoot exceeds the maximum allowed values ($\pm 2\%$). In the case of the DCP criterion, frequency deviation fulfils the desired requirements.

III.1.5.2 Abnormal conditions

A sudden and unexpected disconnection of one wind generator (2.3 MW) is considered as an abnormal situation in the power plant operation. It is assumed that the wind generation do not participate in frequency regulation; thus the hydro plant increases the generated power to compensate the generation loss and recover the frequency.

Figure A11 contains graphical results of the described simulation. DRP criterion reduces the oscillations in the frequency or power at expenses of the excessive frequency overshoot. Nevertheless, when the controller is tuned with DCP criterion the frequency is maintained within the established limits ($\pm 2\%$).

Figure A10, Dynamic response of the central with $\Delta p_d = -0.25$ p.u in 60 s

Figure A11, Dynamic response of the central with $\Delta p_a=0.40$ p.u

Although, unfortunately, these results cannot be compared at the present time with experimental data, it seems reasonable to expect a fairly good agreement, because a similar model has been used in (Mansoor, et al., 2000) for Dinorwig power plant, where the simulation results reproduce with enough accuracy field measurements.

III.1.6 Conclusions

In this paper a model of a hydro power plant with long penstock connected to an isolated system is described. This configuration frequently corresponds to pumped storage power plants coexisting with wind farms in small islands. It has been found that penstock length may affect governor PI gains settings, especially when Allievi parameter is lower than 0.5. Classical tuning criteria do not take into account this issue; so new recommendations are formulated to solve this matter.

A reduced order model based in lumped parameters approach is proposed for stability analysis. The adequacy of a one-segment model adjusted in frequency domain to represent penstock dynamics has been verified. The simulations show that high frequencies do not appear in the power plant response.

Using the reduced order model, two new tuning criteria, based on pole placement method, have been formulated; one of them (DRP) was previously applied in a water level control context. Both are compared to the known classic criteria using a reference power plant with long penstock ($\rho = 0.30$). Results from simulations reveal that new criteria notably improve response quality.

Finally, formulated criteria were applied to Gorona del Viento hydro power plant, located in El Hierro island, where there is also wind generation. Several situations (normal and abnormal) have been modeled with the governor tuned according to the two proposed criteria; classic criterion leaded to instability. The best performance was obtained when the governor gains were tuned using the Double Complex Pole (DCP) criterion. Since the DRP criterion was developed for water level control, the DCP criterion is expected to perform better than DRP in load frequency control, whatever the power plant parameters.

III.1.7 Nomenclature

A	Real part of the solutions of the characteristic polynomial
a_w	Wave speed (m/s)
B	Complex part of the solutions of the characteristic polynomial
b_{ij}	Turbine linear coefficients (p.u.)
C	Turbine mechanical torque (p.u.)
c_d	Net load torque at rated frequency (p.u.)
F	Penstock section (m ²)
G	Gravity acceleration (m/s ²)
H	Net head (p.u.)
h^0	Initial net head (p.u.)
H	Net head (m)
H(s)	Net head in frequency domain (p.u.)
H_b	Base head (m)
h_c	Reservoir water level (p.u.) $\approx h_c^0$ (variations along the time of the study are neglected)
h_c^0	Initial reservoir water level (p.u.)
h_i	Head at the end of the i-th Π element of the penstock (p.u.)
J	$\sqrt{-1}$
K_P	Proportional gain in PI governor
K_I	Integral gain in PI governor
K	Load self-regulation coefficient
k_{loc}	Localized head losses coefficient (p.u.)
L	Penstock length (m)
N	Frequency (p.u.)
n_r	Reference frequency (p.u.)
n_t	Number of segments in which the penstock is divided
p_d	Net demanded power in system (p.u.)
Q(s)	Flow through the turbine in frequency domain (p.u.)
Q_b	Base flow (m ³ /s)
Q	Flow through the turbine (p.u.)
q^0	Initial flow through the turbine (p.u.)
q_t	Flow at the penstock (p.u.)
q_t^0	Initial flow at the penstock (p.u.)
$q_{t,i}$	Flow at the end of the i-th Π element of the penstock (p.u.)
$r/2$	Continuous head losses coefficient (p.u.)
$T_{2\%}$	Settling time (s)
T_e	L / a_w , water elastic time (s)
T_l	$= T_e / Z$ (s)

T'_1	$= \beta T_1$ (s)
T_m	Mechanical starting time (s)
T_r	Dashpot time constant (s)
T_w	Penstock water starting time (s)
V	Water speed in the penstock (m/s)
Z	Nozzle opening (p.u.)
Z	T_a/T_e , penstock surge impedance (p.u.)
z^0	Initial nozzle opening (p.u.)
B	Correction coefficient
Δ	Temporary speed droop
Σ	Permanent speed droop
ρ	Allievi parameter
$\max \varepsilon_n $	frequency overshoot (p.u.)
$\overline{\sum \varepsilon_n }$	Frequency mean absolute error (p.u.)
$\overline{\sum \varepsilon_n^2}$	Frequency mean square error (p.u.)

III.1.8 Appendix: Turbine-penstock dynamic response

In order to make clear the nature of the lumped parameters approach, the subsystem penstock-turbine has been isolated and a sudden reduction of 50% of the turbine nozzles opening was simulated. The parameters of the reference power plant 2 (Table A1) have been used. The continuous model response is compared to that obtained with the adjusted one-segment model and also with the one obtained with a ten-segment lumped parameters model.

Simulation results show that adjusted one-segment model is able to reproduce the fundamental frequency but ignores higher frequencies. Logically, the ten-segment model response is more accurate and covers a higher frequency range.

Figure A12, Reference power plant 2, isolated system Penstock-Turbine response. $\Delta z = -0.5$ p.u

Then, the number of elements of a lumped parameters model should be selected so as to include the modes within the range of frequencies involved in the plant response.

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III.2 Paper B: Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel

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Abstract

Pumped storage hydropower plants (PSHP) can provide adequate energy storage and frequency regulation capacities in isolated power systems having significant renewable energy resources. Due to its high wind and solar potential, several plans have been developed for La Palma Island in the Canary archipelago, aimed at increasing the penetration of these energy sources. In this paper, the performance of the frequency control of La Palma power system is assessed, when the demand is supplied by the available wind and solar generation with the support of a PSHP which has been predesigned for this purpose. The frequency regulation is provided exclusively by the PSHP. Due to topographic and environmental constraints, this plant has a long tail-race tunnel without a surge tank. In this configuration, the effects of pressure waves cannot be neglected and, therefore, usual recommendations for PID governor tuning provide poor performance. A PI governor tuning criterion is proposed for the hydro plant and compared with other criteria according to several performance indices. Several scenarios considering solar and wind energy penetration have been simulated to check the plant response using the proposed criterion. This tuning of the PI governor maintains La Palma system frequency within grid code requirements.

Keywords:

Wind-solar-hydro systems; Pumped hydro storage system; Long tail-race tunnel; Speed governor tuning; Pole placement method; Root locus plot.

III.2.1 Introduction

Generally, fossil fuels are very expensive in islands, principally because of transportation cost. Nevertheless, many islands have an excellent local wind and solar potential, so that economic, environmental and social costs of fuel electricity generation may be avoided. In last years, renewable energy sources have been used to substitute

fossil fuels in small isolated systems (Kaldellis & Kavadias, 2001) (Kaldellis, et al., 2001) (Iglesias & Carballo, 2011) (Merino, et al., 2012).

One of the economic and technical drawbacks of the high participation of intermittent energy sources in isolated systems is the need to reject substantial amounts of the produced energy due to penetration limits in the local electric grids (Anagnostopoulos & Papantonis, 2008). This affects to both, wind and PV generation.

The vast majority of studies agree that the introduction of storage systems is the most effective mean to significantly increase wind penetration levels in power system (Anagnostopoulos & Papantonis, 2008) (Papaeftymiou, et al., 2010) (Papaeftymiou & Papathanassiou, 2014) (Papaeftymiou, et al., 2015). Pumped storage hydropower plans (PSHP) can contribute to this role, being able to compensate uncertainly in intermittent renewable energy (wind and solar). In fact, some current research is focused on the feasibility of the combination of solar, wind and hydro energy in islands (Figure B1) (Ma, et al., 2014). This issue is also being considered in small isolated systems on some inland areas (Murage & Anderson, 2014).

In some cases, sites available for building new PSHP may require long hydraulic conduits due to geographic, environmental or economic constraints. The main technical problem associated with long pipes is related to elastic phenomena, especially in those cases where for economic and environmental constraints no surge tank is built. In long pipelines, under-pressure and overpressure downstream or upstream of the turbine may result from the gate position movement. As an example, in long discharge pipes, cavitation phenomena may appear downstream the turbine due to an excessive suction pressure caused by gate closing movements (Dorji & Ghomashchi, 2014).

The construction of a realistic model that takes into account all the phenomena involved in system operation is essential in order to draw relevant conclusions, applicable to predict the response of the station during design phase (Mansoor, et al., 2000).

In particular, when the tail-race tunnel has a great length, the rigid-water-column models are not adequate (Jiménez & Chaudhry, 1987) and consequently the controller settings based on it (Sanathanan, 1987). There are several researches which describe how to model the dynamic response when elastic phenomena cannot be neglected (Souza Jr, et al., 1999) (Nicolet, et al., 2007) (Liu & Liu, 2007) (Naik, et al., 2012).

The use of PI controllers in hydropower plants to control speed governors is a usual practice (Kishor, et al., 2007) and several criteria for gain tuning have been developed in last decades (Hagigara & Yokota, 1979) (Wozniak, 1990) (Kundur, 1994). Classic Control techniques, as root locus plot, have been successfully applied in order to obtain recommendations or expressions for PID speed governor tuning in the plant design phase (Hagigara & Yokota, 1979) (Abdolmaleki, et al., 2008) (Sarasúa, et al., 2014) (Hušek, 2014), but this rules do not include water elasticity effects.

Regarding long pipes, very few studies have been found in the literature focused on the adjustment of PID governor gains in such cases. In (Martínez-Lucas, et al., 2015(a)), a hydropower plant with long penstock is modeled. In this study, authors propose two criteria to adjust PI gains assuming isolated system and wind energy penetration. In (Martínez-Lucas, et al., 2015(b)), a hydropower plant with long tail-race tunnel is modeled. In this case, the plant is aimed to contribute to secondary regulation.

La Palma is an island belonging to the Canary Islands archipelago and declared a Biosphere Reserve by UNESCO since 2002. Currently, the vast majority energy is provided by thermal plants, while only a small proportion is provided by wind and solar farms. The objective for next years is to reduce consumption of fossil fuel and increase the use of renewable resources (Gobierno de Canarias, 2007). For this purpose, it is expected to increase the installed capacity of wind and solar farms and to build a PSHP. One of the main objectives to be achieved is that at certain times, the energy is produced exclusively from renewable sources, thus overriding the thermal generation. In this case, the contribution of the hydropower plant to frequency regulation becomes very important, since the possible contribution of modern wind generators entails a cost: some wind energy will be lost (Vidyanandan & Senroy, 2013).

In this paper, a PSHP in La Palma Island has been predesigned and modeled taking into account the penetration increasing rate of renewable energies (wind, solar and hydro) in recent years (Gobierno de Canarias, 2014), as well as several published expansion plans (Gobierno de Canarias, 2007) (Gobierno de Canarias, 2012).

In order to model the hydropower plant adequately, a detailed model which includes nonlinearities, head losses and distributed elasticity effects has been used. According to this aim, it is necessary to obtain the PI gains that allow to PSHP operate correctly. A

methodology based on root locus plot to obtain these gains, taking into account water and tail-race tunnel elasticity effects has been developed. For this purpose, a simplified linearized model is obtained using the adjusted lumped parameter approach (Souza Jr, et al., 1999) (Nicolet, et al., 2007) (Martínez-Lucas, et al., 2015(a)). With this simplified model, an analysis in the frequency domain is developed, obtaining the transfer function of the control loop and the participation factor of each variable (Liu & Liu, 2007) (Kundur, 1994).

The adequacy of the proposed criterion for controller adjustment has been checked by comparison with other criteria, using some performance parameters belonging to the frequency and time domains (gain margin, phase margin, damping ratio...) as proposed in (IEEE Power & Energy Society, 2014). In order to evaluate the plant dynamic response due to different perturbations (Jones, et al., 2004) (and its ability to operate in an isolated system with high penetration of solar and wind power) several simulations have been carried out. No contribution to frequency regulation from the wind farm has been considered.

The paper is organized as follows. In Section III.2.2, the power system of La Palma Island (Canary archipelago) and the projected pumped storage hydropower plant are described. In Section III.2.3, the hydropower plant dynamic model is presented, describing each element of the PSHP. In Section III.2.4, a reduced order model is used in order to analyze the system in frequency domain. In Section III.2.5, a tuning criterion based on root locus method is formulated, being compared with others classic ones. In Section III.2.6, some real cases are proposed in order to simulate the PSHP dynamic response with the tuning criterion proposed. Finally, in Section III.2.7 main conclusions of the paper are properly summarized.

Figure B1. A hybrid solar-wind system with pumped storage system

III.2.2 Power system and PSHP description

The amount of electrical energy generated in 2013 on the island of La Palma was 262 375 MWh of which only 9.1% came from renewable sources, while the remaining 90.9% was produced by fossil fuels. The maximum peak demand for that year was 42 MW (Gobierno de Canarias, 2014). In order to reduce the share of fossil fuels, the authorities of the island of La Palma intend to carry out a major project to increase the penetration of renewable energy (Gesplan, 2007).

Currently, the installed generation capacity from fossil fuels is 82.8 MW in diesel generators and 22.5 MW in gas turbines. The renewable sources are shown in Figure B2, including four wind farms (W) distributed throughout the island with an installed capacity of 9 MW and two solar photovoltaic (Pv) plants with an installed capacity of 4.9 MW (Gobierno de Canarias, 2014). In the last years, several expansion plans have been developed in order to increase the penetration of renewable energy throughout the archipelago (Gobierno de Canarias, 2007) (Gobierno de Canarias, 2012). According to the penetration rate of these energies in recent years (Gobierno de Canarias, 2014) and taking into account the development plans of the energy system (Gobierno de Canarias, 2012) it is considered that the most likely action would be to install a wind farm of about 20 MW. In this scenario, it would be necessary to have sufficient power regulation capacity in a pumped storage hydroelectric plant (PSHP) for integration of the other renewable energy sources (Gesplan, 2007) (Platero, et al., 2014).

Figure B2. Geographical location of La Palma island in the Canary Archipelago, and its renewable power plants.

The PSHP is to be placed in the northeast area of the island, using as lower reservoir an existing irrigation pond, Barlovento, which has excess of capacity for the current demand. According to the expansion plan, the upper reservoir would be placed in Las Cancelitas (Figure B3). Published studies are preliminary in a very basic level, so it was considered necessary to complete them; thus, the PSHP was pre-dimensioned to carry out the present study.

The power plant will have two 25 MW pump-turbines. The powerhouse will be placed in a cavern under the valley between "Las Cancelitas" and "El Lomito" where the tail-race tunnel starts. As it is shown in Figure B3 and Figure B4, the tail-race conduit runs from this point, under the rock masses of "El Lomito" and "Llanadas de Verone" to the lower reservoir of Barlovento. The characteristics of the PSHP are summarised in Table B1. A preliminary assessment has shown that this PSHP together with wind and solar power would supply the demand at some time intervals without the contribution of fossil fuel power plants.

Figure B3. PSHP layout

Figure B4. Plant and topography profile schemes

Table B1. Barlovento hydro power plant main data

Power Plant	Penstock	Tail-race tunnel
H 304 m	L _p 550 m	L _d 1950 m
Q 17.8 m ³ /s	D _p 2.00 m	D _d 2.50 m
P 50 MW	v _p 5.67 m/s	v _d 3.63 m/s

III.2.3 Simulation model

The electric power system of La Palma Island has been modeled as an isolated system, where the PSHP would be the only generation plant supplying the *net demand*, i.e. the residual demand remaining after subtracting the intermittent wind and solar

generation. This hypothesis implies that wind and solar generation do not contribute to frequency regulation; this service being exclusively provided by the PSHP plant. Therefore, according to work's objectives, PSHP will operate in generation mode during all simulations.

In this study, a hydroelectric plant with a long tail-race conduit is modelled. A PI controller, the penstock and the tail race are included in the model. Elastic effects are considered only in the tail-race. Figure B5 shows the main blocks of the model and their interconnections. The equations associated with each block are detailed in the following sections. All variables are expressed in per unit.

Figure B5. Block diagram of the plant model

III.2.3.1 Penstock

Due to its short length, penstock is modelled assuming the rigid water column approach, including water inertia and head losses (IEEE Working Group, 1992) (Chaudhry, 1987). Thus, the penstock dynamics is given by equation (B1).

$$\frac{dq_p}{dt} = \frac{1}{T_{wp}} \left(h_c - h - h_t - \frac{r_p}{2} \cdot q_p \cdot |q_p| \right) \quad (B1)$$

Where T_{wp} is the penstock water starting time and it is defined as (B2):

$$T_{wp} = \frac{L_p}{gF_p} \frac{Q_b}{H_b} \quad (B2)$$

The relationship between turbine pressures up-stream and down-stream and net head is shown in Figure B4 and is expressed by (B3):

$$h = h_p - h_t \quad (B3)$$

Water level variations in both reservoirs are neglected due to their very large time constant.

III.2.3.2 Turbine

Turbine operation is described by two functions. First function relates flow with net head and wicket-gate position. The second one relates the generated power with the flow, net head, gate position and speed. This model is recommended in (IEEE Working Group, 1992) and the expressions are (B4) and (B5).

$$q = z\sqrt{h} \quad (B4)$$

$$p_g = A_t h(q - q_{nl}) - Dz\Delta n \quad (B5)$$

The modelled power plant has two identical units, which are supposed to work at the same operating point. Thus, a single equivalent turbine has been considered.

III.2.3.3 Generator and External System

As stated above, the hydro power plant is connected to an isolated system comprising intermittent energy sources and loads. Intermachine mechanical oscillations will be neglected, so that the frequency is represented by a unique value; then, the frequency dynamics (B6) results from the imbalance between generator power, p_g and net demand, p_d (Mansoor, et al., 2000) (Grenier, et al., 2005) (Van Cutsem, et al., 2006).

$$p_g - p_d - k\Delta n = (T_m + T_{ps})n \frac{dn}{dt} \quad (B6)$$

where inertia mechanical starting time, T_m , corresponds to the hydro plant and T_{ps} , corresponds to the inertia of rotating loads; wind and PV generation have been included in p_d as a negative demand; wind generators are supposed to be connected to the system through frequency converters and do not contribute to system inertia. The parameter k includes only load frequency sensitivity effects, as it has been assumed that wind and solar generation do not contribute to frequency regulation.

III.2.3.4 PI controller

A conventional proportional-integral (PI) controller processes the frequency error signal $(n_{ref} - n) - \sigma z$. Equation (B7) gives the changes in the gate position due to the controller action (Sanathanan, 1987).

$$z = \left[\frac{1}{\delta} + \frac{1}{\delta T_r} \int dt \right] [(n_{ref} - n) - \sigma z] \quad (B7)$$

The PI gains are:

$$K_P = \frac{1}{\delta} \text{ and } K_I = \frac{1}{\delta T_r} \quad (B8)$$

As it is shown in Figure B6, the gate movement has a rate limiter (± 0.1 p.u./s) and a minimum and a maximum position (IEEE Working Group, 1992). These non-linear elements can affect the response to a great perturbation. However, they have not been considered in the analytical study because it is based on a small perturbation linearized model.

Figure B6. Block diagram of PI controller

III.2.3.5 Tail-race

In order to consider water and conduit elasticity, expression (B9) is used (Martínez-Lucas, et al., 2015(a))

$$\frac{\Delta H_t(s)}{\Delta Q_d(s)} = - \frac{T_{wd} \frac{a_d}{L_d} \left(1 - e^{-2 \frac{L_d}{a_d} s} \right)}{1 + e^{-2 \frac{L_d}{a_d} s}} \quad (B9)$$

The head losses, $(r_d/2)$, are included as shown in Figure B7 (IEEE Working Group, 1992).

Figure B7. Block diagram of tail race

III.2.4 Reduced order model

For control design purposes in plants with long conduits, it is convenient in general to use a reduced order model including elasticity effects (Kishor, et al., 2007). In this case, it has been considered necessary only in the tail-race tunnel.

III.2.4.1 Lumped parameters approach

In last years some authors (Souza Jr, et al., 1999) (Nicolet, et al., 2011(b)) (Pérez-Díaz, et al., 2012) have obtained good results with their hydro power plant models, representing penstock elasticity effects by means of several consecutive elements, where the conduit properties, inertia, elasticity and friction, are assigned proportionally to the segment length. Accordingly, long conduits can be modeled considering the lumped parameter approach. In (Martínez-Lucas, et al., 2015(a)) it has been verified that the simplest model, one Π -shaped segment model having one series branch and two shunt branches can be accurate enough. Here, tail-race tunnel will be modelled assuming these guidelines. Since the height at the downstream end of tail-race can be considered as constant, a second order model will result, (B10) and (B11):

$$\frac{dq_d}{dt} = \frac{1}{T_{wd}} \left(h_t - h_d - \frac{r_d}{2} \cdot q_d \cdot |q_d| \right) \quad (\text{B10})$$

$$\frac{dh_t}{dt} = \frac{2T_{wd}}{\beta T_{ed}^2} (q_p - q_d) \quad (\text{B11})$$

The single Π -shaped segment-model is corrected through the coefficient β (Martínez-Lucas, et al., 2015(a)). The correction coefficient β is adjusted so that the natural frequency of the one-segment transfer function matches the first peak of the frequency response of continuous model (B9).

III.2.4.2 Linearization

Some of the components described above are represented by nonlinear expressions and, therefore, are not suitable for adjustment of the controller using linear methods. Thus, a linearized model is derived for small perturbation analysis in the neighbourhood of an initial equilibrium operating point.

