Frequency Stability Assessment of Deloaded Wind Turbines in Spanish Island Power Systems

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Abstract

This paper investigates under what circumstances the provision of frequency regulation by renewable energy sources can provide technical and economic benefits to real island power systems. In order to do so, the unit commitment problem is simulated, and the frequency stability is analyzed in terms of frequency deviations and the amount of shed load when the wind turbine generator operates at a fixed and variable deloading percentage under normal conditions. The assessment is carried out for La Palma (small size) and Tenerife (medium size) island power systems by considering different wind source availability scenarios for sample weeks of different seasons in current and future years. Results show that in high wind penetration scenarios, considering a fixed deloading ratio to provide both inertia and reserve, improves the total system operating costs and the overall frequency response quality which translates into a lower under-frequency load shedding cost. A variable deloading factor, although leading to lower system operational costs, falls short to ensure a reliable frequency response in certain scenarios after outages. The results of this paper suggest that in order to capture both the minimum system cost and appropriate frequency dynamic behavior while considering the deloading of wind turbines, unit commitment models of real island power systems should include frequency-related constraints.

Acronyms

ED economic dispatch

FOR forced outage rate

KPI key performance indicator

LSC load shedding cost

MPPT maximum power point tracking

MW megawatt

OC outage cost

RES renewable energy sources

RoCoF Rate of Change of Frequency

SFR system frequency response

UC unit commitment

UFLS under frequency load shedding

WTG wind turbine generator

1 Introduction

The improvements in renewable generation technologies together with a growing concern about the environmental impact of thermal generation and a boost in the global energy demand, are leading to an increasing interest in investigating new initiatives to evolve toward electric power systems that are more dependent on renewable energies, with wind power being the preferred option in the case of island systems [1], [2]. Renewable energy sources (RES) offers an attractive solution not only to minimize the use of fossil fuels and increase island sustainability but also to achieve cost-optimal electricity systems [3]. In [4], the possibility of achieving 100% renewable generation in the Canary Islands before 2050 is investigated.

Spinning reserves denote those power and energy capacities that can be deployed in a relatively short time by means of the primary and secondary frequency controls. The amount of reserve needed in the island power system is significant with respect to the demand, so it is essential to adapt the size optimally so that they are sufficient to cover both emergency and non-emergency situations [5]. The common practice among island system operators is to establish a value of minimum spinning reserve requirement to be able to cover the loss of the largest online generating unit, expected RES variations, and loss of interconnections to other island power systems. Currently, RES generation does not provide spinning reserve. In addition, non-synchronous RES does not provide inertia by default, as they are connected to the grid through a power electronic converter that decouples the wind turbine generator (WTG)'s inertia [6]. Under this common practice, thermal generators are the providers of spinning reserve and inertia, functioning below their maximum power to provide the required amount of up reserve in some periods, thus increasing system operation costs.

The increasing penetration of RES without providing spinning reserve and inertia can negatively affect the frequency stability of island power systems further ([7], [8]). Current under frequency load shedding (UFLS) schemes disconnect certain amounts of loads if the frequency or frequency derivative exceeds certain thresholds ([9], [10]). As a result, this non-synchronous generation is often curtailed to ensure frequency stability when over-generation is about to happen. However, technical developments enable RES to provide both reserve and inertia emulation. To provide frequency regulation, wind turbines must have frequency control capabilities and be able to provide power reserves [11]. In [12], various reserve allocation methods are compared and a practice to assess immediate wind primary reserve is presented. Reference [13] has tested various control strategies of active power to improve the system performance and their effectiveness in times of high wind injection. In [14], an aggregated frequency response model for wind generators is presented, considering the different operational modes of WTG. In [15], a stochastic unit commitment formulation that evaluates the advantages of synthetic inertia and primary frequency response provision from WTG in Great Britain's power system is developed. Reference [16] analyses different inertia and frequency regulation approaches for RES, which include inertia emulation, fast power reserve, droop techniques, and deloading techniques. Among all these techniques, deloading is the most reliable one, brings more economical and technical benefits and provides a better overall frequency response [17], [18], even though increasing the pitch dynamics may increase maintenance costs due to increased mechanical tear-and-wear. By deloading, wind turbines are technically able to provide reserves by working below their maximum power point tracking (MPPT) operation [19], by adjusting appropriately rotor speed. Typically, the deloading rate is less than 20% of the available wind power, depending on the circumstances [20]. An extensive review of the deloading of wind turbines in power systems is presented in [21], and different control methods are compared.