The equations that characterize the hydro power plant are (B1), (B4), (B5), (B6), (B7), (B10) and (B11), where nonlinearities appear in the inertial penstock equation, (B1) in the turbine equations (B4) and (B5) and in the inertial tail-race equation (B10).

Turbine

The linearized model of a hydraulic turbine can be written as follows:

$$\Delta q_p = b_{11}\Delta h + b_{12}\Delta n + b_{13}\Delta z \quad (\text{B12})$$

$$\Delta c_t = b_{21}\Delta h + b_{22}\Delta n + b_{23}\Delta z \quad (\text{B13})$$

$$\Delta p_g = n^0 b_{21}\Delta h + (n^0 b_{22} + c_t^0)\Delta n + n^0 b_{23}\Delta z \quad (\text{B14})$$

The coefficients b_{1i} are the partial derivatives of the water flow (B4) with respect to net head, speed and wicket gate position whereas than the coefficients b_{2i} are the partial derivatives of the torque (B5) with respect to the same variables. Both groups of coefficients are expressed in (B15).

$$\begin{aligned} b_{11} &= \left. \frac{\partial q_p}{\partial h} \right|_{(h,n,z)^0} = \frac{z^0}{2\sqrt{h^0}} & b_{21} &= \left. \frac{\partial c_t}{\partial h} \right|_{(h,n,z)^0} = \frac{A_t}{n^0} \left(\frac{z^0}{2} \sqrt{h^0} + q_p^0 - q_{nl} \right) \\ b_{12} &= \left. \frac{\partial q_p}{\partial n} \right|_{(h,n,z)^0} = 0 & b_{22} &= \left. \frac{\partial c_t}{\partial n} \right|_{(h,n,z)^0} = -\frac{1}{n^0} (Dz^0 + c_t^0) \\ b_{13} &= \left. \frac{\partial q_p}{\partial z} \right|_{(h,n,z)^0} = \sqrt{h^0} & b_{23} &= \left. \frac{\partial c_t}{\partial z} \right|_{(h,n,z)^0} = \frac{A_t}{n^0} (h^0)^{\frac{3}{2}} \end{aligned} \quad (\text{B15})$$

Penstock

Linearizing the friction losses term in the penstock equation (B1), and taking into account the head relations (B3), results in (B16):

$$\frac{d\Delta q_p}{dt} = \frac{1}{\tau_{wp}} \left[-\left(\frac{1}{b_{11}} + r_p q_p^0 \right) \Delta q_p - \Delta h_t + \frac{b_{12}}{b_{11}} \Delta n + \frac{b_{13}}{b_{11}} \Delta z \right] \quad (\text{B16})$$

Tail-race

Likewise the above section, linearizing tail-race equation (B10) results in (B17):

$$\frac{d\Delta q_d}{dt} = \frac{1}{T_{wd}}(\Delta h_t - r_d q_d^0 \Delta q_d) \quad (\text{B17})$$

III.2.4.3 Frequency domain analysis

The objective of the frequency domain analysis is to obtain the transfer function which relates the frequency variation with the demanded power. Perturbation input (net demanded power, P_d) is only considered because the reference frequency, n_{ref} , should remain constant due to the controller objective: to maintain constant system frequency.

To determinate this function, the penstock (B16) and the elastic tail – race expressions (B11) and (B17) are formulated in the frequency domain, subsequently combining them with the turbine flow equation (B12) to obtain the variations in the tail-race flow in terms of the variations in speed and wicket gates position:

$$\Delta Q_p(s) = \frac{(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})(b_{12}\Delta N(s) + b_{13}\Delta Z(s))}{\left((\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})\left(sT_{wp} + \frac{1}{b_{11}} + r_p q_p^0\right) + 2T_{wd}(sT_{wd} + r_d q_d^0)\right)b_{11}} \quad (\text{B18})$$

Taking into account equation (B14), changes in the output power, $\Delta P_g(s)$, can be expressed as:

$$\Delta P_g(s) = \left[\frac{b_{21}(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})(b_{12}\Delta N(s) + b_{13}\Delta Z(s))}{b_{11}^2 \left((\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})\left(sT_{wp} + \frac{1}{b_{11}} + r_p q_p^0\right) + 2T_{wd}(sT_{wd} + r_d q_d^0)\right)} \right] \quad (\text{B19})$$

$$+ \left(b_{22} + \frac{c_t^0}{n^0} - \frac{b_{21}b_{12}}{b_{11}}\right)\Delta N(s) + \left(b_{23} - \frac{b_{21}b_{13}}{b_{11}}\right)\Delta Z(s)$$

And it can be reformulated as:

$$\Delta P_g(s) = G_N(s)\Delta N(s) + G_Z(s)\Delta Z(s) \quad (\text{B20})$$

Where:

$$G_N(s) = \frac{b_{21}b_{12}}{b_{11}^2} \frac{(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})}{(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})\left(sT_{wp} + \frac{1}{b_{11}} + r_p q_p^0\right) + 2T_{wd}(sT_{wd} + r_d q_d^0)} + b_{22} + \frac{c_{t0}}{n_0} - \frac{b_{21}b_{12}}{b_{11}} \quad (\text{B21})$$

$$G_Z(s) = \frac{b_{21}b_{13}}{b_{11}^2} \frac{(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})}{(\beta T_{ed}^2 s(sT_{wd} + r_d q_d^0) + 2T_{wd})\left(sT_{wp} + \frac{1}{b_{11}} + r_p q_p^0\right) + 2T_{wd}(sT_{wd} + r_d q_d^0)} + b_{23} - \frac{b_{21}b_{13}}{b_{11}} \quad (\text{B22})$$

The frequency dynamics equation (B6) is now formulated in frequency domain resulting in:

$$\Delta P_g(s) - \Delta P_d(s) - k\Delta N(s) = (T_m + T_{ps})n^0 s \Delta N(s) \quad (B23)$$

Controller transfer function, G_C , describes speed governor dynamics in frequency domain.

$$G_C = \frac{\Delta Z(s)}{-\Delta N(s)} = \frac{1 + T_r s}{\delta T_r s} \quad (B24)$$

Finally, combining expressions (B20), (B23) and (B24), the system transfer function results:

$$\frac{-\Delta N(s)}{\Delta P_d(s)} = \frac{1}{(T_m + T_{ps})n^0 s + k - G_N(s) + G_Z(s)G_C(s)} \quad (B25)$$

III.2.5 Proposed PI tuning criteria

Three different criteria are described for tuning the PI governor of the speed control loop of hydroelectric power plants with long tail-race tunnel operating in an isolated system. The first one, Double Complex Pole (DCP) is taken from (Martínez-Lucas, et al., 2015(a)). The second one, Fixed Damping Ratio (FDR) is taken from (Sarasúa, et al., 2015). The third one is referred to Fixed Damping Ratio Modified (FDRM) since it is based on FDR where some modifications have been introduced.

The first two criteria are based on fourth order models, due to they were developed to control speed governors in hydropower plants with long penstock, so it has been necessary to adapt them to the case study. The third one is formulated for a fifth order model of a hydropower plant with long tail-race tunnel.

All of them are based on a root locus analysis of the simplified speed control loop. In last years, many works based on the root locus technique to adjust speed governors have been developed (Abdolmaleki, et al., 2008) (Strah, et al., 2005).

For tuning purposes, only, friction losses ($r_p/2$ and $r_d/2$) are neglected (Vournas & Papaioannou, 1995). The plant is supposed to operate in rated conditions. The parameters of expression (B5) have been taken from (Munoz-Hernandez & Jones, 2012). The numerical values of the PSHP are collected in Table B2.

Table B2, Nominal operating point values (p.u.)

q_p^0	1.0	q_d^0	1.0	h^0	1.0
n^0	1.0	c_t^0	1.0	z^0	1.0
p_g^0	1.0	A_t	1.0526	q_{nl}	0.050
D	2.00	$r_p/2$	0	$r_d/2$	0

III.2.5.1 Double Complex Pole (DCP)

According to this criterion, developed for a PSHP with long penstock in an isolated system (Martínez-Lucas, et al., 2015(a)), the two pairs of complex poles of the control loop are forced to have the same value. DCP criterion was formulated considering a Pelton turbine, which has different coefficients b_{2j} . For this reason, the equations system presented in (Martínez-Lucas, et al., 2015(a)) has been re-formulated considering the b_{2j} coefficients indicated in Table B2. Further, in this case, it is necessary to consider the tail-race tunnel inertia. Then, a global water starting time ($T_w = T_{wp} + T_{wd}$) has been used to represent the inertia of the conduits (penstock and tail-race tunnel).

This criterion was designed for a fourth-order system, so in the fifth-order system the poles cannot be located in general at the same place; then, the slower pole pair is placed as far as possible from the imaginary axis. Given the time constants listed in Table B3, the resulting values of the controller gains and the poles of the closed loop transfer function are shown in Table B4. The root locus plot with the poles position highlighted is represented in Figure B8.

Figure B8. Root Locus Barlovento hydropower plant in isolated operation with DCP

III.2.5.2 Fixed Damping Ratio (FDR)

In (Wozniak, 1990) authors recommend using the $\zeta=0.707$ damping ratio as design criterion. This criterion has been applied in (Sarasúa, et al., 2015), where the authors propose some abacuses and approximate expressions to obtain the controller parameters, T_r and δ ($1/K_p$) in terms of plant time constants, T_m , T_e and T_w . These expressions are based on a fourth order model with a long penstock. In this work, for long discharge tubes, the total starting time ($T_w = T_{wp} + T_{wd}$) and the elastic time constant of the discharge pipe

($T_e = T_{ed}$) have been considered. The resulting controller parameters are given in this case by (B26) and (B27):

$$T_r = 0.64(T_{wp} + T_{wd}) + T_m \quad (B26)$$

$$\delta = 0.09 \left(\frac{(T_{wp} + T_{wd})T_{ed}}{T_m} \right)^2 + 0.03 \frac{(T_{wp} + T_{wd})T_{ed}}{T_m} + 2.23 \quad (B27)$$

The values of the controller gains for the time constants listed in Table B3 and the poles of the closed loop transfer function are shown in Table B4. Note that controlled poles are λ_4 and λ_5 . Also, the root locus and poles location are shown in Figure B9, which shows that a couple of poles are located near the line of fixed damping. The differences found are due to applying a criterion based on a fourth order model to a fifth order model.

Figure B9. Root Locus Barlovento hydropower plant in isolated operation with FDR

III.2.5.3 Fixed Damping Ratio Modified (FDRM)

The plant model in study is of fifth order, so there are 5 poles. At least, one of these poles is on the real axis. The condition imposed by the previous criterion on the mechanical-water pole ($\zeta=0.707$) may remain in force, but now a condition should be imposed to the real pole. As discussed in (Sarasúa, et al., 2014) (Martínez-Lucas, et al., 2015(a)), the tuning criterion influences the controlled variable settling time. Specifically, it reduces it by increasing the pole real part (in absolute value). This consideration implies having a lower settling time, at the expense of the overshoot.

According to this criterion, the five generic transfer function poles are forced to be of the form $\{a, a \pm ja, b \pm jc\}$; so, the closed loop transfer function denominator can be written as (B28).

$$(x - a)(x - (a - ja))(x - (a + ja))(x - (b - jc))(x - (b + jc)) \quad (B28)$$

Then, the closed loop poles are given by the solution of a fifth order equation system (B29), where the five unknown variables are: a , b , c , K_p and Tr .

$$\begin{aligned}
 \frac{2T_{wp} + 2T_m + kT_{wp} - 2T_{wp}K_p}{(T_m + T_{ps})T_{wp}} &= -3a - 2b \\
 \frac{4T_rT_{ed}^2 + 2kT_rT_{ed}^2 - 2K_pT_{ed}^2T_{wp} + 2.1051T_rK_pT_{ed}^2 + 2.4673T_rT_m(T_{wp} + T_{wd})}{(T_m + T_{ps})T_rT_{wp}T_{ed}^2} &= 4a^2 + 6ab + b^2 + c^2 \\
 \frac{4.9348T_r(T_{wp} + T_{wd} - K_p(T_{wp} + T_{wd}) + T_m + T_{ps}) + 2.4674kT_r(T_{wp} + T_{wd}) + 2.1052T_{ed}^2K_p}{(T_m + T_{ps})T_rT_{wp}T_{ed}^2} &= -a(2a^2 + 8ab + 3b^2 + 3c^2) \quad (B29) \\
 \frac{9.8692T_r - 4.9346K_p(T_{wp} + T_{wd}) + 5.1942T_rK_p + 4.9348kT_r}{(T_m + T_{ps})T_rT_{wp}T_{ed}^2} &= 4a^2(ab + b^2 + c^2) \\
 \frac{5.194177K_p}{T_r(T_m + T_{ps})T_{wp}T_{ed}^2} &= 2a^3(-b^2 - c^2)
 \end{aligned}$$

The essential parameters of the plant under study are the time constants listed in Table B3. Poles of the closed loop transfer function are shown in Table B4.

Table B3. Barlovento hydropower plant time constants

T_{wp}	0.9927 s
T_{wd}	2.2525 s
T_{ed}	1.9500 s
$T_m + T_{ps}$	6.00 s
k	0

It is supposed that loads connected to the power plant are resistive, as it is usual in power plants connected to isolated systems (IEEE Power & Energy Society, 2014).

Figure B10. Root Locus Barlovento hydropower plant in isolated operation with FDRM criterion

III.2.5.4 Modal analysis

The controller parameters obtained using the previously described criteria are summarized in Table B4, along with the corresponding closed loop poles of the speed control loop. The participation factors of each variable have been determined by means of a modal analysis (Kundur, 1994). These columns express the module of the

participations factors of each variable in each oscillation mode in relative terms. In order to determine the variables prevailing in each mode, it has been used the rule developed in (Liu & Liu, 2007), assuming that the sum of the participation factor module of the predominant variables should be greater than 0.8. At the same time, it has been considered appropriate to compare the proposed criteria with a classic criterion (Paynter, 1955).

Table B4. PI parameters, closed-loop poles, participation factor modules (p.u.) of variables in response modes, corresponding to each proposed criteria.

Criteria	PI Parameters		Closed loop poles	Participation factor module (p.u.)					Response mode
	δ (p.u.)	T_r (s)		q_p	q_d	h_t	n	Z	
DCP	1.8169	2.9952	-0.6536±j1.0594	0.3338	0.1661	0.3967	0.0001	0.1033	A
			-0.2587±j0.1144	0.1699	0.3265	0.0402	0.0037	0.4596	B
			-0.34	0.0724	0.1184	0.0211	0.6428	0.1452	C
FDR	2.3618	8.0769	-0.6464±j0.9891	0.3128	0.1819	0.3914	0.0200	0.0939	A
			-0.4437±j0.3559	0.1854	0.2871	0.1432	0.1540	0.2304	B
			-0.0266	0.0283	0.0641	0.0001	0.1430	0.7646	C
FDRM	1.4552	3.2272	-0.6962±j1.1107	0.3572	0.1421	0.3763	0.0027	0.1216	A
			-0.2422±j0.2422	0.1539	0.3381	0.0611	0.0491	0.3977	B
			-0.2422	0.1112	0.2122	0.0192	0.3154	0.3421	C
Paynter	1.3522	16.226	-0.7757±j1.1334	0.3757	0.1161	0.3374	0.0318	0.1389	A
			-0.2655±j0.4676	0.1088	0.3328	0.1483	0.1547	0.2553	B
			-0.0192	0.0182	0.0412	0	0.2641	0.6765	C

In all cases the fifth-order system, shows two oscillatory modes and one exponential mode. In the first of them, A, clearly present in all settings, the predominant variables are q_p , q_d and h_t ; it is the elastic mode (Liu & Liu, 2007), on which any condition has been imposed. In the second one, B, it can be distinguished two different modal shapes; on the one hand, criteria DCP and FDRM present greater influence the variables q_d and z ; while on the other hand, in FDR and Paynter criteria there are no predominant variables. This behaviour may be related to the settling time control in DCP and FDRM criteria. Also, this similarity in the oscillation modes in pairs will be also observed in Figure B11 and Figure B14. Finally, in the oscillation mode C prevails in all cases the variables n and z , thus it is a mechanic-water mode.

III.2.5.5 Evaluation of the proposed tuning criteria

In order to evaluate and compare the different tuning criteria, some performances indices for governor control systems proposed in (IEEE Power & Energy Society, 2014) have been used. The numerical values of these indices corresponding to each tuning

criterion are obtained from the complete simulation model, including head losses, and given in Table B5.

Table B5. Performance indices for different tuning criteria for reference power plant.

Performance index		DCP	FDR	FDRM	Paynter	IEEE Recommendations	
						Typical ranges	Good performance
Gain (dB)	margin	3.8029	6.3540	4.2005	6.6702	2.0-20	3
Phase (dB)	margin	39.0357	88.3593	44.0564	104.9461	20-80	40
Mp		0.6484	0.4673	0.6842	0.4567	1-4	1.1-1.6
Settling time (s)		25.7094	152.9497	20.0814	201.1503	2-100	
Damping ratio		0.9146	0.780	0.707	0.494	0.25-1	0.6-1

Figure B11 shows the hydro power plant response due to a unit impulse, considering all the proposed tuning criteria and the classic Paynter criterion. It can be seen, as given in the previous table, that DCP and FDRM have much lower settling times than FDR and Paynter criteria, while there are not significant differences in the maximum peak values.

Figure B11. Hydro plant dynamic response due to a unit impulse using Paynter, DCP, FDR and FDRM Criteria.

III.2.6 Simulations and results

In most power systems, the main contribution to frequency regulation corresponds to thermal power plants. However, in the system studied here this service is uniquely provided by the PSHP which should compensate the fluctuations of wind and solar energy. Then, one of the main functions of PSHP is to maintain the system frequency within the power quality limits according to regulation (European Standards EN 50160, 2007). Two different limits are established for non-interconnected supply systems: $50 \text{ Hz} \pm 2\%$ for 95% and $50 \text{ Hz} \pm 15\%$ for 100% of a week.

Due to the long tail-race tunnel cavitation phenomena can appear downstream of the turbine. To avoid this harmful effect, the absolute pressure at that point should be greater than the vapor pressure (Warnick, 1984). In this case, this is equivalent to keep the relative pressure downstream of the turbine greater than -10 meters of water column.

In (Jones, et al., 2004) it is stated that to check the suitability of a controller adjustment it is sufficient to simulate a step, a ramp and a random signal. In this way all possible scenarios are considered.

In order to applying this methodology, three different events, related to wind and solar generation, have been proposed to be simulated and checked. The first one, analogously to the random signal, is taken from wind and solar power generation signals. The second one consists on a wind power output ramp. Both events are assumed as normal operating conditions. Finally, step signal is assumed as abnormal operation conditions; specifically, it consists on a sudden disconnection of a wind farm. Wind/Solar generation is introduced in the simulation model through the “Net Power Demand” block.

In all these cases, the participation of fossil thermal energy is zero.

III.2.6.1 Normal operating conditions

Wind and solar power fluctuations

Combinations of three different real scenarios in terms of real production of wind and photovoltaic solar energy have been considered (Wada & Yokoyama, 2012). Due to the unpredictability of these renewable energies, every possible combination of their production levels has been taken into account (9 different scenarios). These power output levels are shown, in per unit values, in Figure B12.

Figure B12. Wind and solar power output

As an example, Figure B13 shows the first 500 seconds of PSHP simulation in the case with high penetration of wind and solar energy. Table B6 summarizes for each

scenario, frequency medium square error, power medium square error, maximum positive and negative frequency deviation and minimum pressure downstream of the turbine for each tuning criteria.

Table B6. Response quality parameters due to wind and solar power fluctuations (Low, Medium and High)

Setting		Criteria	Quality Parameters				
Wind	Solar		$\sum \varepsilon_n^2 \times 10^{-5}$	$\sum \varepsilon_p^2 \times 10^{-5}$	desv _{n,max} ⁺ (%)	desv _{n,max} ⁻ (%)	$H_{t,min}$ (m)
L	L	Paynter	2.4371	0.2540	1.5609	-1.4760	8.8985
		DCP	0.7335	0.3694	0.7058	-0.8045	8.3211
		FDR	2.4999	0.2837	1.5537	-1.5259	8.9740
		FDRM	0.6144	0.3822	0.6885	-0.7370	8.1874
L	M	Paynter	2.5480	0.2617	1.6133	-1.5635	8.1186
		DCP	0.7379	0.3840	0.7716	-0.8293	7.5771
		FDR	2.6053	0.2929	1.5964	-1.6083	8.2429
		FDRM	0.6168	0.3985	0.7179	-0.7580	7.4338
L	H	Paynter	2.7569	0.2825	1.4438	-1.6785	7.4422
		DCP	0.7927	0.4224	0.7898	-0.8048	6.9604
		FDR	2.8171	0.3196	1.4631	-1.6009	7.5010
		FDRM	0.6613	0.4364	0.7585	-0.7417	6.7756
M	L	Paynter	6.9132	0.4830	2.0333 (*)	-2.0257 (*)	5.2115
		DCP	1.5629	0.6693	1.6520	-1.3103	3.5297
		FDR	6.8367	0.5588	2.0130	-2.0118 (*)	5.5169
		FDRM	1.2640	0.6706	1.5794	-1.3013	3.0821
M	M	Paynter	6.9758	0.5019	1.9717	-2.0755 (*)	4.5720
		DCP	1.5766	0.7064	1.5941	-1.2919	2.9031
		FDR	6.9182	0.5840	1.9520	-2.0243 (*)	4.8907
		FDRM	1.2734	0.7080	1.5552	-1.2907	2.4406
M	H	Paynter	7.1814	0.5340	2.1593 (*)	-2.1154 (*)	3.7422
		DCP	1.6349	0.7652	1.7867	-1.3873	1.8320
		FDR	7.1296	0.6281	2.3020 (*)	-2.1768 (*)	4.0772
		FDRM	1.3181	0.7654	1.6905	-1.3734	1.3531
H	L	Paynter	4.7002	0.8076	2.0094 (*)	-1.9522	3.8903
		DCP	1.8447	1.4403	1.7093	-1.6302	2.7923
		FDR	4.8006	0.9314	2.1303 (*)	-1.9885	4.5961
		FDRM	1.5763	1.4709	1.6177	-1.5761	2.1626
H	M	Paynter	4.7934	0.8463	2.1072 (*)	-1.9287	3.2578
		DCP	1.9219	1.5416	1.7339	-1.6948	2.0148
		FDR	4.9441	0.9839	2.2584 (*)	-2.0650 (*)	3.9907
		FDRM	1.6366	1.5700	1.6797	-1.6362	1.3475
H	H	Paynter	4.7541	0.8946	2.1369 (*)	-1.9436	2.6824
		DCP	2.0240	1.6742	1.6958	-1.7374	1.3574
		FDR	4.9887	1.0515	2.2853 (*)	-2.0678 (*)	3.4608
		FDRM	1.7169	1.6957	1.6010	-1.6740	0.6719

(*) marks the frequency deviations exceeding system requirements. Adjustments based on FDRM and DCP criteria do not fail in any of the cases provided. None of the cases compromises the security of the pipeline due to cavitation problems.

Figure B13. 500 seconds simulation of PSHP with high penetration of wind and solar energy (H-H)

Power wind ramp

An event usually considered in isolated systems with high penetration of intermittent energies (wind and solar), is produced by a substantial variation in wind power generation (Nicolet, et al., 2009). Here a linear increase in the wind power generated will be considered. Because of this increase in wind generation, the hydro power plant should reduce its production in order to maintain system frequency. Due to the proximity of the proposed wind farm (9 MW) to Garafia (1.6 MW) wind farm (see Figure B2), wind speed in both wind farms is assumed as equal. The simulated power variation is a 25% of the considered wind farm capacity (10.6 MW) in 60 seconds (0.053p.u./s). Simulations are shown in Figure B14. In Table B7 the response quality parameters are shown.

Figure B14. Hydro plant response due to a power ramp

Table B7. Response quality parameters due to a ramp in wind power production

Criteria	Quality Parameters			
	$\sum \varepsilon_n^2 \times 10^{-6}$	$\sum \varepsilon_p^2 \times 10^{-7}$	$\text{des}v_{n,\max}^+$	$T_{2\%}^n$ (s)
Paynter	34.97	6.33	1.39 %	150.22
DCP	5.00	3.71	0.53 %	27.66
FDR	32.47	7.31	1.49 %	99.64
FDRM	3.80	3.30	0.46 %	32.95

As stated in Table B7, adjustment with less error, frequency overshoot and settling time is FDRM criterion. Figure B14 shows, as previously explained that there are two types of responses, each one for each pair of tuning criteria.

III.2.6.2 Abnormal conditions

A sudden disconnection of the new wind farm (9 MW) is considered as an abnormal situation in the power plant operation. In this case, the hydro plant must increase its generated power in order to compensate for the generation loss in the system and recover the frequency. Figure B15 shows the hydro power plant response while its quality parameters are shown in Table B8.

Figure B15. Hydro plant response due to a power step

Table B8. Quality parameters due to a step in wind power production

Criteria	Quality Parameters			
	$\sum \varepsilon_n^2 \times 10^{-4}$	$\sum \varepsilon_p^2 \times 10^{-4}$	$\text{des}v_{n,\max}^-$	$T_{2\%}^n$ (s)
Paynter	12.32	5.00	-10.09%	177.63
DCP	9.62	6.84	-10.09 %	63.77
FDR	12.22	4.84	-10.07%	133.34
FDRM	11.12	7.74	-10.55 %	78.25

In this case, in which two pairs of results are also observed in settling time, both FDRM or DCP present a better performance than the other ones. Despite the fast closing movement in gate position, the safety of pipelines is not compromised due to cavitation phenomena.

Although frequency deviations are within the limits required in (European Standards EN 50160, 2007), a 10% frequency variation would be inadmissible. In order to correct this undesirable situation two actions have been included in the simulation model: a flywheel, so that T_m is increased in 50% and a load shedding scheme consisting in three load disconnection steps of 2.15, 4.23 and 2.55 MW which are shut down if the frequency is lower than 48.9, 48.8 and 48.5 Hz respectively. The load shedding scheme is taken from other load shedding schemes in similar islands in the Canary Archipelago. Figure B16 shows the new hydro power plant response while its quality parameters are shown in Table B9. In this case, maximum frequency drop is 3.01% and Paynter criterion is more competitive.

Figure B16. Hydro plant response due to a power step including an increased inertia ($T_m = 9$ s) and the load shedding scheme

Table B9. Quality parameters due to a step in wind power production step including an increased inertia ($T_m = 9$ s) and the load shedding scheme

Criteria	Quality Parameters			
	$\sum \varepsilon_n^2 \times 10^{-5}$	$\sum \varepsilon_p^2 \times 10^{-4}$	$\text{des}v_{n,\max}$	$T_{2\%}^n$ (s)
Paynter	2.96	3.24	-3.010%	26.37
DCP	4.28	3.52	-3.008 %	37.36
FDR	3.29	3.09	-3.003%	40.86
FDRM	3.56	3.38	-3.006 %	35.46

III.2.7 Conclusions

In this paper, a model of a hydropower plant with long tail-race tunnel connected to an isolated system with wind and solar energy generation is developed.

It has been considered as a case study La Palma island (Canary archipelago, Spain), where is planned to increase the penetration of renewable sources: wind, solar and pumped storage hydropower. In order to use realistic data in the case study, a pre-design of the pumped-storage hydropower plant has been done, taking into account existing energy expansion plans.

Due to the tail-race tunnel length, cavitation phenomena may appear in response to very fast maneuvers. Thus, it has been necessary to consider water and conduit elasticity in this component, where a continuous elasticity model has been applied. A reduced order model based on lumped parameters has been used for analysis purposes and subsequent development of recommendations for setting the speed controller.

A study in the frequency domain has been carried out, obtaining the transfer function of the control loop. Using the root locus technique, it has been derived a setting criterion for the PI controller. Some performance indices have been obtained and compared with those obtained with a classic setting and other criteria developed previously for similar cases. If FDR or Paynter tuning criteria are used, a slow mechanical mode appears in the response, giving rise to much larger settling times than with the other two criteria.

Several simulations have been performed considering realistic cases under normal and abnormal operating conditions, in different scenarios of intermittent (wind and solar) generation. Possible occurrence of cavitation in problematic conduit points has been checked. It has been found that the best performance in all cases is obtained with the proposed controller setting, FDRM.

As a general conclusion is worth noting the feasibility to operate the island power system without the thermal power plants, when there are sufficient solar and wind resources, supplying demand and maintaining the system frequency, without compromising the conduits in the PSHP by cavitation phenomena.

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III.2.8 Nomenclature

a	Pole parameter
a_d	Wave speed (m/s) in tail-race
A_t	Turbine parameter
b	Pole parameter
b_{ij}	Turbine linear coefficients (p.u.)
c_t	Turbine mechanical torque (p.u.)
c	Pole parameter
c_t^0	Initial turbine mechanical torque (p.u.)
D	Turbine parameter
D_d	Tail-race tunnel diameter (m)
$desv_{n,max}^-$	Maximum negative frequency deviation (%)
$desv_{n,max}^+$	Maximum positive frequency deviation (%)
D_p	Penstock diameter (m)
F_d	Tail-race tunnel section (m ²)
F_p	Penstock section (m ²)
g	Gravity acceleration (m ² /s)
G_C	Controller transfer function
G_{CL}	Closed loop transfer function
G_{OL}	Open loop transfer function
H	Net head (m.w.c.)
h	Net head (p.u.)
h^0	Initial net head (p.u.)
H_b	Base head (m)
h_c	Upper reservoir water level (p.u.)
h_d	Lower reservoir water level (p.u.)
h_p	Head upstream of the turbine (p.u.)
h_t	Head downstream of the turbine (p.u.)
$H_t(s)$	Head downstream of the turbine in frequency domain (p.u.)
$H_{t,min}$	Minimum high pressure downstream of the turbine (m.w.c.)
j	$\sqrt{-1}$
k	Load sensitivity
K_I	Integral gain in PI governor
K_P	Proportional gain in PI governor
L_d	Tail-race tunnel length (m)
L_p	Penstock length (m)
n	Frequency (p.u.)
$N(s)$	Frequency in frequency domain (p.u.)
n^0	Initial frequency (p.u.)
n_{ref}	Reference frequency (p.u.)
P	Power (MW)

p_d	Net demanded power (p.u.)
$P_d(s)$	Net demanded power in frequency domain (p.u.)
p_g	Generated electric power output (p.u.)
$P_g(s)$	Generated electric power output in frequency domain (p.u.)
p_g^0	Initial generated power (p.u.)
q	Flow through the turbine (p.u.)
Q_b	Base flow (m ³ /s)
q_d	Flow at the tail-race tunnel upstream end (p.u.)
$Q_d(s)$	Flow at the tail-race tunnel upstream end in frequency domain (p.u.)
q_d^0	Initial flow at the tail-race tunnel upstream end (p.u.)
q_{nl}	No-load flow (p.u.)
q_p	Flow at the penstock (p.u.)
$Q_p(s)$	Flow at the penstock in frequency domain (p.u.)
q_p^0	Initial flow at the penstock (p.u.)
$r_d/2$	Continuous head losses coefficient in tail-race tunnel (p.u.)
$r_p/2$	Continuous head losses coefficient in penstock (p.u.)
$T_{2\%}^n$	Frequency settling time (s)
T_{ed}	$=L_d/a_d$. Tail-race tunnel water elastic time (s)
T_m	Generator mechanical starting time (s)
T_{ps}	Power system starting time (s)
T_r	Dashpot time constant (s)
T_{wd}	Tail-race tunnel water starting time (s)
T_{wp}	Penstock water starting time (s)
v_d	Water velocity in tail-race tunnel (m/s)
v_p	Water velocity in penstock (m/s)
z	Wicket gate opening (p.u.)
$Z(s)$	Wicket gate opening in frequency domain (p.u.)
z^0	Initial wicket gate opening (p.u.)
β	$=8/\pi^2$. Correction coefficient
δ	Temporary speed droop
ζ	Damping ratio
λ_i	Closed transfer unction poles
σ	Permanent speed droop
$\overline{\sum \varepsilon_n^2}$	Frequency mean square error, MSE (p.u.)
$\overline{\sum \varepsilon_p^2}$	Power mean square error, MSE (p.u.)

III.3 Paper C: Frequency regulation of a hybrid wind–hydro power plant in an isolated power system

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Abstract

Currently, some small islands with high wind potential are trying to reduce the environmental and economic impact of fossil fuels using its renewable resources. Nevertheless, the characteristics of these renewable resources negatively affect the quality of the electrical energy causing frequency disturbances, especially in isolated systems. In this study, the combined contribution to frequency regulation of variable speed wind turbines (VSWT) and a pump storage hydropower plant (PSHP) is analyzed. Different control strategies, using the kinetic energy stored in the VSWT, are studied: inertial, proportional, and their combination. In general, the gains of the VSWT controller for interconnected systems proposed in the literature are not adequate for isolated systems. Therefore, a methodology to adjust the controllers, based on exhaustive searches are proposed for each of the control strategies. The control strategies and the methodology have been applied to a hybrid wind-hydro power plant committed in El Hierro island in the Canary archipelago. At present, in this isolated power system, frequency regulation is only provided by the PSHP and diesel generators. The improvements in the quality of frequency regulation including the VSWT contribution have been proven based on simulating different events related to wind speed, or variations in the demanded power.

Keywords: Wind-hydro systems; variable speed wind turbine; governor tuning; wind turbine frequency regulation; inertia emulation

III.3.1 Introduction

The increased use of intermittent renewable energy sources in most electric power systems have been documented, (Denholm, et al., 2010) (Papaefthymiou, et al., 2015). These increases constitute a good way to reduce polluting gases generated by fossil fuel combustion. However, this class of renewable energies involves inherent drawbacks, such as unpredictability (Albadi & El-Saadany, 2010) or demand independence (The Electric Power Research Institute, Inc, 2011). These characteristics of renewable sources negatively affect the quality of the supplied electrical energy causing frequency (Wang, et al., 2016) and power disturbances (Georgilakis, 2008).

According to Albadi and El-Saadany (Albadi & El-Saadany, 2010), the impact of renewable energies on power systems depends mainly on its penetration rate and the system inertia. For this reason, the negative effects of renewable energy sources are amplified in isolated systems. Nevertheless, in islands with wind potential, economic and environmental costs of fossil fuels can be reduced. Therefore, the reduced use of fossil fuels owing to the increasing use of renewable energies in small isolated systems has become the main focus of interest of numerous researchers during the past few years (Kaldellis & Kavadias, 2001) (Kaldellis, et al., 2001) (Merino, et al., 2012). For example, R. Kaneshiro (Kaneshiro, 2013) has analyzed how the wind ramps affect to the quality of supply in a Hawaiian power system considering different rates of renewable penetration, highlighting the importance of wind forecasting in the medium- and long-term in order to operate the system safely and efficiently. In (Hamsic, et al., 2006), the penetration of wind energy in Flores island has been shown to be limited because of low-frequency problems. According to (Delille, et al., 2012), the increased penetration of wind and solar energy in the power systems of the French islands of Martinique and Reunion have generated serious problems of frequency deviations, thereby establishing the load shedding operations as common operations for all these power systems. In fact, the French government—by ministerial order—has limited the penetration of renewable sources in power systems to 30%.

Different methods exist in the literature that mitigate these negative effects. In (Georgilakis, 2008), a penalty system has been introduced for generators that cause frequency disturbances. Energy storage can contribute to this aim. Others (Ibrahim, et al., 2008) (Zhao, et al., 2015) have carried out exhaustive reviews of available energy storage technologies in the last few years remarking, among others, the importance of pump storage hydropower plants (PSHP), flywheels, batteries, capacitors, or superconductors. Specifically, in the case of isolated systems, it has been shown that the long-term variability of renewable energy is well managed by combining wind and solar farms with PSHPs (Díaz-Gonzalez, et al., 2012) (Kapsali & Kaldellis, 2010) (Pérez-Díaz & Jiménez, 2016). However, in the short-term, PSHPs need complementary technologies capable of injecting or absorbing power over brief time periods that span a few seconds to avoid inadmissible frequency variations (Zhao, et al., 2015) (Brown, et al., 2008) (Makarov, et al., 2008). These contributions to frequency regulations can be provided by flywheels

(Lazarewicz & Ryan, 2010) (Sarasúa, José I., et al., 2016), variable-speed hydro-pump turbines (Martínez-Lucas, et al., 2017), and others.

Variable speed wind turbines (VSWT) can also provide frequency regulation to mitigate large frequency deviations after disturbances (Badihi, et al., 2015). Several approaches can be found in the literature on the contributions of frequency support to the regulation of wind turbines (Gonzalez-Longatt, 2012) (Chamorro, et al., 2013). In general, VSWT provide negligible inertia since the fast control of power electronic converters maintains a practically constant output power irrespective of changes in the frequency of the grid (Aziz, et al., 2017). However, it is possible to achieve short-term inertial responses from variable-speed wind turbines by modifying their control loops (Lalor, et al., 2005) (Mullane & O'Malley, 2005) (Morren, et al., 2006(a)) (Eriksson, et al., 2016). According to this idea, synthetic inertia of a VSWT is modelled in, highlighting the important improvement in the minimum frequency (NADIR). Different activation schemes for the synthetic inertia on VSWT based on full converters have been proposed in (Gonzalez-Longatt, 2015). The same authors have established the practical limits of synthetic inertial gains in the inertia controller used in full-converter VSWT generators in (Gonzalez-Longatt, et al., 2016).

Primary frequency regulation can also be provided by VSWT. The primary frequency response stabilizes the frequency at a new value by modifying the power generation proportionally to different frequency variations. Admittedly, a non-optimal working point can be reached in the response curve of torque and rotor speed of the turbine (de Almeida, et al., 2006) (Courtecuisse, et al., 2008). Furthermore, the impact of using doubly fed induction wind generators participating in primary frequency regulation has been evaluated in (de Almeida & Peças Lopes, 2007) (Ullah, et al., 2008) (Díaz-González, et al., 2015). Moreover, primary frequency regulation can be combined with inertia emulation (Morren, et al., 2006(b)) (Ramtharan, et al., 2007). In (Fu, et al., 2017), a control loop acting on the frequency deviation is added to the inertia emulation loop in order to enhance the inertia support from the wind turbine maintaining a permanent frequency error.

The main problem of the contribution of VSWT to the primary regulation is that VSWT do not operate at their optimum operational point. This non-optimal operation would reduce the generated energy to some extent, and inevitably leads to economic

losses (Singarao & Rao, 2016). To mitigate this drawback, Mauricio et al. (Mauricio, et al., 2009) have presented a new method to improve the use of variable-speed wind energy conversion systems by modifying the inertial control scheme through the addition of a proportional loop which weights the frequency deviation. Both classical and modified inertial control loops allow the release of the stored fraction of the kinetic energy in rotational masses to provide earlier frequency support, thereby taking advantage of the fast response capability of electronically controlled converters. This control strategy does not need to have a regulation reserve, and thus allows a better use of wind resources.

The aim of this study is to evaluate the VSWT contribution to frequency regulation in an isolated power system when it operates solely based on the use of wind and hydro resources. Different control strategies for the VSWT are analyzed: inertial, proportional, and their combination. Primary regulation is not considered adequate in avoiding the negative economic effects associated with VSWT. The VSWT controller gains that have been proposed in the literature have been previously employed in interconnected systems, but these settings may not be adequate for isolated systems. Therefore, new controller adjustments will be used herein for each control strategy based on an exhaustive search. Additionally, this study has also analyzed if it is necessary to modify the PSHP governor settings owing to the VSWT contribution to frequency regulation.

To achieve these objectives, a dynamic model has been developed. The construction of a realistic model that takes into account all the phenomena involved in system operations is essential in order to draw relevant conclusions (Mansoor, et al., 2000). The PSHP configuration includes a large penstock, thereby limiting the applicability of rigid-water column models, and making it necessary to consider elastic phenomena (Jiménez & Chaudhry, 1987). In order to model the VSWT properly, the VSWT speed governor, VSWT inertial control loop, VSWT blade pitch angle control, and VSWT aerodynamics, have been used.

Control strategies and adjustment methodology extracted from this study are applied to the El Hierro power system. El Hierro is an island in the Canary island archipelago. Historically, electric generation was based on diesel generators. The island aims to become entirely free from carbon dioxide emissions (Iglesias & Carballo, 2011). In order to contribute to the achievement of this objective, a power hybrid wind–pumped storage hydropower plant (W-PSHP) at a rated power of 22.8 MW was committed in June 2014

to minimize utilization of fossil fuels (Pezic & Cedrés, 2013). As a matter of fact, the electrical energy generated in 2015 by the W-PSHP in Gorona del Viento was 9 GWh, which corresponded to 22.5% of the total electrical energy demand in the island. During 2015, the maximum power demand was 7.7 MW. In fact, only just 1000 h of operation have been achieved since the onset of 100% renewable generation (Gorona del Viento, 2017). This underutilization of renewable resources may have been caused by inadmissible frequency deviations. Although the inertia and the regulation capacity of PSHP are insufficient to elicit adequate responses to the fluctuations in demand and wind generation, the regulation capacity of the VSWT is currently not used. It is expected that frequency deviations will be reduced owing to the contribution of VSWT to frequency regulation, thereby approaching the fulfilment of the objective of operating the island with 100% renewable energy.

The paper is organized as follows. In Section III.3.2, the W-PSHP dynamic model is presented. The VSWT control loops and the control strategy are described in Section III.3.3. The methodology used to adjust the VSWT control loop gains based on an exhaustive search is proposed in Section III.3.4. In Section III.3.5, some realistic events applied to El Hierro power system are proposed to simulate the W-PSHP dynamic response so as to evaluate the proposed methodology. Finally, Section III.3.6 outlines the main conclusions of this study.

III.3.2 Hybrid wind-hydro power plant simulation model description

A PSHP and a VSWT connected to an isolated system have been modelled in MATLAB with Simulink. Frequency regulation will be provided by the VSWT and the PSHP. Therefore, the simulation model includes the dynamic behavior of an isolated power system, a PSHP and a VSWT. PSHP will operate in generation mode during all simulations. The VSWT converter dynamics and the PSHP alternator are supposed to be very fast when compared with the other components of the model. Therefore, the PSHP alternator and the VSWT converter will be neglected, and the VSWT inertia is thus uncoupled from the electric system. Figure C1 shows the block diagram of the hybrid wind-hydro power plant and the power system.

Figure C1. Block diagram of the power system with a hybrid wind-hydro plant and the power system

III.3.2.1 Power system

As stated above, the PSHP is connected to an isolated system comprising intermittent energy sources and loads. Therefore, the frequency dynamics described by equation (C1) are the result of the imbalance between the sum of the hydroelectric p_h and wind converter powers p_{nc} and the power demand p_{dem} .

$$T_m \frac{dn}{dt} = \frac{1}{n} (p_h + p_{nc} - p_{dem}) - k \Delta n \quad (C1)$$

Inertial mechanical time refers only to PSHP. VSWT is supposed to be connected to the system through a frequency converter, and does not contribute to the system inertia. The parameter k includes the load frequency sensitivity. It is assumed that $k = 1$, which corresponds to static loads.

III.3.2.2 Pumped storage hydropower plant

A PSHP plant has been modelled with a long penstock in generation mode. Due to the length of the penstock, the elasticity of water and conduit is needed to be considered. All the variables, parameters, and coefficients used, are explained in the nomenclature section.