2 Gaps and Contributions

The objective of this paper is to investigate under what circumstances the provision of spinning reserves and inertia by RES provides technical benefits to real island power systems. The assessment is carried out by analyzing the impact of WTG when they operate at a fixed and at a variable deloading percentage under normal conditions. The unit commitment (UC) problem is simulated, and the system frequency dynamics are analyzed in terms of security and stability. The assessment is carried out for real island power systems by considering different wind source availability scenarios for sample weeks of different seasons in current and future years. The islands of Tenerife (medium size) and La Palma (small scale) are chosen for simulations because they are representative of the Spanish isolated systems. These two islands fit in two of the five prototype islands identified through clustering techniques in [22].

In [23] it's shown that the system operational costs of these two real islands can be reduced when RES provides up and down reserve. By taking the optimal UC schedules obtained in [23], this paper simulates the dynamic responses of the system to the thermal generator and wind outages and assesses the system response by a set of key performance indicator (KPI)s, such as frequency nadir or the amount of UFLS. This paper complements the findings in [23] by contemplating the actual impact of providing reserve on frequency stability. It should be noted that the UC used is deterministic since the purpose of the analysis is to get an idea of whether RES should provide reserve to improve frequency response, both in low and extreme RES penetration scenarios.

Finally, this paper also evaluates the appropriateness of the commonly used spinning reserve criterion to foster the development of RES in future demand scenarios. This criterion only sets the reserve requirement in terms of megawatt (MW), but it ignores the dynamic features (such as the speed or inertia) of the units providing reserve and thus can lead to increased UFLS under contingencies. Results show that a fixed deloading factor improves the frequency dynamics better than the variable deloading factor in most cases.

The rest of the paper is organized as follows. In section 4, the methodology used is explained. In section 5, the description of the case studies and the scenarios are presented. In section 6 and section 7, the obtained results for la Palma and Tenerife under no UFLS and under the current UFLS schemes are analyzed. Conclusions are drawn in section 8.

3 Review of the Frequency Requirements in Spanish Islands

This section provides a short review of the frequency requirements of Spanish isolated power systems. The Spanish isolated power systems are the power systems of the Canary Islands, Balearic Islands, and the Spanish towns in North Africa: Ceuta and Melilla. These systems are of very different sizes. The largest system is the Balearic system with a peak demand of around 1100 MW and the smallest system is the El Hierro system with a peak demand of 7 MW.

3.1 Reserve Requirement

The technical regulatory framework of the Spanish isolated power systems is defined in a set of operational procedures [24]. Among others, operation procedure number 1 (section 8.1) describes the spinning reserve requirements in the isolated Spanish power systems. It points out that the up-spinning reserve, including primary and secondary frequency control reserves, should be greater than the largest online unit, greater than the expected RES power generation variations, and greater than the largest interconnection infeed, following the $N-1$ criteria. In addition, the down spinning reserve must be at least 50% of the upward primary reserve. The operational procedure also recognizes that during the outage of a large unit, primary frequency control makes use of both primary and secondary reserves.

3.2 Frequency ranges

In [25] technical requirements of frequency stability for Spanish isolated power systems are defined. A generating unit must be able to remain connected to the grid if the frequency falls below $47.5Hz$ for less than 3 seconds. The minimum frequency is 47 Hz. The constant Rate of Change of Frequency (RoCoF) that an online unit must stand is $2Hz/s$, measured over a moving time window of 750 ms.

3.3 UFLS schemes

UFLS are crucial in island power systems to avoid frequency instability. Although different schemes have been proposed in the literature, conventional UFLS schemes are mostly employed today [10]. Conventional UFLS schemes shed predefined amounts of load when the frequency and RoCoF reach specified thresholds. The efficiency of the UFLS depends on the design of its parameters.