Penstock

Transient flow in conduits is described by the conservation of mass and momentum equations (C2) and (C3) (Chaudhry, 1987).

$$\frac{\partial H}{\partial t} + \frac{a_w^2}{gS} \frac{\partial Q_p}{\partial x} = 0 \quad (C2)$$

$$\frac{1}{gS} \frac{\partial Q_p}{\partial t} + \frac{\partial H}{\partial x} + f \frac{Q_p |Q_p|}{2gDS^2} = 0 \quad (C3)$$

To solve these equations, different approaches can be found in the specialised literature, such as the method of characteristics (Riasi & Tazraei, 2017), or the transfer function proposed in (IEEE Working Group, 1992). The lumped parameter approach (Souza Jr, et al., 1999) has been used in this study to solve equations (C2) and (C3).

This approach leads to a system of ordinary differential equations that can be represented as a series of consecutive, Γ -shaped elements where the conduit properties (inertia, elasticity, and friction) are proportionally assigned to the segment length L_e . The ‘configuration’ and ‘orientation’ of the Γ -shaped elements may vary according to the upstream and downstream boundary conditions of the pipe. Figure C2 shows the scheme of the penstock model. Equations (C4) and (C5) of the penstock dynamics are,

$$\frac{dh_i}{dt} = n_t \frac{T_w}{T_e^2} (q_{p,i} - q_{p,i+1}) \quad (C4)$$

$$\frac{dq_{p,i}}{dt} = \frac{n_t}{T_w} \left(h_i - h_{i+1} - \frac{r}{2n_t} q_{p,i} |q_{p,i}| \right) \quad (C5)$$

T_w represents the water starting time, as defined in expression (C6) (Fang, et al., 2008).

$$T_w = \frac{L}{gS} \frac{Q_b}{H_b} \quad (C6)$$

The number of segments n_t determines the order of the system.

Figure C2. Scheme of the penstock model.

Turbine

Equation (C7) expresses the relation between flow, head, and nozzle opening (IEEE Working Group, 1992), while equation (C8) expresses the generated power corresponding to ideal rated conditions in Pelton turbines where the absolute fluid speed is twice the runner peripheral speed (Martínez-Lucas, et al., 2015(a)). Pelton turbines are widely used in hydropower plants with high head available.

$$q = z\sqrt{h} \quad (C7)$$

$$p_h = qn(2\sqrt{h} - n) \quad (C8)$$

The modelled hydropower plant has more than one identical unit. These units are supposed to operate at the same time in an identical manner. Thus, a single equivalent turbine has been used instead in the remaining parts of this work.

III.3.2.3 Variable speed wind turbine model

Wind power model

The power extracted from the wind is modelled using the mathematical function in equation (C9) (Miller, et al., 2003) (Bhatt, et al., 2011).

$$P_{wind} = \frac{\rho}{2} A_r s_w^3 C_p(\lambda, \theta) \quad (C9)$$

where λ is the ratio of the rotor blade tip speed and the wind speed (C10), while θ is the blade pitch angle in degrees.

$$\lambda = \frac{\Omega R_b}{s_w} \quad (C10)$$

C_p is usually provided as a group of curves that relates C_p to λ and θ . Expression (C11) represents the curves used in this model (Bhatt, et al., 2011). The C_p curves for the modelled wind turbine are shown in Figure C3a. These curves are a good approximation for values of $2 < \lambda < 13$. C_p values corresponding to λ smaller than the previous range have been linearly interpolated between $C_p(\lambda=0)$ and $C_p(\lambda=2)$. However, λ values outside the previous range represent either very high or low wind speeds that are outside the continuous rating of the machine. These considerations are also outside the scope of this work.

$$C_p(\lambda, \theta) = \sum_{i=0}^4 \sum_{j=0}^4 \alpha_{i,j} \theta^i \lambda^j \quad (\text{C11})$$

The values of the coefficient α_{ij} are listed in Table C7 in Appendix A

Figure C3. (a) Wind power $C_p(\lambda, \theta)$ curves; (b) Comparison between C_p (red) and power (blue) responses resulting from the model (continuous lines) and response provided by the manufacturer (dashed line) (ENERCON GmbH, 2016)

In order to check the validity of the C_p curves expression (C11), real data from a manufacturer (ENERCON GmbH, 2016) have been used. As it can be seen in Figure C3b, both the C_p curve and the generated power curve obtained by the dynamic simulation model matched approximately those provided by the manufacturer.

Blade pitch angle control

Figure C4 shows the block diagram of the blade pitch angle control. This control is a combination of a traditional pitch angle control and pitch compensation. The traditional pitch angle control implements PI control that computes the difference between rotor and reference rotor speeds (Sun, et al., 2010). Furthermore, pitch angle control takes into account the compensation through a different PI control that computes the difference between mechanical wind power and maximum rated power for each wind speed (Ahmadyar & Verbic, 2015).

Figure C4. Block diagram of pitch control model

The reference speed ω_{ref} is usually 1.2 p.u. but it can be lower. Speed reference is incorporated in the model by using the quadratic expression which has been obtained by taking into account the operational curves provided by the manufacturers (ENERCON GmbH, 2016).

Mechanical model of rotor

The VSWT model includes the rotor inertial expression for the wind turbine rotor (C12) (Eriksson, et al., 2016). This expression computes the rotor speed variances owing to differences between the torque provided by the wind torque and the torque demanded by the power converter.

$$\frac{d\omega}{dt} = \frac{1}{2H_{wt}} \frac{1}{\omega} (p_w - p_{nc}) \quad (C12)$$

III.3.3 Proposed hybrid wind-hydro contribution to frequency regulation

In addition to the frequency regulation, usually provided by the hydroelectric power plant, the regulation capacity of the VSWT will be used. In this study, different VSWT control strategies are analysed in addition to hydropower frequency regulation. VSWT can contribute to frequency regulation through different control strategies: inertial, proportional, and their combination. In the following section, the PSHP governor and the VSWT control loops are described. Moreover, a wind rotor speed control is necessarily included to make the VSWT restore the reference rotor speed, otherwise the VSWT will be destabilized. Figure C5 shows the block diagram of the hybrid wind-hydro controllers.

Figure C5. Block diagram of the hybrid wind-hydro controllers

III.3.3.1 PSHP Governor

The proposed PSHP governor model, which is based on (Mansoor, et al., 2000), is formulated in (C13). The main function of this regulator is to control the unit speed through the feedback frequency error signal, modifying the turbine nozzles and regulating the water flow through the penstock. The error signal is processed by a conventional proportional-integral (PI) controller. The limits in the positions of the turbine nozzles and their rates of change are considered in the model by the use of a rate limiter and a saturator element.

$$\Delta z = \left[\frac{1}{\delta} + \frac{1}{\delta T_r} \int dt \right] (n_{ref} - n) \quad (C13)$$

III.3.3.2 VSWT inertial and proportional control loop

Synthetic inertia is defined in (Eriksson, et al., 2016) as ‘the response of a generating unit to frequency changes, and in particular, a power exchange which is proportional to RoCoF (Rate of Change of Frequency)’. Expression (C14) represents the inertial control loop.

$$\Delta p_{dn} = K_{dn} \frac{d}{dt} (n_{ref} - n) \quad (C14)$$

The same authors have also defined ‘fast frequency response’ as the controlled contribution of electrical power from a unit that quickly corrects frequency deviations (C15).

$$\Delta p_{pn} = K_{pn}(n_{ref} - n) \quad (C15)$$

Therefore, three control strategies can be defined. Inertial control strategy only takes the RoCoF as the control loop input. Proportional control strategy only takes the variation in frequency as the control loop input. Finally, inertial and proportional control strategy takes both variations as the control loop input.

These inertial and proportional control loops allow a fraction of the kinetic energy stored in rotational masses to be released in order to provide earlier frequency support, thereby taking advantage of the fast response capability associated with electronically controlled converters. These control strategies allows not have a regulation reserve so a better use of the wind resource is achieved.

Owing to the existence of a wind energy conversion system, the inertial and proportional control loops add a power signal Δp_n to the power reference output to be tracked by the converter (C16) (Mauricio, et al., 2009).

$$\Delta p_n = \Delta p_{dn} + \Delta p_{pn} \quad (C16)$$

K_{pn} weighs the frequency deviation, while K_{dn} is a constant weighing of the frequency variation rate. When inertial or proportional control is executed individually, the other controller is disabled by cancelling the corresponding gain listed in equations (C14) and (C15).

A methodology to adjust gain values is described in the following section. In practice, the value of K_{dn} is limited given its relationship with the inertial constant of the real wind turbine, H_{wt} (Gonzalez-Longatt, et al., 2016). This limitation has been used for its estimation.

III.3.3.3 VSWT rotor speed control

The speed control, which controls the rotational speed by regulating the electromagnetic torque, aims to recover the optimal speed once the frequency transient has subsided (Shang, et al., 2016). Rotational speed control is more convenient than pitch

control when the rotational speed is below the maximum value (Sun, et al., 2010). Therefore, a PI controller obtains a power reference, Δp_ω (C17), based on the difference between the rotational speed and the optimal rotational speed. The PI controller proposed in this study is based on (Mauricio, et al., 2009). The speed control must always be enabled, otherwise the VSWT will be destabilized.

$$\Delta p_\omega = \left[K_{p\omega} + K_{i\omega} \int dt \right] (\omega - \omega_{ref}) \quad (C17)$$

The total power supplied by the electronic converter (C18) will be the sum of the mechanical power initially produced by the wind and both of the power increments that have been previously described.

$$p_{nc} = p_{nc}^0 + \Delta p_n + \Delta p_\omega \quad (C18)$$

III.3.4 Controllers adjustment methodology

A methodology based on exhaustive searches is proposed for the adjustment of the PSHP and VSWT controller gains for each of the strategies described above. The benefits of the adjustments of the PSHP and VSWT controllers used together or individually were also analyzed. To achieve these strategies, two cases were considered: 1) known gains for the PSHP controller were assumed, and the gains of the VSWT controllers were then obtained, and 2) a search was conducted for all the controller gains. In order to obtain the PSHP governor gains and assess the contribution of the VSWT regulation, a strategy was considered in which VSWT did not provide frequency regulation, classified under ‘case A’.

Blade pitch angle variations are slow enough to be decoupled from the dynamic responses of other variables. In the literature, there is agreement on the value of these gains. Therefore, gains proposed in (Miller, et al., 2003) (Bhatt, et al., 2011) have been assumed. Blade pitch angle control parameters are summarized in Table C8 in Appendix A.

Taking into account the casuistry described previously, seven different cases for the exhaustive searches are distinguished. These cases are summarized in Table C1.

Table C1 Exhaustive summary of search cases

Strategy	Case	PSHP gains	adjustable	VSWT adjustable gains
Regulation is only provided by PSHP	A	δ, T_r		-
VSWT inertial control	B	-		K_{dn}, K_{pw}, K_{iw}
	C	δ, T_r		
VSWT proportional control	D	-		K_{pn}, K_{pw}, K_{iw}
	E	δ, T_r		
VSWT inertial and proportional control	F	-		$K_{dn}, K_{pn}, K_{pw}, K_{iw}$
	G	δ, T_r		

For cases B, D, and F, the PSHP governor gains obtained in case A were assumed. To obtain PSHP governor gains and VSWT controller gains for the cases described previously, several exhaustive searches had been carried out by varying the PSHP and VSWT controller gains when a 5% step increase in the load of the island had been simulated, according to the recommendation in (IEEE Power & Energy Society, 2014) for the speed governor of hydraulic turbines.

For each studied case, at least two different wind speeds should be considered for the exhaustive search representing high and low wind speeds, thus assessing the VSWT operating point influence on the adjustment of the controllers. Gains bounds are summarised in Table C2. It was assumed that one equivalent turbine and one VSWT were operating. It has been verified that gains outside of these bounds can de-stabilise the system.

Table C2. Gains bounds based on the exhaustive search conducted

	Minimum value	Maximum value
δ	0.5	5.0
T_r	0.5	5.0
K_{dn}	0.5	6.0
K_{pn}	0.5	6.0
K_{pw}	0.1	1.0
K_{iw}	0.005	0.010

NADIR, the settling power time, or settling frequency time, are technical indicators which are used to define the system's warranted frequency operating region from the unwarranted when an instant variance in the power demand takes place. These frequency response indicators can be used in any network to assess the frequency response owing to a loss of a generator (Seneviratne & Ozansoy, 2016). In this case, the settling frequency time (T_n) is defined as the time it takes for the frequency to lie within the normal limits established by the TSO for isolated systems (Red Electrica de España, 2012). The settling

power time (T_p) is defined as the time it takes for the power supplied by the VSWT and PSHP to be within $\pm 2\%$ of the power demand value.

It is difficult to find a group of controller gains that jointly provide the best values for these indicators. In the effort to achieve a compromising solution that improves these quality indicators, a coefficient has been proposed that favoured increased NADIR values, and which penalised increased values for both settling times. This coefficient is expressed in accordance to equation (C19).

$$\varphi = \frac{NADIR}{T_n \cdot T_p} \quad (C19)$$

Therefore, NADIR, frequency settling time, power settling time, and the coefficient φ , are used to characterise the quality of the system's response. Adjustment criterion is defined as that aimed to extract the VSWT and PSHP controller gains based on the exhaustive searches, thereby yielding the best value of the coefficient φ .

III.3.5 Simulations and results

Control strategies and adjustment methodology extracted from this study are applied to the El Hierro power system.

III.3.5.1 Case study: El Hierro power system

El Hierro is an island in the Canary island archipelago that was declared a biosphere reserve by UNESCO. The island aims to become 100% free from carbon dioxide emissions (Iglesias & Carballo, 2011). The electrical capacity of the island is 35.9 MW, contributed by diesel generators (13 MW), solar farms (0.03 MW), and a W-PSHP rated at a power of 22.8 MW. The PSHP generates 11.32 MW, and the five VSWT provide the remaining 11.48 MW (Gobierno de Canarias, 2015). The electrical energy generated in 2015 by the Gorona del Viento W-PSHP was 9 GWh. This corresponded to 22.5% of the total electrical energy demand of the island. The maximum peak demand in that year was 7.7 MW, while the minimum was approximately 4 MW (Red Electrica de España, 2016). Nowadays, only 1000 h of plant operation have been achieved since the onset of power generation using 100% renewable sources in June 2014 (Gorona del Viento, 2017). Currently, the VSWT are not assigned to contribute to frequency regulation. Therefore, as the PSHP inertia and regulation capacity are insufficient to respond to the power

demand and wind power fluctuations, a contribution from diesel generators is required to achieve frequency regulation. It is expected that the percentage of demand supplied by renewable resources will be increased. Thus, the number of hours of operation required to establish the island as self-sufficient based on the use of 100% renewable sources may be increased proportionally. In this context, it is assumed that the W-PSHP operates in isolation. Therefore, variations in power demand and wind power fluctuations are balanced by the VSWT itself and by the operation of the PSHP.

Data from the W-PSHP in Gorona del Viento used in the model have been obtained from (Platero, et al., 2014) (Carrillo, et al., 2013) (ENERCON GmbH, 2016). They are summarized in Table C3.

Table C3. Gorona del Viento W-PSHP ratings

PSHP generating unit	Rated power	2.830 MW
	Rated flow	0.5 m ³ /s
	Number of units	4
	Rated speed	1000 rpm
	Mechanical starting time (T_m)	6 s
	Gross head	670 m
PSHP penstock	Length	2577 m
	Diameter	1 m
	Darcy–Weisbach friction loss coefficient	0.015
	Wave speed (a_w)	1193 m/s
	Elastic time (T_e)	2.16 s
VSWT	Number of VSWT	5
	Model	ENERCON E-70
	Rated power	2.3 MW
	Blade radius	35.5 m
	Wind turbine inertia constant (H_{wt})	1.971 p.u.

III.3.5.2 Adjustment of control strategies

Prior to checking the adequacy of the proposed methodology, it has been proven that the VSWT controller gains proposed in (Mauricio, et al., 2009) for interconnected systems are not adequate for an isolated system, as shown in Figure C6, since isolated systems are more sensitive to power disturbances than interconnected systems.

Figure C6. System response owing to a 5% step in power demand assuming the inertial control gains proposed in (Mauricio, et al., 2009) for $w_s=10$ m/s

Table C4 list the results of the exhaustive searches and response indicators for all the cases proposed previously for representative wind speeds of 10 m/s and 20 m/s, when a 5% power demand step is imposed.

Table C4. Exhaustive search results

Case	w_s	Controllers gains						Frequency response indicators			
		PSHP		VSWT							
	(m/s)	δ	T_r	K_{dn}	K_{pn}	K_{pw}	K_{iw}	NADIR (Hz)	T_n (s)	T_p (s)	φ
A	10	0.70	2.00	-	-	-	-	49.08	21.95	47.93	0.047
	20	0.60	3.60	-	-	-	-	49.06	9.93	63.19	0.078
B	10	0.70	2.00	0.50	-	1.00	0.015	49.09	23.19	43.85	0.048
	20	0.60	3.60	0.50	-	0.10	0.025	49.08	11.34	53.34	0.081
C	10	0.50	1.90	1.50	-	0.10	0.030	49.31	25.26	34.93	0.056
	20	0.50	1.90	3.50	-	0.10	0.005	49.41	15.80	37.23	0.084
D	10	0.70	2.00	-	4.00	0.10	0.010	49.59	9.64	37.22	0.138
	20	0.60	3.60	-	4.00	0.80	0.010	49.56	16.38	36.46	0.083
E	10	3.50	0.30	-	5.00	0.10	0.005	49.62	8.51	19.23	0.303
	20	3.50	0.30	-	4.50	0.50	0.050	49.58	8.81	19.51	0.288
F	10	0.70	2.00	4.00	3.00	0.10	0.005	49.56	10.94	19.55	0.232
	20	0.60	3.60	4.50	1.50	0.10	0.010	49.43	14.84	20.90	0.159
G	10	1.50	0.50	4.50	5.00	0.10	0.015	49.68	8.20	12.17	0.498
	20	1.50	0.50	4.00	5.00	0.10	0.015	49.69	7.56	11.80	0.557

Case A, in which the VSWT does not provide frequency regulation, is similar to the strategy proposed in (Martínez-Lucas, et al., 2015(a)). It has been proven that the PSHP governor gains proposed by the authors, and the gains obtained in this study, match closely.

Figure C7 shows the comparison of the quality indicators between the seven proposed cases. It can be observed that the fast frequency response elicited by the proportional controller improves the NADIR value, thereby reaching an even better value when it acts synergistically with inertial control. In the same way, the power settling time is reduced. To reduce the frequency settling time, it is convenient that both controls act jointly. In contrast, if only the inertial control is effective, the frequency settling time is increased.

Figure C7. Evolution of response indicators for different cases.

Although the proposed criterion does not aim towards the improvement of any particular quality indicator, the three previously mentioned are improved. It is important to highlight the system's improvement by obtaining the set of gains jointly (PSHP + VSWT) rather than individually (VSWT), comparing elicited results from cases C, E, and G, compared to B, D, and F, respectively. Finally, the need to take into account the wind speed is verified since the latter determines the operating point of the VSWT, and therefore the operating point of the PSHP. Once the wind speed has been taken into account in the setting of the controllers, it will not significantly affect the quality of the power system.

III.3.5.3 Simulations results

To check the suitability of controller adjustments, Jones et al. (Jones, et al., 2004) affirmed that it is enough to simulate a step, a ramp, and a random signal. In accordance to this methodology, three different events related with renewable sources generation were simulated in (Martínez-Lucas, et al., 2016). Therefore, a load step, a wind-speed ramp (see Figure C8a) and a wind-speed fluctuation (see Figure C8b) have been simulated. Notwithstanding, unfortunately, these results cannot be compared at the present time with experimental data, it seems reasonable to expect a fairly good agreement, because a similar model has been used in (Mansoor, et al., 2000) for Dinorwig power plant, where the simulation results reproduce with enough accuracy field measurements.

Figure C8 (a) Wind speed ramp; (b) wind speed time series.

Cases from B to G have been compared with case A, and have been considered as the base case to highlight the variation of each parameter mentioned previously. For case A, simulations with variable wind speeds, and gains K_{pw} and K_{iw} have been extracted from (Mauricio, et al., 2009) and assigned to 1.5 and 0.15, respectively, since they could not be extracted from the exhaustive search.

Figure C9 and Figure C10 show the dynamic response comparison between the base case (case A) and the different cases of VSWT contributions to frequency regulation, when a 5% power demand step is imposed, considering constant wind speeds of 10 m/s and 20 m/s, respectively, and for the cases in which PSHP and VSWT controller gains have been obtained jointly.

Figure C9 Comparison of the dynamic response of the system between the base case and the case in which VSWT contributes to frequency regulation by combining the inertial and proportional control, and by considering a sudden power demand variation and a constant wind speed of $w_s=10$ m/s.

Figure C10 Comparison of the dynamic response of the system between the base case and the case in which the VSWT contributes to frequency regulation by combining the inertial and proportional control, and by considering a sudden power demand variation and a constant wind speed of $w_s=20$ m/s.

It can be verified that, regardless of the wind speed, the contribution of the VSWT to the frequency regulation is positive for the system, since it increases the value of the

NADIR reducing the frequency and power settling time. In addition, VSWT contribution moderates the PSHP mechanical equipment movements.

Additionally, Figure C11 also shows the dynamic response comparison between the base case (case A) and the different cases of VSWT contributions to frequency regulation, when a 5% power demand step is imposed, considering constant wind speed of 6 m/s and for the cases in which PSHP and VSWT controller gains have been obtained jointly. In this low wind speed regime, the blade pitch control does not act and the rotor speed variances are only controlled by changing generator torque. Despite the low power generated by the VSWT due to the low wind speed, the VSWT can still contribute to the frequency regulation by improving all the mentioned system quality indicators. However, as can be seen in the simulation, proportional control makes the rotor speed would take too long to recover its reference speed after the disturbance. Nevertheless, inertial control can improve the system dynamics without compromising the stability of VSWT.

Figure C11 Comparison of the dynamic response of the system between the base case and the case in which the VSWT contributes to frequency regulation by combining the inertial and proportional control, and by considering a sudden power demand variation and a constant wind speed of $w_s=6$ m/s.

Figure C12 shows the comparison of the dynamic responses of the system between the strategy in which VSWT did not contribute to the regulation, and the various other strategies of contribution, in instances when a linear wind speed variation takes place.

Figure C12 Comparison of the dynamic responses of the system between the base case and the cases in which the VSWT contributes to the regulation assuming different control strategies during a wind speed ramp.

Table C5 summarises for each strategy, medium frequency deviation calculated based on equation (C20), NADIR, maximum frequency peak, nozzle movements per second, and blade angle movements per second when a wind ramp is simulated.

$$MDF = \frac{\int_0^t |n - n_{ref}|}{t} \quad (C21)$$

Table C5. Simulations results with a ramp wind speed.

Case	MFD		NADIR		Max. Frequency peak		$\int \Delta z /t$		$\int \Delta \theta /t$	
	Hz	Δ over A	Hz	Δ over A	Hz	Δ over A	10-5 p.u./s	Δ over A	%/s	Δ over A
A	0.0195	Base	49.8719	Base	50.5947	Base	20.229	Base	0.1818	Base
B	0.0110	-43.59%	49.9997	0.26%	50.1329	-0.91%	10.171	-49.72%	0.1820	0.11%
C	0.0044	-77.44%	50.0000	0.26%	50.0350	-1.11%	9.189	-54.58%	0.1844	1.43%
D	0.0123	-36.92%	49.9778	0.21%	50.1683	-0.84%	11.690	-42.21%	0.1833	0.83%
E	0.0077	-60.51%	49.9814	0.22%	50.1354	-0.91%	14.581	-27.92%	0.1818	0.00%
F	0.0109	-44.10%	50.0000	0.26%	50.0648	-1.05%	10.052	-50.31%	0.1839	1.16%
G	0.0038	-80.51%	50.0000	0.26%	50.0297	-1.12%	10.105	-50.05%	0.1832	0.77%

As it is shown in Figure C12, when a wind speed ramp takes place, and frequency regulation is only provided by the PSHP (case A), the frequency attains values outside the limits established by the TSO ($50 \text{ Hz} \pm 0.15 \text{ Hz}$) (Red Electrica de España, 2012). In addition, the medium frequency deviation, NADIR, maximum frequency peak and nozzle

movement values are improved supposing a small increase in the movements of the VSWT blades.

The elicited results from the simulation of a wind speed fluctuation are summarized in Table C6, listing for each strategy the wind energy generated, medium frequency deviation, NADIR, maximum frequency peak, nozzle movements per second, and blade angle movements per second. Moreover, Figure C13 shows the frequency comparison between cases A, C, E and G. In addition, in Appendix B are shown the dynamic responses of the system in cases A, C E and G during the wind speed fluctuation.

Figure C13 Frequency comparison between cases A, C,E and G during a wind speed fluctuation

Table C6. Simulation results using variable wind speeds.

Case	Wind energy		MFD		NADIR		Maximum frequency peak		$\int \Delta z /t$		$\int \Delta \theta /t$	
	MWh	Δ over A	Hz	Δ over A	Hz	Δ over A	Hz	Δ over A	10-5 p.u./s	Δ over A	%s	Δ over A
A	2.6707	Base	0.0400	Base	49.677	Base	50.2781	Base	46.493	Base	0.0800	Base
B	2.6686	-0.08%	0.0119	-71.75%	49.715	0.08%	50.0967	-0.36%	11.340	-75.61%	0.0874	9.25%
C	2.6616	-0.34%	0.0030	-92.50%	49.927	0.50%	50.0521	-0.45%	6.7713	-85.44%	0.0854	6.75%
D	2.6697	-0.04%	0.0133	-66.75%	49.773	0.19%	50.1780	-0.20%	13.966	-69.96%	0.0856	7.00%
E	2.6701	-0.02%	0.0102	-74.50%	49.837	0.32%	50.1101	-0.33%	19.375	-58.33%	0.0858	7.25%
F	2.6644	-0.24%	0.0069	-82.75%	49.809	0.27%	50.0539	-0.45%	6.7310	-85.52%	0.0863	7.88%
G	2.6658	-0.18%	0.0031	-92.25%	49.908	0.46%	50.0288	-0.50%	8.3311	-82.08%	0.0874	9.25%

As it can be seen in Table C6, the VSWT contribution to frequency regulation implies a negligible loss of wind energy (less than 0.25%). Nevertheless, the medium frequency deviation, NADIR, maximum frequency peak and nozzle movement values are improved.

In both simulations assuming variances in wind speed, it is verified that for the proposed cases, the VSWT contribution to frequency regulation implies an improvement in the frequency indicators of the quality system. In regard to the moving parts, an important reduction in the movements of the turbine nozzle (more than 80%) takes place, thereby increasing its remaining lifetime. These reductions in movements suppose a small increase (less than 10%) in the movements of the VSWT blades. It can be observed that emulation of inertia improves the minimum and maximum frequency peaks as well as the medium frequency deviation in a better manner compared to proportional control. More importantly, these indicators reach an even better value when proportional control acts together with inertial control. The system improvement is also evaluated by obtaining the set of combined gains (PSHP + VSWT) instead of individually gains when wind variation is simulated comparing results from cases C, E, and G, to those from B, D, and F, respectively, in both simulations assuming variances in wind speed.

III.3.6 Conclusions

In this study, the capacity of a hybrid wind-hydro power plant to contribute to frequency regulation in an isolated system has been evaluated. To achieve this, a PSHP operating in generation mode, and a VSWT connected to an isolated system, have been modelled.

In addition to the frequency regulation, usually provided by the hydroelectric power plant, VSWTs can contribute to frequency regulation according to different proposed control strategies, including inertial, proportional, and their combination. To the author's knowledge, there is no control strategies for VSWTs to contribute to frequency regulation in conjunction with a hydroelectric plant in an isolated system proposed previously. It has been proven that VSWT controller gains recommended for interconnected systems are not adequate for isolated systems, since isolated systems are more sensitive to power disturbances than interconnected systems. Therefore, a methodology based on exhaustive searches for the set of gains for the PSHP and VSWT controllers has been conducted according to a proposed criterion. The convenience of adjusting jointly PSHP and VSWT regulators and taking into account the wind speed regime has been demonstrated.

Control strategies and adjustment methodology extracted from this study have been applied to the El Hierro power system, evaluating by simulating different events related

to fluctuations in wind speed, or variations in power demand. Considerable improvements concerning frequency deviations have been achieved. When a load step occurs, the fast frequency response provided by the proportional controller improves the NADIR value, thereby reaching an even better value when it acts synergistically with inertial control. Nevertheless, inertial control improves the minimum and maximum frequency peaks as well as the medium frequency deviation in a better manner compared to proportional control when wind speed variations are simulated. For both disturbances, better quality indicators were achieved even when proportional control acted together with the inertial control. In addition, wind energy lost owing to the VSWT contribution to frequency regulation could be considered negligible.

Moreover, a simulation with a very low wind speed has been carried out. In this speed regime, the blade pitch control does not act and the rotor speed variances are only controlled by changing generator torque. It has been proved that proportional control can destabilize the VSWT. Nevertheless, inertial control can improve the system dynamics without compromising the stability of VSWT.

Finally, it has been verified that the VSWT contribution to frequency regulation improves the lifetime of the hydro turbine governing system owing to the reduction of their movements at the expense of an admissible and increased workload imposed on the wind turbine blades.

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Conflicts of Interest: The authors declare no conflict of interest.

III.3.7 Nomenclature

A_r	[m ²]	Area swept by rotor blades
a_w	[m/s]	Wave speed
c_h	[p.u.]	Hydraulic turbine mechanical torque
C_p		VSWT power coefficient
D	[m]	Penstock diameter
f		Darcy Weisbach friction factor
g	[m/s ²]	Gravity acceleration
h	[p.u.]	Net head
H	[m]	Net head
h^0	[p.u.]	Initial net head
H_b	[m]	Base head
h_i	[p.u.]	Head at the end of the i-th Π element of the penstock
H_{wt}	[p.u.]	Wind turbine inertia constant
k	[p.u.]	Load – self regulation coefficient
K_{dn}		Constant which weights the frequency variation in the VSWT
K_{ic}		Integral gain in PI blade pitch angle compensation
K_{ip}		Integral gain in PI blade pitch angle control
$K_{i\omega}$		Integral gain in PI VSWT speed control
K_{pc}		Proportional gain in PI blade pitch angle compensation
K_{pn}		Constant which weights the frequency deviation in the VSWT
K_{pp}		Proportional gain in PI blade pitch angle control
$K_{p\omega}$		Proportional gain in PI VSWT speed control
L	[m]	Penstock length
L_e	[m]	Segment length
MFD		Mean frequency deviation
n	[p.u.]	Frequency
n^0	[p.u.]	Initial frequency
n_{ref}	[p.u.]	Reference frequency
n_t		Number of segments in which the penstock is divided
P_d^0	[MW]	Initial power demand
p_{dem}	[p.u.]	Power demand
p_{dn}	[p.u.]	Power reference provided by VSWT inertial control
p_h	[p.u.]	Power supplied by PSHP
P_h^0	[MW]	Initial power supplied by PSHP
p_n	[p.u.]	Power reference provided by VSWT proportional and inertial control
p_{nc}	[p.u.]	Power supplied by VSWT converter
p_{nc}^0	[p.u.]	Initial power supplied by VSWT converter
P_{nc}^0	[MW]	Initial power supplied by VSWT converter
p_{pn}	[p.u.]	Power reference provided by VSWT proportional control
p_{wind}	[p.u.]	Wind mechanical power
p_{ω}	[p.u.]	Power reference provided by VSWT speed control
q	[p.u.]	Flow through the turbine
Q_b	[m ³ /s]	Base flow
Q_p	[m ³ /s]	Flow at the penstock
q_p	[p.u.]	Flow at the penstock
$q_{p,i}$	[p.u.]	Flow at the end of the i-th Π element of the penstock
q_p^0	[p.u.]	Initial flow at the penstock
$r/2$	[p.u.]	Continuous head losses coefficient in the penstock
R_b	[m]	VSWT radius
S	[m ²]	Penstock section

s_w	[m/s]	Wind speed
t	[s]	Time
T_e	[s]	Water elastic time (L/a_w)
T_l		$=T_e^2/T_w$
T_m	[s]	Mechanical starting time
T_n	[s]	Frequency settling time
T_p	[s]	Power settling time
T_r	[s]	Hydro governor dashpot time constant
T_s	[s]	Time constant in servo motor transfer function
T_w	[s]	Penstock water starting time
x	[m]	axial distance along the streamline
z	[p.u.]	Nozzle opening
z^0	[p.u.]	Initial nozzle opening
α_{ij}		C_p curves coefficients
δ		Hydro governor temporary speed droop
θ	[°]	VSWT blade pitch angle
θ^0	[°]	VSWT initial blade pitch angle
θ_{max}	[°]	VSWT maximum blade pitch angle
λ		Ratio of the rotor blade tip speed and the wind speed
ρ	[kg/m ³]	Air density: 1.225 kg/m ³
φ		Coefficient proposed
ω	[p.u.]	VSWT rotational rotor speed
Ω	[rad/s]	VSWT rotational rotor speed
ω^0	[p.u.]	Initial VSWT rotational rotor speed
ω_{ref}	[p.u.]	Reference VSWT rotational rotor speed

III.3.8 Appendix A

Table C7. C_p coefficients α_{ij}

α_{00}	$-4.1909 \cdot 10^{-1}$	α_{01}	$2.1808 \cdot 10^{-1}$	α_{02}	$-1.2406 \cdot 10^{-2}$	α_{03}	$-1.3365 \cdot 10^{-4}$	α_{04}	$1.1524 \cdot 10^{-5}$
α_{10}	$-6.7606 \cdot 10^{-2}$	α_{11}	$6.0405 \cdot 10^{-2}$	α_{12}	$-1.3934 \cdot 10^{-2}$	α_{13}	$1.0683 \cdot 10^{-3}$	α_{14}	$-2.3895 \cdot 10^{-5}$
α_{20}	$1.5727 \cdot 10^{-2}$	α_{21}	$-1.0996 \cdot 10^{-2}$	α_{22}	$2.1495 \cdot 10^{-3}$	α_{23}	$-1.4855 \cdot 10^{-4}$	α_{24}	$2.7937 \cdot 10^{-6}$
α_{30}	$-8.6018 \cdot 10^{-4}$	α_{31}	$5.7051 \cdot 10^{-4}$	α_{32}	$-1.0479 \cdot 10^{-4}$	α_{33}	$5.9924 \cdot 10^{-6}$	α_{34}	$-8.9194 \cdot 10^{-8}$
α_{40}	$1.4787 \cdot 10^{-5}$	α_{41}	$-9.4839 \cdot 10^{-6}$	α_{42}	$1.6167 \cdot 10^{-6}$	α_{43}	$-7.1535 \cdot 10^{-8}$	α_{44}	$4.9686 \cdot 10^{-10}$

Table C8. Blade pitch angle control parameters

K_{pc}	3	K_{pp}	150	θ_{max}	27
K_{ic}	30	K_{ip}	25	T_s	0.1

III.3.9 Appendix B

Figure C14 Dynamic responses of the system in case A during a wind speed fluctuation

Figure C15 Dynamic responses of the system in case C during a wind speed fluctuation

Figure C16. Dynamic responses of the system in case E during a wind speed fluctuation

Figure C17. Dynamic responses of the system in case G during a wind speed fluctuation

III.4 Paper D: Eigen Analysis of Wind–Hydro Joint Frequency Regulation in an Isolated Power System

Guillermo Martínez-Lucas, José Ignacio Sarasúa, and José Ángel Sánchez-Fernández

Abstract

The wind energy penetration rate is being increased in majority of European countries. However, a high penetration rate could endanger the stability of power systems, particularly in small islands. Hydropower plays an important role in the regulation and control of isolated power systems with renewable sources, but it may not be able to maintain the frequency within grid requirements. This is the case of El Hierro power system (Canary archipelago), where a hybrid wind–pumped storage hydropower plant (PSHP) was committed to reduce the use of fossil fuels. Currently, frequency regulation is only provided by the PSHP and diesel generators. Therefore, it is proposed that variable-speed wind turbines (VSWTs) contribute to frequency regulation, thereby minimizing the need for fossil fuels. This study aims to conduct an analysis on the effect of the VSWT contribution to frequency regulation in the power system of El Hierro. It is based on classical control tools from a linearized mathematical model considering different VSWT regulation strategies. The eigenvalues, damping ratio, and participation factors of the state variables have been obtained. The more significant oscillation modes in the dynamic response of the system have been identified. According to this modal analysis, a methodology for the adjustment of the PSHP and VSWT controller gains is proposed. An improvement in the quality of frequency regulation while maintaining the El Hierro system frequency within grid requirements has been proved based on simulating different events related to wind speed or variations in the power demand, using a nonlinear model of the combined wind–hydro power plant.

Keywords

Hybrid wind–hydro power plant, turbine governor, variable-speed wind turbine, synthetic inertia, modal analysis, eigenvalues

III.4.1 Introduction

Wind-based generation systems have become sustainable and environmentally friendly options to supply power in isolated or off grid locations (Singh, et al., 2016). In

islands with isolated power systems, the development of renewable energies is not only linked to the environmental problems of fossil fuels. The costs of transporting these fuels to the places of consumption are higher than in continental systems. Therefore, their replacement by renewable resources can have a very positive economic impact (Caralis & Zervos, 2007). Some examples of high renewable potential islands are the Aegean Islands (Kaldellis, et al., 2001), the archipelago of the Azores (Vasconcelos, et al., 2015), and Canary Islands (Bueno & Carta, 2006) in Europe, and The Yong Shu Island in South China Sea (Ye, et al., 2017).

The power system frequency regulation impact of renewable energy sources depends mainly on its penetration rate and the system inertia (Albadi & El-Saadany, 2010). Therefore, the negative effects associated with renewable energy sources, which are amplified in isolated systems may cause inadmissible frequency deviations. Nevertheless, in islands with wind potential, the increasing use of renewable energies has become the focus of interest of numerous researchers during the past few years (Iglesias & Carballo, 2011) (Merino, et al., 2012).

The vast majority of studies agree that the introduction of storage systems is the most effective way of significantly increasing wind penetration levels in power systems (Ibrahim, et al., 2008) (Zhao, et al., 2015). Focusing on the case of isolated systems, (Kapsali & Kaldellis, 2010) (Díaz-Gonzalez, et al., 2012) (Pérez-Díaz & Jiménez, 2016) have shown that the long-term variability in renewable energy can be managed well by combining wind and solar farms with pumped storage hydropower plants (PSHPs), which are able to compensate uncertainty in intermittent renewable resources. However, (Brown, et al., 2008) (Makarov, et al., 2008) (Zhao, et al., 2015) proved that PSHPs need complementary technologies in the short term (owing to its slowness caused by the water inertia), which are capable of injecting or absorbing power over brief periods that span a few seconds to avoid inadmissible frequency variations.

These rapid contributions to frequency regulations can be provided by variable-speed wind turbines (VSWTs) (Badihi, et al., 2015). Different approaches can be found in the technical literature on the contributions of VSWTs to support frequency regulation (Gonzalez-Longatt, 2012) (Chamorro, et al., 2013). In general, VSWTs –Type III and IV– provide negligible inertia because the rapid control of power electronic converters maintains a practically constant output power irrespective of changes in the frequency of

the grid (Aziz, et al., 2017). However, it is possible to achieve short-term inertial responses from VSWTs by modifying their control loops (Lalor, et al., 2005) (Mullane & O'Malley, 2005) (Morren, et al., 2006(a)) (Eriksson, et al., 2016). According to this idea, Renuka and Reji modelled a synthetic inertia of VSWTs in (Renuka & Reji, 2015), underlining the important improvement in the minimum frequency peak (nadir). Prof. Gonzalez-Longat proposed different activation schemes for the synthetic inertia on VSWTs based on full converters in (Gonzalez-Longatt, 2015) and established practical limits for the gain of synthetic inertia control loop used in full-converter VSWT generators in (Gonzalez-Longatt, et al., 2016).

Primary frequency regulation can also be provided by VSWTs. Certainly, a nonoptimal operation point is reached in the VSWT power curve (de Almeida, et al., 2006) (Courtecuisse, et al., 2008), thus causing a loss in the wind resource harvesting and, as a consequence, incomings reduction. To mitigate this weakness, Mauricio et al. (Mauricio, et al., 2009) presented a new method for improving the use of variable-speed wind energy conversion systems by modifying the inertial control scheme through the addition of a proportional loop that weights the frequency deviation. The inertial control loop and inertial and proportional control loop proposed allow the release of the stored fraction of kinetic energy in rotational masses to provide earlier frequency support, thus taking advantage of the rapid response capability of electronic power converters. Both control strategies do not need to have a regulation reserve, allowing a better use of wind resources. According to these strategies, the authors in (Martínez-Lucas, et al., 2018) analysed the combined contribution to frequency regulation of a wind-hydro hybrid power plant equipped with a PSHP and VSWT in the El Hierro isolated system with 100% renewable generation, proposing a methodology based on exhaustive searches to adjust the controllers for each of the control strategies, obtaining successful results. The evaluation of the results obtained only by simulations should be completed with an analytical study of the dynamic model to analyse the intervention of the new control strategies in the system response. This analytical study is the main contribution of the present paper.

El Hierro is an island in the Canary archipelago which aims to become 100% free from carbon dioxide emissions (Iglesias & Carballo, 2011). To achieve this objective, a power hybrid wind-PSHP (W-PSHP) was committed in June 2014 to minimize the

utilization of fossil fuels (Pezic & Cedrés, 2013). However, currently, VSWTs are not aimed at providing frequency regulation, underutilizing the island wind potential.

Different modern studies analyse the dynamics of small disturbances using classic control techniques, such as root locus plot, having been successfully applied to obtain recommendations for proportional-integral (PI) derivative speed governor tuning (Hušek, 2014) (Sarasúa, et al., 2014). A procedure based on mathematical models of the controlled system is given in for designing speed and active power controllers for hydro turbine units obtaining the controller parameters from closed-loop poles. An improvement in the system frequency owing to VSWTs equipped with adequately controlled doubly fed induction machines is shown in (Fernández, et al., 2007) through an eigenvalue analysis. In (Amjady & Reza Ansari, 2008), the authors analysed different aspects of small disturbance voltage stability from eigenvalues position, studying the influence between the dynamic characteristics of the system such as those of generators, controllers, and loads. Different practical tuning criteria for the governor of hydropower plants equipped with long conduits are proposed in (Martínez-Lucas, et al., 2015(a)) (Sarasúa, et al., 2015) (Martínez-Lucas, et al., 2016) by using the pole placement method. In (Silva, et al., 2017), the authors presented a case study illustrating the effects of pressure pulsations due to vortex rope precession on the draft tube of Francis turbines through a modal analysis combined with frequency-domain and time-domain simulations.

The aim of this study is to analyse the effect of the VSWT contribution to frequency regulation in the isolated power system of El Hierro Island with classical control tools. The study of a linearized model is carried out for this hybrid wind–hydro power plant for each of the strategies described above (inertial, proportional, and their combination) by obtaining the eigenvalues, damping ratios, and participation factors of the state variables, identifying from the modal analysis the oscillation modes that interfere with the dynamic behaviour of the system. The influence of the PSHP and VSWT controller gains in varying the participation of the state variables in the oscillation modes is analysed. According to the study of the damping ratio and the oscillation modes, a methodology for the adjustment of the PSHP and VSWT controller gains based on the eigen analysis is proposed. The modal analysis and the proposed adjustment of the PSHP and VSWT controller gains for each control strategy have been verified by realistic simulations carried out using the completely nonlinear model.