4 Methodology

This section presents the methodology to assess the technical impacts of providing frequency regulation by WTG in island power systems and details the KPIs that will be used to evaluate the dynamic frequency response. The assessment is based on the simulation of the economic operation by means of an hourly UC on a weekly basis, which determines the hourly generation set point as well as the hourly start-up and shut-down decisions. Then the operation points are used as the input of the system frequency response (SFR) model. This model simulates the dynamic system response in terms of frequency to the outage of every generator (including WTG) in every hour of the week. Dynamic simulations are conducted both with and without UFLS schemes. The simulations of the economic operation of the islands consider different scenarios for demands and RES penetration and cases of reserve provision capabilities. For a given weekly demand profile, the corresponding current wind penetration profiles are scaled up according to the considered future installed capacity. The cases of reserve provision differ in the ability of WTG to provide reserves and frequency regulation.

Figure 1 shows a flowchart of the methodology. The input of the weekly UC includes the weekly hourly demand, wind, and solar generation forecast, list of thermal generators, and their data sheet for each island and each sampling week under study. Considered scenarios and reserve provision cases are further discussed in section 5.

4.1 UC model

The UC is formulated as a minimization problem where generation set points and start-up and shut-down decisions are such that the total weekly opera-

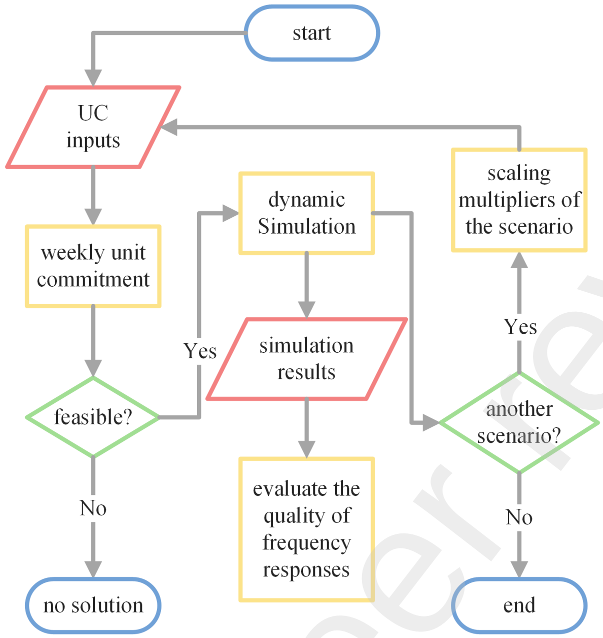

Figure 1: Flowchart of the methodology.

tion cost is minimized by considering technical constraints. For details on the formulation of the UC please refer to [23].

4.2 SFR Model

This section briefly presents SFR model used to analyze the frequency stability of small isolated power systems. These models are able to reflect the underlying short-term frequency dynamics of small isolated power systems. Figure 2 details the power-system model used to design UFLS schemes of a small isolated power system, consisting of I generating units. Each generating unit i is represented by a second-order model approximation of its turbine-governor system. In fact, frequency dynamics are dominated by rotor and turbine-governor system dynamics. Excitation and generator transients can be neglected for being much faster than the turbine-governor dynamics. Since frequency can be considered uniform, equivalent system inertia H can be defined. The overall response of loads can be considered by means of a load-damping factor D if its value is known.

The gain k_i and parameters $a_{i,1}$, $a_{i,2}$, $b_{i,1}$ and $b_{i,2}$, of each generating unit i can be deduced from more accurate models or field tests. Since the primary spinning reserve is finite, power output limitations $\Delta p_{i,min}$ and $\Delta p_{i,max}$ are forced. So the units can only participate as much as their available reserve. The complete model is explained in [26]. The inclusion of converter-connected

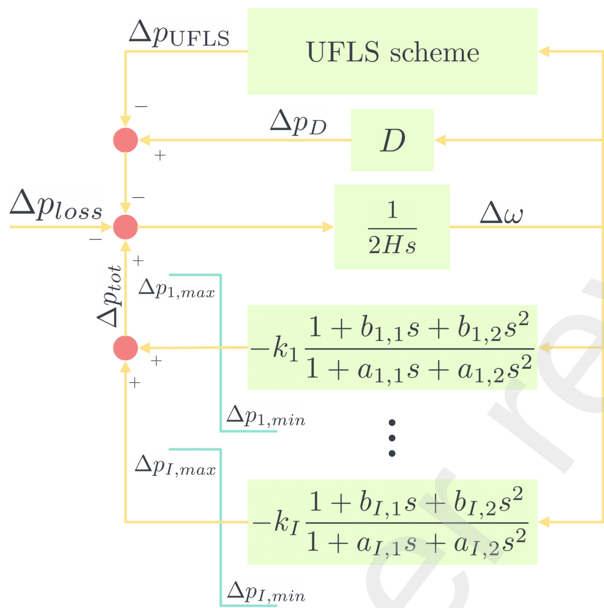

Figure 2: SFR model schematic.