This paper is organized as follows. In Section III.4.2, the hybrid W–PSHP and El Hierro power system are described. The W–PSHP nonlinear dynamic model is presented in Section III.4.3. Section III.4.4 describes the simplifications assumed for the modal analysis and the model linearization. The developed modal analysis, proposing a controller gains adjustment method, is presented in Section III.4.5. In Section III.4.6, some realistic events simulated to support the modal analysis and the controller gains adjustment method are presented. Finally, the main conclusions of this study are outlined.

III.4.2 Hybrid wind–hydro power plant and power system description

El Hierro is an island belonging to the Canary Islands archipelago, which was declared as a biosphere reserve by UNESCO. The island aims to become 100% free of greenhouse gas emissions (Iglesias & Carballo, 2011). The electrical capacity of the island is 37.8 MW, mainly distributed by diesel generators and a W–PSHP of 22.8 MW. The PSHP has 11.32 MW capacity and the five VSWTs ENERCON E-70 (ENERCON GmbH, 2016) provide the remaining power (Gobierno de Canarias, 2016). The maximum peak demand in that year was 7.7 MW, whereas the minimum was approximately 4 MW (Red Electrica de España, 2017). The VSWTs are not assigned to frequency regulation; therefore, as PSHP inertia and regulation capacity are insufficient to absorb power demand and wind power fluctuations, the contribution of diesel generators is required for frequency regulation. It is expected that the percentage of demand supplied by renewable resources will be increased. In this context, it is assumed that the W–PSHP operates in isolation. The Gorona del Viento W–PSHP data used in the model and the layout shown in Figure D1 have been extracted from (Platero, et al., 2014) (Carrillo, et al., 2013) (ENERCON GmbH, 2016).

Figure D1. El Hierro combined wind and PSHP layout.

III.4.3 Hybrid wind–hydro power plant model description

A PSHP and VSWT connected to an isolated system have been modelled in MATLAB Simulink. In addition to the PSHP frequency regulation, the possible contribution of the VSWT to frequency regulation will be analysed. Therefore, the simulation model will include the dynamic behaviour of the PSHP and VSWT. The PSHP will operate in generating mode during all simulations. Because the PSHP electromagnetic transients and VSWT converter dynamics are supposed to be very rapid compared with the other components of the model, both will be neglected. Therefore, the VSWT inertia is thus uncoupled from the electric system. Figure D2 shows the block diagram of the hybrid wind–hydro power plant and the power system.

Figure D2. Block diagram of hybrid wind–hydro power plant and power system.

III.4.3.1 Power system model description

As stated above, the PSHP is connected to an isolated system comprising intermittent energy sources and loads. Thus, the frequency dynamics described by equation (D1) are the result of the imbalance between the sum of the hydroelectric p_h and wind converter generated power p_{nc} and the power demanded by the loads p_{dem} (Mansoor, et al., 2000).

$$T_m \frac{dn}{dt} = \frac{1}{n} (p_h + p_{nc} - p_{dem}) - k \Delta n \quad (D1)$$

Inertial mechanical time refers only to PSHP. VSWTs are supposed to be connected to the system through a frequency converter, and do not contribute to the system inertia. The parameter k includes the load frequency sensitivity and it is assumed that $k = 1$, which corresponds to a static load.

III.4.3.2 PSHP model description

Penstock

The transient flow in conduits is described by expressions of conservation of mass and momentum (Chaudhry, 1987). Because of the penstock length, the water and pipe material elasticity cannot be neglected (Martínez-Lucas, et al., 2015(a)) and different approaches can be found in specialised literature. In recent years, some authors (Nicolet, et al., 2007) (Platero, et al., 2014) had obtained good results with their hydro power plant models using a lumped parameter approach.

This approach, which has been used in this study, leads to a system of ordinary differential equations that can be represented as a series of consecutive Γ -shaped elements, where the conduit properties (inertia, elasticity, and friction) are proportionally assigned to the segment length. The ‘orientation’ and ‘configuration’ of the Γ -shaped elements may vary according to the upstream and downstream boundary conditions of the pipe. Equations (D2) and (D3) of the penstock dynamics are

$$\frac{dh_i}{dt} = n_t \frac{T_w}{T_e^2} (q_{p,i} - q_{p,i+1}) \quad (D2)$$

$$\frac{dq_{p,i}}{dt} = \frac{n_t}{T_w} \left(h_i - h_{i+1} - \frac{r}{2n_t} q_{p,i} |q_{p,i}| \right) \quad (D3)$$

The number of segments n_t determines the order of the system. For this PSHP, authors in (Martínez-Lucas, et al., 2015(a)) demonstrated that simulations assuming a lumped parameter approach with 10 segments match significantly with simulations provided by the transfer function proposed in (IEEE Working Group, 1992).

Turbine

Turbine is modelled considering the relation between the flow, head, and nozzle opening (IEEE Working Group, 1992). The assumed generated torque corresponds to ideal conditions in Pelton turbines, where the absolute fluid speed is twice the runner

peripheral speed for rated conditions (Martínez-Lucas, et al., 2015(a)). The modelled hydropower plant has more than one identical unit; each unit is supposed to operate in an identical manner at the same time. Therefore, a single equivalent turbine has been considered in the remaining parts of this study.

PSHP governor

The proposed PSHP governor model, which is based on (Mansoor, et al., 2000), is formulated in equation (D4). The main function of this governor is to control the unit speed by monitoring the frequency error signal, modifying the turbine nozzles, and regulating the water flow through the penstock. The error signal is processed by a conventional PI controller. The limits in the positions of the turbine nozzles and their rates of change are considered in the model using a rate limiter and a saturation element.

$$\Delta z = \left[\frac{1}{\delta} + \frac{1}{\delta T_r} \int dt \right] (n_{ref} - n) \quad (D4)$$

III.4.3.3 VSWT model description

Wind power model

The power extracted from the wind is modelled using the mathematical function in equation (D5) (Miller, et al., 2003) (Bhatt, et al., 2011).

$$P_{wind} = \frac{\rho}{2} A_r s_w^3 C_p(\lambda, \theta) \quad (D5)$$

The power coefficient C_p is a fourth order function of the turbine tip speed ratio λ and the pitch angle β (Bhatt, et al., 2011).

Blade pitch angle control

Figure D3 shows the block diagram of the blade pitch angle control. This control is a combination of a conventional pitch angle control and pitch compensation. The conventional pitch angle control implements a PI control that computes the difference between rotor and reference rotor speeds (Sun, et al., 2010). Furthermore, the pitch angle control considers the compensation through a different PI control that computes the difference between the mechanical wind power and maximum rated power for each wind speed (Ahmadyar & Verbic, 2015).

It is expected that blade movements were smoothed if pitch control is improved considering advanced techniques (Duong, et al., 2014) (Yin, et al., 2015) (Yin, et al., 2014). However, the simplest controller was considered to make conclusions more general. Blade pitch angle variations are slow enough to be decoupled from the dynamic responses of other variables. In the literature, there is agreement on the value of these gains. Therefore, gains proposed in (Miller, et al., 2003) (Bhatt, et al., 2011) have been assumed. Blade pitch angle control parameters are listed in

Figure D3. Block diagram of pitch control model.

Table D1. VSWT pitch control parameters

K_{pc}	3	K_{pp}	150	β_{max}	27	K_{pw}	0.10
K_{ic}	30	K_{ip}	25	T_s	0.1	K_{io}	0.010

The reference speed ω_{ref} is usually 1.2 p.u. but it can be lower. Speed reference is incorporated in the model by using a quadratic expression (Miller, et al., 2003), which has been obtained by considering the operational curves provided by the manufacturer (ENERCON GmbH, 2016).

Mechanical model of rotor

The reduced order two-mass shaft model is the most appropriate for transient stability analysis (Honrubia-Escribano, et al., 2018), however some manufacturers recommend the use of the simple one-mass shaft model in cases where the power converter decouples the generator from the grid (Nanou, et al., 2011). The VSWT model includes the rotor inertial equation for the wind turbine rotor (equation (D6)) (Miller, et al., 2003).

$$\frac{d\omega}{dt} = \frac{1}{2H_{wt}} \frac{1}{\omega} (p_w - p_{nc}) \quad (D6)$$

VSWT inertial and proportional control loops

The regulating capacity of the VSWT will be used. In this study, different VSWT control strategies proposed in (Martínez-Lucas, et al., 2018) (inertial, proportional, and their combination) are analysed. Owing to the existence of the wind energy conversion system, the inertial and proportional control loops add a power signal Δp_n to the power reference output to be tracked by the converter (D7) (Mauricio, et al., 2009).

$$\Delta p_{dn} = K_{dn} \frac{d}{dt} (n_{ref} - n) \quad (D7)$$

K_{dn} weights the RoCoF, while K_{pn} is a weighting constant of the frequency deviation. When inertial or proportional control is executed individually, the other controller is disabled by cancelling the corresponding gains from equations (D7). A methodology to adjust gain values will be described in the following section.

VSWT rotor speed control

Because of VSWT contribution to frequency regulation through the inertial and proportional control loops, a wind turbine rotor speed control is required. This last control loop restores the VSWT rotor optimal speed after a frequency disturbance; otherwise, the VSWT will be destabilized.

This speed control, which controls the rotational speed by regulating the electromagnetic torque, aims to recover the optimal speed once the frequency transient has subsided (Shang, et al., 2016). Actually, when the wind speed is very low, the rotor speed is only controlled by changing the generator torque while the blade pitch is constant. Authors are aware of the existence of advanced maximum power point tracking controllers based on modern control techniques (Yin, et al., 2015). However, it was considered the simplest controller to make the conclusions more general. Therefore, a PI controller obtains a power reference, Δp_ω (equation (D8)), based on the difference between the rotational speed and the optimal rotational speed (Mauricio, et al., 2009).

$$\Delta p_\omega = \left[K_{p\omega} + K_{i\omega} \int dt \right] (\omega - \omega_{ref}) \quad (D8)$$

The total power supplied by the electronic converter (equation (D9)) will be the sum of the mechanical power initially produced by the wind and both power increments that have been previously described. As the converter internal dynamics is much faster than

the processes studied in this paper, the converter action is supposed to be instantaneous; the power electronic controller is assumed to work ideally.

$$p_{nc} = p_{nc}^0 + \Delta p_n + \Delta p_\omega \quad (\text{D9})$$

III.4.4 Linearized reduced order model

For control design purposes, a linearized model for small perturbation analysis in the neighbourhood of an initial equilibrium operating point is usually employed. However, considering that a linearized model is not enough to perform a systematic analysis, the previously described model will be simplified because some of the phenomena included are negligible when small disturbances occur. The assumed simplifications are described in the following sections.

III.4.4.1 Reduced order model

One-segment lumped parameter approach

In (Martínez-Lucas, et al., 2015(a)), the authors verified that the simplest one Π -shaped segment model having one series branch and two shunt branches would be sufficiently accurate to consider penstock elasticity effects. Therefore, for analytic purposes, the penstock is modelled following this recommendation obtaining a second-order model, whose state variables are $\{\Delta q_p, \Delta h\}$.

VSWT model simplification

Assuming small perturbations in the neighbourhood of an initial equilibrium operating point and a short-term framework, the mechanical power from the wind can be considered constant (Mauricio, et al., 2009) (Papangelis & Vournas, 2014). Furthermore, because of the slowness of blade pitch movements, these ones have been neglected and the pitch angle position has been considered static for analytic purposes.

III.4.4.2 Linearization

Some of the expressions that model the system described previously are composed of nonlinear terms and are not suitable for the modal analysis of the system. They are also not suitable for controller gains tuning using linear methods. Therefore, a linearized

model is proposed for small perturbation analysis in the neighbourhood of an initial equilibrium operating point.

The linearized model of a hydraulic turbine can be written assuming linear variations of flow and torque respect to net head, rotational speed and wicket gate position. Friction losses in the penstock have also been linearized.

III.4.5 Eigen analysis and controller tuning methodology

Based on the VSWT control loops described previously, three control strategies are proposed in (Martínez-Lucas, et al., 2018). Inertial control strategy, which takes the RoCoF as the control loop input (case ‘A’), proportional control strategy, which takes the variation in frequency as the control loop input (case ‘B’), and finally, inertial and proportional control strategy, which takes both variations as the control loop input (case ‘C’). These inertial and proportional control loops allow a fraction of the kinetic energy stored in rotational masses to be released to provide earlier frequency support, thereby taking advantage of the rapid response capability associated with electronically controlled converters. These control strategies can allow no regulation reserve, and thus, a better use of the wind resource is achieved. A base case in which the VSWTs are not assigned to contribute to frequency regulation is considered to highlight system improvements owing to the VSWT contribution to frequency regulation. In the cases in which the VSWTs do not provide frequency regulation or it is provided through the inertial control loop, the dynamic system is a fourth-order system because the state variables ($\Delta\omega, \Delta p_\omega$) are not active in the system. When the VSWTs provide proportional frequency regulation (or inertial and proportional), the dynamic system is a sixth-order system.

The main problem caused by long conduits, studied in (Martínez-Lucas, et al., 2015(a)) (Martínez-Lucas, et al., 2016), is the transmission of water elasticity oscillations to the generated power, and thus to the system frequency in isolated systems. Therefore, the oscillating modes that interfere with the dynamic behaviour of the system are identified from the modal analysis, differentiating the dominant variables of each oscillation mode. The influence of the PSHP and VSWT controller gains in varying the participation of the state variables in the oscillation modes is analysed. This can reduce the influence of water inertia and elasticity on the system frequency, preventing the hydraulic oscillatory phenomena that are transmitted to the electrical network. The study

of small disturbance dynamics of the linearized model is carried out for this hybrid wind–hydro power plant for each of the strategies described above. The eigenvalues, damping ratio, and participation factors of the state variables in the oscillation modes are obtained. From the study of the damping ratio and oscillation modes, a method for tuning the PSHP and VSWT controller gains based on the eigen analysis is proposed.

The modal analysis starts from the calculation of the state matrix eigenvalues. The eigenvalues (λ_i) are the main indicators of the dynamics and stability of the system. One of the classic tools that allow analysing the dynamics of the system from the position of the poles is the root locus, which will be used in the modal analysis. The participation factors are employed to measure the relative association between the i^{th} state variable and the j^{th} eigenvalue (Liu & Liu, 2007). Three oscillation modes can be found in this system:

- a) Oscillation mode I: Water elasticity mode, in which the state variables of the hydraulic system ($\Delta h, \Delta q_p$) have the highest participation. In root locus figures, this mode is plotted in blue colour.
- b) Oscillation mode II: Electromechanical mode, in which the state variables of the PSHP governor and the system frequency ($\Delta z, \Delta n$) have the highest participation. In root locus figures, this mode is plotted in red colour.
- c) Oscillation mode III: Aeromechanical mode, in which the state variables of the VSWT ($\Delta \omega, \Delta p_\omega$) have the highest participation. This oscillation mode appears when the VSWTs are aimed at contributing proportionally to frequency regulation (cases ‘B’ and ‘C’). In root locus figures, this mode is plotted in green colour.

Moreover, the damping ratio (ξ_i) of the corresponding oscillation mode can be obtained from the state matrix. Analyses involve damping ratios corresponding to different eigenvalues in the system for each strategy. The smallest damping ratio is selected as the main indicator of the system stability (Yang, et al., 2018). Therefore, the tuning criterion is based on obtaining the VSWT and PSHP controller gains that provide the higher smallest damping ratio. Two wind speeds have been compared to analyse their influence on the behaviour of the system. The electric demand is the same in both cases, so PSHP operating point will be adjusted to cover this power demand taking into account the different power supplied by the VSWT.

III.4.5.1 Base case: frequency regulation provided by PSHP

A base case in which the frequency regulation is only provided by the PSHP is considered to highlight in the following sections the system improvement owing to the VSWT contribution to frequency regulation. Figure D4 shows the system's smallest damping ratio as a function of PSHP controller gains (δ, T_r) when the VSWTs do not contribute to frequency regulation, for a constant speed of 10 m/s and 20 m/s. The white line corresponds to the null damping ratio, dividing the unstable region coloured in dark blue. The PSHP controller gains that correspond to the maximum smallest damping ratio are marked with an asterisk for both speed regimes.

Figure D4 Smallest damping ratio when VSWTs do not provide frequency regulation being $s_w=10$ m/s (a) and $s_w=20$ m/s (b).

Table D2 lists the PSHP controller gains, eigenvalues, damping ratios, and participation factors applying the proposed criterion when frequency regulation is provided only by the PSHP for wind speeds of 10 m/s and 20 m/s. Although the sum of the variables' participation factors does not reach the minimum value of 0.8 established in (Liu & Liu, 2007), two oscillation modes are identified corresponding respectively to elastic phenomena oscillations and PSHP governor oscillations, that is, the isolated system frequency. Both oscillation modes are very strongly interrelated, which may cause the elastic water mode oscillations to be transmitted to the electrical system.

Table D2. PSHP controller gains and participation factors when VSWTs do not provide frequency regulation

w_s (m/s)	PSHP gains		λ_i	ζ_i	Participation factors						Oscillation mode
	δ	T_r			Δq_p	Δh	Δz	Δn	$\Delta \omega$	Δp_ω	
10	0.6	1.7	-0.113	$\pm$	0.244	0.357	0.225	0.174	-	-	I
			j0.592								
			-0.085	$\pm$							II
			j0.481								
20	0.6	1.4	-0.102	$\pm$	0.233	0.334	0.236	0.197	-	-	I
			j0.600								
			-0.081	$\pm$							II
			j0.528								

To analyse the influence of the PSHP governor gains in the system dynamics, the root locus plot when parameter δ is varied assuming no VSWT contribution to frequency regulation is shown in Figure D5. The instability region (positive real half plane) has been shaded grey. The poles corresponding to the tuning used are marked with an asterisk. As can be observed, the criterion based on obtaining the maximum smallest damping ratio tends towards the double complex pole criteria proposed in (Martínez-Lucas, et al., 2015(a)). Owing to the proximity of the poles, the damping ratios of both oscillation modes are similar.

Figure D5. Root locus plot when VSWTs do not contribute to frequency regulation ($w_s = 20$ m/s). System poles corresponding to the proposed tuning are marked with an asterisk.

III.4.5.2 Case 'A': inertial VSWT contribution to frequency regulation

Owing to the frequency requirements ($50 \text{ Hz} \pm 0.15 \text{ Hz}$) established by the Spanish transmission system operator (TSO) for isolated systems (Red Eléctrica de España, 2012), the electromechanical oscillation, in which the system frequency is one of the dominant state variables, is controlled. To verify if the inertial regulation of the VSWT decreases

the participation of the hydraulic variables in the electromechanical mode, the evolution of participation factors of the dominant state variables into that mode due to VSWT inertial contribution to frequency regulation are shown in Figure D6. The participation factor of the variables $(\Delta z, \Delta n)$ in the electromechanical mode, increases as the VSWT synthetic inertia increases, decreasing the participation of the water elasticity mode dominant variables. When the inertial contribution is null ($K_{dn} = 0$), the electromechanical oscillation mode is strongly influenced by the dominant variables of the water elasticity mode $(\Delta h, \Delta q_p)$ with the oscillation of this mode being transmitted to the power system. The water elasticity mode has a higher participation factor in cases when the wind speed is low than in cases when the wind speed is high. This is because the PSHP operating point is higher in the first than in the second case because the power supplied by the VSWT is lower. Please note that the power demand is assumed to be constant.

Figure D6. Participation factors of dominant variables into electromechanical mode evolution due to VSWT inertial frequency regulation. Blue lines represent constant wind speed of 20 m/s scenario while red lines represent 10 m/s scenario.

According to (Martínez-Lucas, et al., 2018), adjusting the PSHP and VSWT regulators' joint gains is recommended. Therefore, following the proposed criterion, new PSHP and VSWT gains are obtained. Figure D7 shows the system's smallest damping ratio of case 'A', for a constant speed of 10 m/s and 20 m/s, in relation to the three adjustable gains. The continuous lines correspond to K_{dn} values that provide the maximum damping ratio for each pair of values (δ, T_r) . The white line corresponds to the null damping ratio, dividing the unstable region coloured in dark blue. The new PSHP and VSWT controller gains, which correspond to the maximum smallest damping ratio, are marked with an asterisk for both speed regimes.

Figure D7. Smallest damping ratio when VSWTs provide frequency regulation through an inertial control loop being $s_w=10$ m/s (a) and $s_w=20$ m/s (b).

Figure D8 shows the root locus, which is plotted by fixing the PSHP controller gains and varying the gain of the inertial control loop. The instability region (positive real half plane) has been shaded grey. The controller gains obtaining the smallest damping ratio are marked with an asterisk. The poles corresponding to the base case are marked with diamonds. The displacement of the poles in the plane can be observed: the pole of the electromechanical mode moves towards the negative real half plane, whereas the pole of the water elasticity mode moves towards the opposite direction. However, owing to the increase in the real part of the pole associated with the electromechanical mode, the system behaviour is improved. It is noteworthy that with these PSHP controller gains, the system would be unstable if the VSWTs did not provide frequency regulation ($K_{dn} = 0$) because of having the pole corresponding to the water elasticity mode in the positive real half plane. Furthermore, it is confirmed that a practical limit in the inertial contribution of VSWT exists, as it is stated in (Gonzalez-Longatt, et al., 2016) because the poles tend to the real half plane. This is the reason that the proposed values for the VSWT inertial control loop gains for interconnected systems are not suitable in isolated systems. The value proposed in (Mauricio, et al., 2009) ($K_{dn} = 15$) applied in an isolated system, as the case studied, caused the real part of the eigenvalues to be positive, destabilizing the system as demonstrated in (Martínez-Lucas, et al., 2018) with different simulations.

Table D3 lists the PSHP and VSWT controller gains, eigenvalues, damping ratios, and participation factors by applying the proposed criterion when the VSWTs provide inertial frequency regulation for wind speeds of 10 m/s and 20 m/s. The participation factors have been modified, decreasing the presence of variables associated with the water

elasticity in the electromechanical mode, thus preventing the hydraulic oscillations to be transmitted to the power system.

Figure D8. Root locus plot when VS WT contribute to frequency regulation with proportional control loop ($w_s = 20$ m/s).