generation can be realized if emulated inertia and parameters of the second-order generating unit model are given. In [26] wind turbines are modeled as thermal units with zero inertia H_i and zero gain k_i unless they emulate inertia or operate below the MPPT. In hours with enough wind production where deloading is considered, wind units work below the MPPT and are able to participate in the recovery of the frequency response when an outage happens. The control strategy of wind turbines is presented in fig. 3 and has been applied in different literature studies such as [11],[20],[27], and [28]. This configuration implements

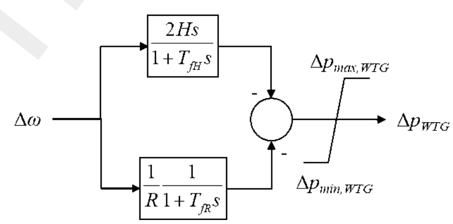

Figure 3: Control strategy of wind turbines ($H = 3s, R = 0.05, T_{fH} = 0.01$).

the inertia emulation control loop and is capable of steady-state power-sharing. The same method is used here. Wind systems provide both reserve and inertia emulation, where parameters for dynamic simulation are taken from [29].

For the purpose of this work, a 10% outage of wind power generation has been considered ($k_{\text{outage}} = 0.1$), following the information provided in the analysis of real wind patterns [30] for Tenerife and La Palma wind farms. Wind generation is modeled as two conventional units. One of them represents the remaining power and the other one represents the outage. P_s is the total forecasted amount of wind generation. In this way, the actual RES production after deloading is $P_s \times (1 - k_{\text{deloading}})$, and $P_s \times k_{\text{deloading}}$ is the amount of wind that can be used as reserve.

4.3 Key Performance Indicators

In order to analyze the results from a technical point of view, different input states are compared regarding a set of KPIs. When the simulations are executed without UFLS schemes, the following KPIs have been defined according to the frequency ranges. According to technical requirements of frequency stability for Spanish isolated power systems, a generating unit must be able to remain connected to the grid if the frequency falls below $47.5Hz$ for less than 3 seconds. The minimum frequency is $47Hz$. RoCoF that an online unit must stand is $2Hz/s$, measured over a moving time window of $750ms$.

- The number of severe cases per state: it counts the number of times in all the simulations of a particular state that the frequency reaches a value lower than $47.5Hz$ for more than 3 seconds.
- The number of minimum frequency violations: it counts the number of times that the frequency reaches a value under $47Hz$.
- The number of online units in the whole week: it counts every unit that is online during the simulations of the considered state.
- The frequency violation percentage: calculated as the percentage of simulations in which the minimum frequency is violated [31].

When UFLS schemes are activated, UFLS prevents the frequency violations. Instead, the summation of UFLS for all contingencies in all of the hours will be measured in each state. In addition, the total load shedding cost (LSC) will also be obtained by adding the load shedding cost in each hour (C_t^{UFLS}), which is computed by multiplying the load shedding caused by the outage of every online generator in every hour (LS) by the forced outage rate (FOR) of each generator and the outage cost (OC) [31].

$$C_t^{UFLS} = LS_t \times \text{FOR} \times \text{OC} \tag{1}$$

$$\text{LSC} = \sum_{t \in \tau} C_t^{UFLS} \tag{2}$$

Where LS is the total UFLS in megawatts and C^{UFLS} is the cost of UFLS in euros. According to [31], the FOR of each type of generator listed in table 1 and the OC is 3000€/MWh to quantify the LSC. The actual cost of load shedding is difficult to assess. It depends on the time of the incident, the spread, etc. In addition, penalization can be imposed on system operators and gencos. As another example, in [32] OC is assumed to be 11000€/MWh.

type of generator	FOR
diesel	0.004%
steam	0.002%
gas	0.0045%
wind	0.007%

Table 1: Forced outage rate of the generators in La Palma and Tenerife, according to their type

5 Case Studies and Scenarios

This paper builds on the economic analysis of [23] and extends its findings by simulating the technical impact of providing reserve by RES. In this section, the case studies are described and the scenarios are defined.