Table D3. PSHP controller gains and participation factors when VS WT provide inertial frequency regulation (case ‘A’)

w_s (m/s)	PSHP gains		VS WT gains K_{dn}	λ_i	ζ_i	Participation factors						Oscillation mode
	δ	T_r				Δq_p	Δh	Δz	Δn	$\Delta \omega$	Δp_ω	
10	0.4	1.8	2.8	$-0.106 \pm j0.595$	0.175	0.253	0.368	0.217	0.162	-	-	I
				$-0.087 \pm j0.470$	0.182	0.102	0.239	0.353	0.296	-	-	II
20	0.4	1.4	3.2	$-0.107 \pm j0.616$	0.171	0.257	0.349	0.216	0.178	-	-	I
				$-0.066 \pm j0.508$	0.129	0.121	0.245	0.334	0.290	-	-	II

III.4.5.3 Case ‘B’: proportional VS WT contribution to frequency regulation

When the VS WT provide frequency regulation through a proportional control loop, the aeromechanical oscillation mode appears (now the dynamic system is a sixth-order system). Figure D9 shows the evolution of the participation of the dominant state variables into the electromechanical mode. As can be observed, the participation factor of the variables ($\Delta z, \Delta n$) in the electromechanical mode, increases as the VS WT proportional contribution rises, reaching a maximum for K_{pn} values between 1.5 and 2— independently of the wind speed—decreasing the participation of the water elasticity dominant variables. This is because the positive participation variation rate of the aeromechanical dominant variables into the electromechanical mode is higher than the negative variation rate of the participation of the water elasticity dominant values.

In this case, the water elasticity mode also has a higher participation factor in cases when the wind speed is low than in cases when the wind speed is high.

Figure D9. Participation factors of dominant variables into electromechanical mode evolution due to VSWT proportional frequency regulation. Blue lines represent simulations assuming constant wind speed of 20 m/s while red lines are for 10 m/s.

Following the recommendations and the methodology described previously, Figure D10 shows the system's smallest damping ratio for case 'B'. The white line corresponds to the null damping ratio, dividing the unstable region coloured in dark blue. The new PSHP and VSWT controller gains, which correspond to the maximum smallest damping ratio, are marked with an asterisk for both wind speed regimes. The values of the PSHP governor gains are significantly different from those obtained in the base case.

Figure D10. Smallest damping ratio when VSWTs provide frequency regulation through a proportional control loop being $s_w=10$ m/s (a) and $s_w=20$ m/s (b).

Figure D11 shows the root locus when the VSWTs provide frequency regulation through a proportional control loop having obtained the PSHP and VSWT controller gains jointly. The instability region (positive real half plane) has been shaded grey. The electromechanical mode poles tend to the negative real values, whereas the water elasticity mode poles tend to the positive real values as the proportional gain is increased.

In this case, the aeromechanical mode appears. With this VSWT regulation strategy, the poles of the two dominant oscillation modes, water elasticity and electromechanical mode, move to the real negative half plane, stabilizing the system. With these PSHP controller gains, the system would be unstable if the VSWTs did not provide frequency regulation because of having the electromechanical mode pole corresponding to $K_{pn} = 0$ in the positive real half plane. Because the poles corresponding to the base case tuning have been displaced to the left in the water elasticity and electromechanical modes, it is expected that a better dynamic behaviour can be attained with the proportional control strategy than with the inertial strategy.

Figure D11. Root locus plot when VSWTs contribute to frequency regulation with proportional control loop ($w_s = 20$ m/s).

Table D4 lists the PSHP and VSWT controller gains, eigenvalues, damping ratios, and participation factors by applying the proposed criterion when the VSWTs provide proportional frequency regulation for wind speeds of 10 m/s and 20 m/s.

Table D4. PSHP controller gains and participation factors when VSWTs provide proportional frequency regulation (case ‘B’)

w_s (m/s)	PSHP gains		VSWT gains K_{pn}	λ_i	ζ_i	Participation factors						Oscillation mode
	δ	T_r				Δq_p	Δh	Δz	Δn	$\Delta \omega$	Δp_ω	
10	1.0	0.8	1.4	$-0.126 \pm j0.604$	0.204	0.252	0.352	0.219	0.170	0.001	0.006	I
				$-0.132 \pm j0.509$	0.251	0.113	0.237	0.350	0.286	0.002	0.012	II
				$-0.020 \pm j0.054$	0.347	0.000	0.001	0.033	0.001	0.476	0.489	III
20	1.8	0.4	1.6	$-0.121 \pm j0.662$	0.180	0.307	0.361	0.174	0.153	0.001	0.004	I
				$-0.103 \pm j0.499$	0.202	0.127	0.230	0.335	0.291	0.002	0.015	II
				$-0.020 \pm j0.053$	0.353	0.000	0.001	0.034	0.001	0.476	0.488	III

The participation factors have been modified as when the VSWTs contribute to frequency regulation through the inertial control loop. The presence of the variables associated with the water elasticity mode in the electromechanical mode has decreased,

preventing the hydraulic oscillations to be transmitted to the power system. It is also observed that the dominant variables of modes I and II do not influence the dynamics of the aeromechanical mode.

III.4.5.4 Case 'C': inertial and proportional VSWT contribution to frequency regulation

As with the cases described above, Figure D12 shows the system's smallest damping ratio for case 'C'. The dashed lines correspond to K_{pn} values and the dotted lines correspond to K_{dn} , which provide jointly the maximum damping ratio for each pair of values (δ, T_r) . The unstable region is coloured in dark blue. Owing to the large number of controller gains involved in the system, the root locus technique is not effective.

Figure D12. Smallest damping ratio when VSWTs provide frequency regulation through inertial and proportional control loops being $s_w=10$ m/s (a) and $s_w=20$ m/s (b).

Table D5 lists the PSHP and VSWT controller gains, eigenvalues, damping ratios, and participation factors by applying the proposed criterion when the VSWTs provide inertial and proportional frequency regulation for wind speeds of 10 m/s and 20 m/s. Because of the proportional contribution, the values of the PSHP governor gains are significantly different from those obtained in the base case, as with case 'B'. The tendency observed in the previous cases is confirmed because the smallest damping ratio increases. Therefore, this control strategy is expected to be the most effective one to control the frequency.

Table D5. PSHP controller gains and participation factors when VSWTs provide inertial and proportional frequency regulation (case 'C')

w_s (m/s)	PSHP gains		VSWT gains		λ_i	ζ_i	Participation factors						Oscillation mode
	δ	T_r	K_{dn}	K_{pn}			q_p	h	z	n	ω	p_ω	
10	1.2	0.4	2.8	3.4	$-0.155 \pm j0.611$	0.246	0.240	0.323	0.235	0.192	0.001	0.009	I
					$-0.138 \pm j0.525$	0.254	0.133	0.214	0.351	0.284	0.002	0.016	II
					$-0.020 \pm j0.055$	0.342	0.000	0.002	0.047	0.001	0.466	0.484	III
20	2	0.2	3.2	3.8	$-0.143 \pm j0.623$	0.224	0.233	0.303	0.244	0.209	0.001	0.010	I
					$-0.127 \pm j0.561$	0.221	0.136	0.217	0.351	0.279	0.002	0.015	II
					$-0.020 \pm j0.054$	0.347	0.000	0.001	0.044	0.002	0.469	0.484	III

The participation factors have been modified, preventing the hydraulic oscillations to be transmitted to the power system owing to the decrease of the presence of variables associated with the water elasticity mode in the electromechanical mode. Because of the very high participation factors of the dominant variables of the aeromechanical mode into its own oscillation mode, it can be concluded that the dominant variables of modes I and II do not influence the dynamics of the aeromechanical mode.

As a summary of the modal analysis developed and the controller-tuning criterion proposed, the evolution of the minimum damping ratio (orange lines) and the participation of the water elasticity mode dominant variables into the electromechanical mode (blue lines) are shown in Figure D13. The reduction in participation of the water elasticity mode dominant variables is verified including the increase in the minimum damping ratio owing to the hybrid control strategies and the proposed tuning of PSHP and VSWT controllers.

Figure D13. Evolution of the participation factor of the water elasticity mode dominant variables in the electromechanical oscillation mode and system minimum damping ratio.

The modal analysis developed, as well as the PSHP and VSWT controller tuning criterion proposed, are based on the simplified linear model. Therefore, both must be contrasted by simulations in a completely nonlinear model.

III.4.6 Simulations and results

To check the suitability of controller tuning, Jones et al. (Jones, et al., 2004) suggested that it is enough to simulate a step, a ramp, and a random signal. In accordance to this methodology, three different events related to renewable source generation were simulated in (Martínez-Lucas, et al., 2015(a)). Therefore, a load step, a wind speed ramp, and a real wind speed fluctuation (Martínez-Lucas, et al., 2018), assumed as realistic events, have been simulated in the completely nonlinear model. To reinforce the results obtained from these simulations, a group of 100 synthetic wind speed fluctuations have been obtained from the real wind speed signal which have been also simulated. However, these results cannot be compared to the current experimental data, and it seems reasonable to expect a fairly good agreement because a similar model has been used in (Mansoor, et al., 2000) for Dinorwig power plant, where the simulation results were sufficiently accurate compared to field measurements.

Figure D14. Comparison of dynamic response of the system between the base case and cases 'A', 'B', and 'C' of hybrid contribution to frequency regulation and by considering a sudden power demand variation and a constant wind speed of 10 m/s.

Cases 'A', 'B', and 'C' have been compared with the base case (frequency control provided only by PSHP) to highlight the variation of each parameter mentioned previously.

Figure D15. Comparison of dynamic response of the system between the base case and cases ‘A’, ‘B’, and ‘C’ of hybrid contribution to frequency regulation and by considering a sudden power demand variation and a constant wind speed of 20 m/s.

Figure D14 and Figure D15 show the dynamic response comparison between the base case and the different cases of VSWT contributions to frequency regulation (‘A’, ‘B’, and ‘C’), when a 5% power demand step is imposed, considering constant wind speeds of 10 m/s and 20 m/s, respectively. A 12 s period oscillation is observed in the frequency response, corresponding to the oscillation period of the water hammer effect existing in the penstock. The proposed control strategies do not eliminate these oscillations, but dampen them, decreasing the oscillation amplitude and settling time. It can be verified that, regardless of the wind speed, the contribution of the VSWT to the frequency regulation is beneficial to the system, as it increases the value of the nadir. This confirms the observations made through the modal analysis. In addition, the VSWT contribution moderates the PSHP mechanical equipment movements.

When a wind speed ramp takes place and frequency regulation is only provided by the PSHP, as listed in Table D6, the frequency attains values outside the limits established by the TSO ($50 \text{ Hz} \pm 0.15 \text{ Hz}$) (Red Electrica de España, 2012). In addition, the mean frequency deviation (MFD) calculated based on equation (D10), nadir, maximum frequency peak, and nozzle movement values are improved supposing a small increase in the movements of the VSWT blades.

$$MDF = \frac{\int_0^t |n - n_{ref}|}{t} \quad (D10)$$

Table D6. Simulation results with a wind speed ramp

Case	MFD		Nadir		Max. Frequency peak		$\int \Delta z /t$		$\int \Delta \beta /t$	
	Hz	Δ	Hz	Δ	Hz	Δ	10^{-5} p.u./s	Δ	%/s	Δ
base	0.0504		49.8744		50.3515		14.029		0.7268	
'A'	0.0056	-88.89%	49.9996	0.25%	50.0224	-0.65%	2.0266	-85.55%	0.7334	0.91%
'B'	0.0188	-62.70%	49.9798	0.21%	50.1387	-0.42%	5.2422	-62.63%	0.7276	0.11%
'C'	0.0072	-85.71%	50.0000	0.25%	50.0194	-0.66%	3.6044	-74.31%	0.7311	0.59%

The frequency comparison from the simulation of wind speed fluctuations between the base case and VSWT contribution cases 'A', 'B', and 'C' is shown in Figure D16. It is observed that the frequency oscillations caused by wind speed fluctuations are clearly minimized, particularly when considering control strategies in which the inertial controls A and C are enabled. Moreover, the simulation results are summarized in Table D7, listing for each strategy the wind energy generated, MFD, nadir, maximum frequency peak, nozzle movements per second, and blade angle movements per second.

Figure D16. System frequency comparison between base case and cases 'A', 'B', and 'C' during wind speed fluctuations. Frequency limits required by the TSO are marked in dashed line.

Table D7. Simulation results using variable wind speeds

Case	Wind energy		MFD		Nadir		Maximum frequency peak		$\int \Delta z /t$		$\int \Delta \beta /t$	
	MWh	Δ	Hz	Δ	Hz	Δ	Hz	Δ	10^{-5} p.u./s	Δ	%/s	Δ
base	2.6707		0.0216		49.8511		50.1675		57.514		0.0796	
'A'	2.6617	-0.34%	0.0018	-91.67%	49.9581	0.21%	50.0374	-0.26%	9.9124	-87.98%	0.0853	7.16%
'B'	2.6704	-0.01%	0.0083	-61.57%	49.9036	0.11%	50.0750	-0.18%	23.187	-59.68%	0.0845	6.16%
'C'	2.6669	-0.14%	0.0017	-92.13%	49.9579	0.21%	50.0229	-0.29%	8.4037	-85.39%	0.0873	9.67%

In Table D8, the averages of the results obtained simulating the group of synthetic wind speed fluctuations are listed.

Table D8. Average results using 100 synthetic signals of wind speed

Case	Wind energy		MFD		Nadir		Maximum frequency peak		$\int \Delta z /t$		$\int \Delta \beta /t$	
	MWh	Δ	Hz	Δ	Hz	Δ	Hz	Δ	10^{-5} p.u./s	Δ	%/s	Δ
base	2.6914		0.0284		49.8217		50.2087				0.0660	
'A'	2.6912	-0.007%	0.0014	-95.07%	49.9883	0.33%	50.0110	-0.39%	32.439		0.0688	4.242%
'B'	2.6914	0.000%	0.0061	-78.52%	49.9562	0.27%	50.0429	-0.33%	3.2747	-89.91%	0.0681	3.182%
'C'	2.6913	-0.004%	0.0012	-95.78%	49.9891	0.33%	50.0077	-0.40%	11.195	-65.49%	0.0688	4.242%

As observed in Table D7 and Table D8, results obtained from the real wind speed fluctuation simulation and the averages of the results obtained by simulating the group of synthetic wind speed fluctuations match significantly. Furthermore, the MFD, nadir, maximum frequency peak, and nozzle movement values are improved in all cases owing to the VSWT contribution to frequency regulation, with a negligible loss of wind energy (less than 0.35%). In both simulations, assuming variations in wind speed, it is verified that for the proposed cases, the VSWT contribution to frequency regulation results in a significant improvement in the MFD, nadir, and maximum peak of frequency. As to the mechanical parts, an important reduction in the movements of the turbine nozzle (more than 85% in cases 'A' and 'C') takes place, thereby increasing its remaining lifetime. These reductions in movements suppose an assumable increase (less than 10%) in the movements of the VSWT blades. It can be observed that emulation of inertia improves the minimum frequency peaks as well as the MFD better than proportional control. Notwithstanding the above, the vast majority of these indicators reach an even better value when proportional control acts together with inertial control.

III.4.7 Conclusions

In this study, a modal analysis on the contribution to frequency regulation of a hybrid wind–hydro power plant was performed for the El Hierro isolated power system. The hybrid wind–hydro power plant committed in El Hierro was modelled in Matlab Simulink with enough detail to obtain comparable results with experimental models. From the mathematical model, certain realistic hypotheses have been assumed to simplify and linearize it, with the aim of undertaking the modal analysis. The oscillation modes that interfere with the dynamic behaviour of the system were identified from the state matrix by obtaining the eigenvalues and participation factors, identifying also the variables on

which these modes depend. Three control strategies were analysed, comparing them with the cases in which the VSWTs do not provide frequency regulation.

As significant contributions of this study, it has been proved analytically from the position of the system poles that VSWT controller gains recommended for interconnected systems are not adequate for isolated systems. Also, a tuning criterion based on the smallest damping ratio has been proposed to unlink the hydraulic state variables from the electromechanical oscillation mode, preventing the hydraulic oscillations to be transmitted to the system frequency. Control strategies and tuning criterion extracted from this study have been evaluated by simulating different events related to fluctuations in wind speed or variations in power demand. As a general conclusion, it is worth noting the feasibility of operating the island power system without the diesel generators when there are sufficient wind potentials owing to the VSWT contribution to frequency regulation, supplying demand and maintaining the system frequency within the limits established by the TSO.

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III.4.8 Nomenclature

A_r	[m ²]	Area swept by rotor blades
C_p		Variable-speed wind turbine (VSWT) power coefficient
h	[p.u.]	Net head
h_i	[p.u.]	Head at the end of the i^{th} Π element of the penstock
H	[p.u.]	Wind turbine inertia constant
k	[p.u.]	Load self-regulation coefficient
K_{dn}		Constant that weights the frequency variation in the VSWT
K_{ic}		Integral gain in proportional-integral (PI) blade pitch angle compensation
K_{ip}		Integral gain in PI blade pitch angle control
K_{io}		Integral gain in PI VSWT speed control
K_{pc}		Proportional gain in PI blade pitch angle compensation
K_{pn}		Constant that weights the frequency deviation in the VSWT
K_{pp}		Proportional gain in PI blade pitch angle control
K_{po}		Proportional gain in PI VSWT speed control
MFD		Mean frequency deviation
n	[p.u.]	Frequency
n^0	[p.u.]	Initial frequency

n_{ref}	[p.u.]	Reference frequency
n_t		Number of segments in which the penstock is divided
P_b	[MW]	Base power
p_{dem}	[p.u.]	Power demand
p_h	[p.u.]	Power supplied by PSHP
p_n	[p.u.]	Power reference provided by VSWT proportional and inertial control
p_{nc}	[p.u.]	Power supplied by VSWT converter
p_{nc}^0	[p.u.]	Initial power supplied by VSWT converter
P_{wind}	[MW]	Wind mechanical power
p_{wind}	[p.u.]	Wind mechanical power
p_ω	[p.u.]	Power reference provided by VSWT speed control
q	[p.u.]	Flow through the turbine
q_p	[p.u.]	Flow at the penstock
$q_{p,i}$	[p.u.]	Flow at the end of the i^{th} Π element of the penstock
$r/2$	[p.u.]	Continuous head loss coefficient in the penstock
s_w	[m/s]	Wind speed
T_e	[s]	Water elastic time (L/a_w)
T_m	[s]	Mechanical starting time
T_r	[s]	Hydro governor dashpot time constant
T_s	[s]	Time constant in servo motor transfer function
T_w	[s]	Penstock water starting time
z	[p.u.]	Nozzle opening
α_{ij}		C_p curve coefficients
δ		Hydro governor temporary speed droop
ζ		Damping ratio
β	[°]	VSWT blade pitch angle
β^0	[°]	VSWT initial blade pitch angle
β_{max}	[°]	VSWT maximum blade pitch angle
λ		Ratio of the rotor blade tip speed and wind speed
λ_i		Eigenvalue associated with each state variable
ρ	[kg/m ³]	Air density: 1.225 kg/m ³
ω	[p.u.]	VSWT rotational rotor speed
ω_{ref}	[p.u.]	Reference VSWT rotational rotor speed

IV. General discussion

This chapter presents in section IV.1 a detailed analysis of the results achieved in each publication and the main contributions and conclusions of the Thesis in section IV.2. Furthermore, several targets and challenges that are not yet solved but which the Author is interested in contributing to solving, in the coming years, are described in section IV.3.

IV.1 Results analysis

The most outstanding results of each publication of this Thesis are described below.

In Paper A, it is confirmed that including elasticity effects in the tuning criteria is needed. If governor gains obtained from a model not including elasticity effects are used in the model which include them, the system is unstable. It is demonstrated that results obtained with both a non-linear model and an adjusted reduced order model match significantly. In fact, due to the philosophy of the reduced order adjustment (equating the frequency corresponding to the poles of the one-segment transfer function with the first peak of the frequency response of continuous model), it can be observed that during first swing of power deviation, adjusted one segment model exactly replicates the continuous model. Four eigenvalues are obtained, corresponding to two oscillating modes. From simulations, an elastic oscillating mode and a mechanical oscillating mode are identified. It is observed that the elastic oscillating mode is hardly controllable. The DCP criterion couples both oscillating modes dynamics, matching the two pairs of eigenvalues. The DRP criterion does real parts of eigenvalues equal, thus acting only in the mechanical oscillating mode.

It is observed that when a linear wind power variation takes place, the response with the controller tuned with the DRP criterion is not strong enough, so the frequency overshoot exceeds the maximum allowed values ($\pm 2\%$) while in the case of the DCP criterion, frequency deviation fulfils the desired requirements. Similar results are obtained when a sudden and unexpected disconnection of one wind generator (2.3 MW) is considered: the DRP criterion reduces the oscillations in the frequency or power at the expense of excessive frequency overshoot. Nevertheless, when the controller is tuned with the DCP criterion, the frequency is maintained within the established limits.

In Paper B five poles are identified in the linearized model, corresponding to three oscillating modes: water elasticity mode (damped), mechanical model (damped) and frequency mode (over damped). In this system, all state variables are strongly coupled. DCP (Martínez-Lucas, et al., 2015(a)) and FDR (Sarasúa, et al., 2015) tuning criteria based on fourth order models from PSHP equipped with long penstocks are analysed. A new tuning criterion named FDRM, aimed at fixing a widely recommended damping ratio in the mechanical mode is proposed. Due to the frequency mode being over damped, frequency settling time is controlled matching its associated eigenvalue with the real part of the mechanical mode eigenvalue.

It is shown that, when different combinations of wind and solar power fluctuations take place, tuning based on FDRM and DCP criteria do not fail in any of the cases provided and none of the cases compromise the security of the conduit due to cavitation problems. When a wind power ramp takes places, the tuning criterion which provides fewer errors, less frequency overshoot and a shorter settling time, is the FDRM criterion. Furthermore, when a sudden disconnection of the new wind farm (9 MW) is considered, both FDRM and DCP present a better performance than the other classic tuning criteria. Despite the fast closing movement in gate position, the safety of pipelines is not compromised due to cavitation phenomena.

In Paper C, the VSWT contribution to frequency regulation is analysed considering three control strategies. It is demonstrated that power system quality indicators are improved. After an instant variance in power demand, it is shown that the fast frequency response elicited by the proportional inertial controller improves the NADIR value, thereby reaching an even better value when it acts synergistically with inertial control. Although the proposed criterion does not aim towards improving any particular quality indicator, the three considered indicators (nadir, frequency settling time and power settling time) are improved. It can be verified that, regardless of wind speed, when an instant increment in power demand takes place, the contribution of the VSWT to frequency regulation is positive for the system, since it increases the value of the NADIR, reducing the frequency and power settling time. In addition, VSWT contribution moderates the PSHP mechanical equipment movements. Furthermore, when a variation in wind speed occurs and frequency regulation is only provided by the PSHP, the frequency reaches values outside the limits established by Spain TSO ($50 \text{ Hz} \pm 0.15 \text{ Hz}$). This problem is solved when the VSWT provides frequency regulation according to the

proposed strategies. Assuming variations in wind speed, it is verified that for the proposed cases, the VSWT contribution to frequency regulation implies an improvement in the quality indicators of the system. In regard to the moving parts, an important reduction in the movements of the turbine nozzle (more than 80%) takes place, thereby increasing its remaining lifetime. These reductions in movements suppose a small increase (less than 10%) in the movements of the VSWT blades. It is demonstrated that no significant wind energy losses occur when VSWTs provide frequency regulation with the control strategies analysed, confirming that inertial control does not have economic losses associated.

In Paper D, dynamic phenomena due to VSWT contribution to frequency regulation is described. To this aim, a modal analysis is carried out in the linearized model proposed in Paper C. Assuming the VSWT control strategies described in Paper C, a tuning criterion based on classical control techniques is proposed, following the methodology in Papers A and B. The proposed control strategies in paper D do not eliminate frequency oscillations, but dampen them, decreasing the oscillation amplitude and settling time. The reduction in participation of the water elasticity mode dominant variables is verified including the increase in the minimum damping ratio owing to the hybrid control strategies and the proposed tuning of PSHP and VSWT controllers. It can be verified that, regardless of the wind speed, the contribution of the VSWT to the frequency regulation is beneficial to the system, as it increases the value of the nadir. This confirms the observations made through the modal analysis. Additionally, it is observed that frequency oscillations caused by wind speed fluctuations are clearly minimized, particularly when considering control strategies in which the inertial controls are enabled.

Table 4 and Table 5 list the simulation results assuming the governor gains obtained both in Paper C (based on the non-linear model) and in Paper D (based on the linearized reduced order model) when a step in power demand and wind speed fluctuation are considered respectively. As can be seen in these tables, the results achieved assuming both a criterion based on the non-linear model and the linear model are similar. However, when a load step is simulated, both settling time and nadir are light better assuming recommendations based on non-linear criterion (Paper C). This is due to exhaustive searches which are aimed at obtaining the controller gains which improve these quality indicators as a whole when a load step takes place. In contrast, the vast majority of results obtained when a speed fluctuation is simulated, are light better in cases where the tuning

criterion based on the reduced order model is assumed. This similarity in results reinforces the usefulness of the classical criteria in the control analysis of PSHP and VSWT. The reduction in computing time of the classic control tools compared to the exhaustive searches carried out on the non-linear model is also noteworthy.

Table 4. Comparison between results obtained in Paper C and D when a load step is simulated

VSWT control strategy	Paper C			Paper D		
	Nadir	T _n	T _p	Nadir	T _n	T _p
	Hz	s	s	Hz	s	s
Inertial	49.41	15.8	37.23	49.525	41.79	98.3
Proportional	49.58	8.81	19.51	49.400	24.88	52.9
Joint	49.69	7.56	11.80	49.678	11.47	48.27

Table 5. Comparison between results obtained in Paper C and D when a wind speed fluctuation is simulated

VSWT control strategy	Paper C				Paper D			
	MFD	NADIR	Energy	$\int \Delta z /t$	MFD	NADIR	Energy	$\int \Delta z /t$
	Hz	Hz	MWh	10 ⁻⁵ p.u./s	Hz	Hz	MWh	10 ⁻⁵ p.u./s
Inertial	0.0030	49.927	2.6616	6.7713	0.0018	49.958	2.6617	9.9124
Proportional	0.0102	49.837	2.6701	19.375	0.0083	49.904	2.6704	23.187
Joint	0.0031	49.908	2.6658	8.3311	0.0017	49.958	2.6669	8.4037

IV.2 Conclusions

In this Thesis, frequency control in isolated systems equipped with a PSHP, wind farms and diesel units is analysed. These configurations frequently correspond to pumped storage power plants coexisting with wind farms on small islands, in which wind potential can be exploited. It is assumed the critical scene in which power demand is only supplied from renewable resources: PSHP in turbine mode and wind farms.

In the first stage, a system composed of a PSHP equipped with a long penstock and VSWTs not providing frequency regulation is analysed. Then, an analogous system composed of a PSHP equipped with a long tail-race tunnel is studied. Subsequently, the VSWT's capability of providing frequency regulation is investigated in the first of the considered systems, evaluating the benefits of frequency regulation provided by the PSHP and a VSWT jointly.

To this aim, a hydropower plant equipped with a long penstock, a hydropower plant equipped with a long tail-race tunnel and a hybrid wind–hydro power plant with long

penstock were modelled in Matlab with Simulink with enough detail to obtain comparable results with experimental models.

It has been checked that conduit length may affect hydropower plant governor PI gains settings. Furthermore, because of the tail-race tunnel length, cavitation phenomena can appear in response to very fast governor manoeuvres. Thus, both water compressibility and conduit elasticity were necessary considered in the models.

The adequacy of a one-segment model adjusted in the frequency domain to represent penstock dynamics has been verified because the simulations show that high frequencies do not appear in the power plant responses. Therefore, a reduced order model has been used for analysis purposes and the subsequent development of recommendations for setting hydropower governor. Due to classical tuning criteria not taking into account elastic phenomena, new recommendations are formulated both for hydropower plants with long penstock or with long tail-race tunnel when frequency regulation is only provided by a hydropower plant in an isolated system.

Using classical control techniques, various setting criteria for the PI controller have been derived depending on the characteristics of the hydropower plant. If the hydropower plant is equipped with a long penstock, two new tuning criteria have been formulated; one of them (DRP) was previously applied in a water level control context. If the hydropower plant is equipped with a long tail-race tunnel, a new tuning criterion has been formulated.

In addition to the frequency regulation provided by the hydroelectric power plant, VSWTs can contribute to frequency regulation according to different proposed control strategies, including inertial, proportional, and their combination. To the author's knowledge, no control strategies were previously proposed for combined, VSWTs and a PSHP, frequency regulation in an isolated power system. It has been proven that VSWTs' controller gains recommended for interconnected systems are not adequate for isolated systems, since isolated systems are more sensitive to power disturbances than interconnected systems. Therefore, a criterion for tuning both the hydropower plant governor and turbine control loops was also proposed based on the non-linear model.

Furthermore, VSWT contribution to frequency regulation jointly to PSHP is analysed with classical control tools. The oscillation modes that interfere with the dynamic

behaviour of the system were identified from the state matrix by obtaining the eigenvalues and participation factors, identifying also the variables on which these modes depend.

Control strategies and tuning criteria extracted from these studies have been evaluated by simulating different events related to fluctuations in wind speed or variations in power demand. Some performance indices have been obtained and compared with those obtained with a classic setting and other criteria developed previously for similar cases. As a general conclusion, it is worth noting the feasibility of operating isolated power systems without diesel generators when there is sufficient wind potential owing to the VSWT contribution to frequency regulation, supplying demand and maintaining the system frequency within the limits established by the TSO. As specific conclusions, it is remarkable:

In cases in which the hydropower plant has a long penstock, the best performance was obtained when the governor gains were tuned using the Double Complex Pole (DCP) criterion. Since the DRP criterion was developed for water level control, the DCP criterion is expected to perform better than DRP in load frequency control, whatever the power plant parameters.

In cases in which the hydropower plant has a long tail-race tunnel, it has been found that the best performance in all cases is obtained with the FDRM proposed controller setting.

When VSWT turbines provide frequency regulation, it has been verified that the lifetime of the hydro turbine governing system is improved owing to the reduction of their movements at the expense of an admissible and increased workload imposed on the wind turbine blades. Wind energy lost owing to the contribution to frequency regulation could be considered negligible. Also, the need to modify the PSHP governor tuning when the VSWTs provide frequency regulation has been demonstrated from the root locus plot.

Comparing simulations assuming controller gains obtained both in the linear and the non-linear model reinforces the usefulness of the classical criteria in the control analysis of PSHP and VSWT. The reduction in computing time of the classic control tools compared to the exhaustive searches carried out on the non-linear model is also noteworthy.

The author is aware of the limitations that a PI regulator has. However, this regulator serves as a starting point to describe the dynamic behaviour of a system with these characteristics.

IV.3 Further works

During the development of this Thesis, some challenges have remained pending and it is the author's wish to tackle them in the near future.

The hydroelectric power station governor used in this Thesis is widely used in the scientific literature. However, the author is aware that commercial regulators are more complex. This would imply modelling a more complex regulatory, similar to those actually employed in PSHP or replacing by a hardware-in-the-loop (Mansoor, et al., 2000) the regulator model with a real regulator. In this case, the rest of the components of the PSHP would be emulated by the computer model.

In addition, the study of the frequency regulation capability will be extended to the La Palma power system.

In this Thesis, VSWTs are aimed at providing frequency regulation by modifying the inertial control. But also, VSWTs can provide primary and secondary regulation. It is well-known that participation in primary and secondary regulation requires a reserve of energy in VSWTs, which means a decrease in the use of wind potential. However, to the author's knowledge, these energy losses or their translation into economic losses have not been quantified. Taking into account these economic losses, it would be interesting to evaluate the profitability of the participation of VSWTs in primary and secondary regulation against the installation of flywheels, whose capacity to provide frequency regulation has been proven in several publications. Therefore, techno-economic criteria useful for the operator of the electrical system could be established in order to allow choosing between installing flywheels and allowing VSWTs to provide frequency regulation.

On the other hand, it would be realistic to consider that frequency regulation can also be provided by diesel units at some moments. As it has been demonstrated that the participation of VSWTs in frequency regulation implies that the hydroelectric power plant governor tuning must be modified, how the presence of diesel groups providing

frequency regulation affects the hydroelectric power plant governor setting should also be studied.

V. References

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VI. Appendix

VI.1 Front page and last page of Paper A

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Power-frequency control of hydropower plants with long penstocks in isolated systems with wind generation

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ABSTRACT

In this paper the power-frequency control of hydropower plants with long penstocks is addressed. In such configuration the effects of pressure waves cannot be neglected and therefore commonly used criteria for adjustment of PID governors would not be appropriate. A second-order II model of the turbine-penstock based on a lumped parameter approach is considered. A correction factor is introduced in order to approximate the model frequency response to the continuous case in the frequency interval of interest. Using this model, several criteria are analysed for adjusting the PI governor of a hydropower plant operating in an isolated system. Practical criteria for adjusting the PI governor are given. The results are applied to a real case of a small island where the objective is to achieve a generation 100% renewable (wind and hydro). Frequency control is supposed to be provided exclusively by the hydropower plant. It is verified that the usual criterion for tuning the PI controller of isolated hydro plants gives poor results. However, with the new proposed adjustment, the time response is considerably improved.

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1. Introduction

In last years, the use of renewable energy sources to displace fossil fuels in small isolated systems has received considerable attention [1–4]. Many islands have an excellent local wind potential so that economic and environmental costs of fuels may be avoided. Although these sources can contribute to some extent to power-frequency regulation, in many cases this service is provided mainly by conventional power plants. Hydropower plants can assume advantageously this task due to its renewable character. Moreover pumped storage schemes compensate uncertainty in wind production. This type of solution is usually named “combined wind-hydro generation”.

The use of PID governors in hydropower plants is a common practice [5] and suitable criteria for gain adjustment have been thoroughly studied in last decades [6–11]. However the hydropower plant configurations found in the systems mentioned above may include substantial differences with respect to general cases. Specifically, the length of the penstock can be considerably large due to special topographic conditions. This circumstance limits the

applicability of the rigid-water-column models [12] and the PID adjustment criteria based on this assumption [13,14].

Although several contributions have been described to modelling the dynamic response of hydropower plants, when the influence of pressure waves cannot be neglected [15–19] very few attempts have been found in the literature dealing with the adjustment of gains of the PID governor in such cases. It is worth mentioning the work presented in Ref. [20] where the stability boundaries in terms of the PI gains are determined under the influence of the water column elasticity, extending the results obtained for rigid water column. In Ref. [21] a methodology based on a reference model is proposed to obtain a PID governor gains; the turbine-penstock is represented by a synthesized second order model [13]. In Ref. [17] the PID parameters determination is based on a high order plant model, where the turbine transfer function is identified by means of time-domain simulations.

The work of [8,22–25] is aimed to obtain simple rules, recommendations or expressions useful for the PID governor tuning in the plant predesign phase, but they do not include water elasticity effects. For this purpose Classic Control tools and techniques, (root locus plot, bode diagram,...) have been successfully applied.

In this paper, a methodology is presented to achieve a similar objective taking into account water elasticity effects. For this purpose, a simplified linearized model is proposed to define some

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Frequency control support of a wind-solar isolated system by a hydropower plant with long tail-race tunnel

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ABSTRACT

Pumped storage hydro plants (PSHP) can provide adequate energy storage and frequency regulation capacities in isolated power systems having significant renewable energy resources. Due to its high wind and solar potential, several plans have been developed for La Palma Island in the Canary archipelago, aimed at increasing the penetration of these energy sources. In this paper, the performance of the frequency control of La Palma power system is assessed, when the demand is supplied by the available wind and solar generation with the support of a PSHP which has been pre-designed for this purpose. The frequency regulation is provided exclusively by the PSHP. Due to topographic and environmental constraints, this plant has a long tail-race tunnel without a surge tank. In this configuration, the effects of pressure waves cannot be neglected and, therefore, usual recommendations for PID governor tuning provide poor performance. A PI governor tuning criterion is proposed for the hydro plant and compared with other criteria according to several performance indices. Several scenarios considering solar and wind energy penetration have been simulated to check the plant response using the proposed criterion. This tuning of the PI governor maintains La Palma system frequency within grid code requirements.

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1. Introduction

Generally, fossil fuels are very expensive in islands, principally because of transportation cost. Nevertheless, many islands have an excellent local wind and solar potential, so that economic, environmental and social costs of fuel electricity generation may be avoided. In last years, renewable energy sources have been used to substitute fossil fuels in small isolated systems [1–4].

One of the economic and technical drawbacks of the high participation of intermittent energy sources in isolated systems is the need to reject substantial amounts of the produced energy due to penetration limits in the local electric grids [5]. This affects to both, wind and PV generation.

The vast majority of studies agree that the introduction of storage systems is the most effective mean to significantly increase wind penetration levels in power system [5–8]. Pumped storage hydropower plans (PSHP) can contribute to this role, being able to compensate uncertainly in intermittent renewable energy (wind

and solar). In fact, some current research is focused on the feasibility of the combination of solar, wind and hydro energy in islands (Fig. 1) [9]. This issue is also being considered in small isolated systems on some inland areas [10].

In some cases, sites available for building new PSHP may require long hydraulic conduits due to geographic, environmental or economic constraints. The main technical problem associated with long pipes is related to elastic phenomena, especially in those cases where for economic and environmental constraints no surge tank is built. In long pipelines, under-pressure and overpressure downstream or upstream of the turbine may result from the gate position movement. As an example, in long discharge pipes, cavitation phenomena may appear downstream the turbine due to an excessive suction pressure caused by gate closing movements [11].

The construction of a realistic model that takes into account all the phenomena involved in system operation is essential in order to draw relevant conclusions, applicable to predict the response of the station during design phase [12].

In particular, when the tail-race tunnel has a great length, the rigid-water-column models are not adequate [13] and consequently the controller settings based on it [14]. There are several researches which describe how to model the dynamic response

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VI.3 Front page and last page of Paper C

Article

Frequency Regulation of a Hybrid Wind–Hydro Power Plant in an Isolated Power System

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Abstract: Currently, some small islands with high wind potential are trying to reduce the environmental and economic impact of fossil fuels by using renewable resources. Nevertheless, the characteristics of these renewable resources negatively affect the quality of the electrical energy, causing frequency disturbances, especially in isolated systems. In this study, the combined contribution to frequency regulation of variable speed wind turbines (VSWT) and a pump storage hydropower plant (PSHP) is analyzed. Different control strategies, using the kinetic energy stored in the VSWT, are studied: inertial, proportional, and their combination. In general, the gains of the VSWT controller for interconnected systems proposed in the literature are not adequate for isolated systems. Therefore, a methodology to adjust the controllers, based on exhaustive searches, is proposed for each of the control strategies. The control strategies and methodology have been applied to a hybrid wind–hydro power plant on El Hierro Island in the Canary archipelago. At present, in this isolated power system, frequency regulation is only provided by the PSHP and diesel generators. The improvements in the quality of frequency regulation, including the VSWT contribution, have been proven based on simulating different events related to wind speed, or variations in the power demand.

Keywords: wind–hydro systems; variable speed wind turbine; governor tuning; wind turbine frequency regulation; inertia emulation

1. Introduction

The increased use of intermittent renewable energy sources in most electric power systems has been documented [1,2]. These increases constitute a good way to reduce polluting gases generated by fossil fuel combustion. However, this class of renewable energies involves inherent drawbacks, such as unpredictability [3] or demand independence [4]. These characteristics of renewable sources negatively affect the quality of the supplied electrical energy, causing frequency [5] and power disturbances [6].

According to Albadi and El-Saadany [3], the impact of renewable energies on power systems depends mainly on its penetration rate and the system inertia. For this reason, the negative effects of renewable energy sources are amplified in isolated systems. Nevertheless, in islands with wind potential, the economic and environmental costs of fossil fuels can be reduced. Therefore, the reduced use of fossil fuels owing to the increasing use of renewable energies in small isolated systems has become the main focus of numerous researchers during the past few years [7–10]. For example, Kaneshiro [11] has analyzed how wind ramps affect the quality of supply in a Hawaiian power system, considering different rates of renewable penetration and highlighting the importance of wind forecasting in the medium and long term in order to operate the system safely and efficiently. In [12], the penetration of wind energy in Flores Island has been shown to be limited because of

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VI.4 Front page and last page of Paper D

Eigen analysis of wind–hydro joint frequency regulation in an isolated power system

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ABSTRACT

The wind energy penetration rate is being increased in majority of European countries. However, a high penetration rate could endanger the stability of power systems, particularly in small islands. Hydropower plays an important role in the regulation and control of isolated power systems with renewable sources, but it may not be able to maintain the frequency within grid requirements. This is the case of El Hierro power system (Canary archipelago), where a hybrid wind–pumped storage hydropower plant (PSHP) was committed to reduce the use of fossil fuels. Currently, frequency regulation is only provided by the PSHP and diesel generators. Therefore, it is proposed that variable-speed wind turbines (VSWTs) contribute to frequency regulation, thereby minimizing the need for fossil fuels. This study aims to conduct an analysis on the effect of the VSWT contribution to frequency regulation in the power system of El Hierro. It is based on classical control tools from a linearized mathematical model considering different VSWT regulation strategies. The eigenvalues, damping ratio, and participation factors of the state variables have been obtained. The more significant oscillation modes in the dynamic response of the system have been identified. According to this modal analysis, a methodology for the adjustment of the PSHP and VSWT controller gains is proposed. An improvement in the quality of frequency regulation while maintaining the El Hierro system frequency within grid requirements has been proved based on simulating different events related to wind speed or variations in the power demand, using a nonlinear model of the combined wind–hydro power plant.

1. Introduction

Wind-based generation systems have become sustainable and environmentally friendly options to supply power in isolated or off grid locations [1]. In islands with isolated power systems, the development of renewable energies is not only linked to the environmental problems of fossil fuels. The costs of transporting these fuels to the places of consumption are higher than in continental systems. Therefore, their replacement by renewable resources can have a very positive economic impact [2]. Some examples of high renewable potential islands are the Aegean Islands [3], the archipelago of the Azores [4], and Canary Islands [5] in Europe, and The Yong Shu Island in South China Sea [6].

The power system frequency regulation impact of renewable energy sources depends mainly on its penetration rate and the system inertia [7]. Therefore, the negative effects associated with renewable energy sources, which are amplified in isolated systems may cause inadmissible frequency deviations. Nevertheless, in islands with wind potential, the increasing use of renewable energies has become the focus of interest of numerous researchers during the past few years [8,9].

The vast majority of studies agree that the introduction of storage systems is the most effective way of significantly increasing wind penetration levels in power systems [10,11]. Focusing on the case of isolated systems, [12–14] have shown that the long-term variability in renewable energy can be managed well by combining wind and solar farms with pumped storage hydropower plants (PSHPs), which are able to compensate uncertainty in intermittent renewable resources. However, [11,15,16] proved that PSHPs need complementary technologies in the short term (owing to its slowness caused by the water inertia), which are capable of injecting or absorbing power over brief periods that span a few seconds to avoid inadmissible frequency variations.

These rapid contributions to frequency regulations can be provided by variable-speed wind turbines (VSWTs) [17]. Different approaches can be found in the technical literature on the contributions of VSWTs to support frequency regulation [18,19]. In general, VSWTs–Type III and IV– provide negligible inertia because the rapid control of power electronic converters maintains a practically constant output power irrespective of changes in the frequency of the grid [20]. However, it is possible to achieve short-term inertial responses from VSWTs by

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