5.1 Case Studies

The Energy Strategy for the Canary Islands in 2025 aims to reduce carbon dependency. Among others, strategic objectives for RES is achieving 45% of RES participation in final electricity generation by 2025. This would require multiplying the amount of installed RES capacity. In the case of wind power generation, not only on-shore but also off-shore wind farms are contemplated. To achieve realistic results, in this study the most recent actual demand and RES generation of Tenerife and La Palma are used as the inputs. The demand is scaled up for future cases by forecasted multipliers for the corresponding year. Other required inputs, including available power plants and their technical specifications such as cost functions, up and down time limitations, capacities, and ramping limitations are updated real data, obtained from the operators.

5.2 La Palma

The yearly demand in 2018 in La Palma is about 277.8 GWh (average hourly demand of 31.7 MWh), supplied by eleven Diesel generators pre-dominantly, which are presented in table 2. According to [4] the installed capacity of the La Palma island power system mounts to 117.7 MW, where about 6% (7MW) of the installed capacity belongs to wind power generation. Renewable generation covers about 10% of the yearly demand. Figure 4 shows the weekly generation of wind and solar per units of installed capacity. The data in Figure 4 is scaled depending on the available installed capacity for each scenario.

5.3 Tenerife

Total yearly demand in 2018 in Tenerife mounts up to 3,686.2 GWh (average hourly demand of 420.8 MWh). Two combined cycle units (gas and steam) cover around 45.5% of annual demand (generators 9 and 10 of Tenerife in table 3). 4 thermal steam units generate around 35.5% of the annual demand.

Table 2: Generator capacities in La Palma

#	$\underline{\mathcal{P}}_i[MW]$	$\overline{\mathcal{P}}_i[MW]$
1	2.35	3.82
2	2.35	3.82
3	2.35	3.82
4	2.82	4.30
5	3.30	6.70
6	3.30	6.70
7	6.63	11.50
8	6.63	11.20
9	6.63	11.50
10	6.63	11.50
11	4.85	21

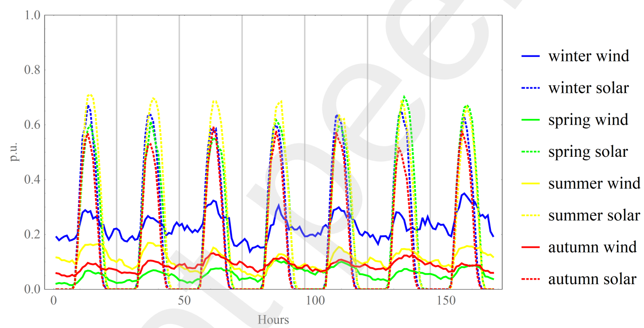

Figure 4: Solar and wind generation per installed unit.

Table 3: Generator capacities in Tenerife

#	$\underline{\mathcal{P}}_i[MW]$	$\overline{\mathcal{P}}_i[MW]$
1	4.85	21.6
2	4.85	21.6
3	4.85	24.3
4	4.85	24.3
5	14.8	19.1
6	29.3	74.2
7	29.3	74.2
8	6.8	39.2
9	9.7	186.1
10	9.7	206.5

The diesel units are recently decommissioned. 4 thermal gas units generate 3.5% of annual electricity demand. The rest is delivered by RES. Operators are planning to decommission some of the more expensive thermal units and add to the renewable capacity before 2025. The weekly demand for each season in 2020 on Tenerife island is shown in fig. 5.

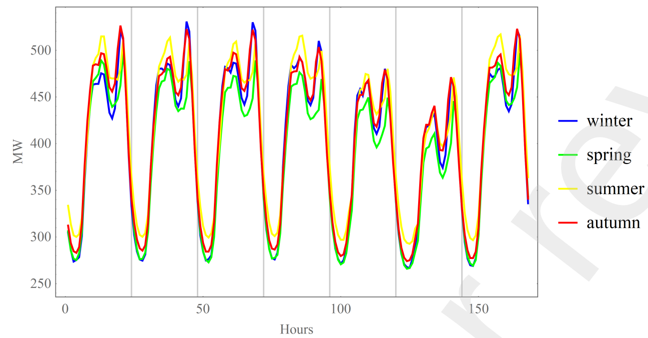

Figure 5: Weekly demand for each season of the year 2020.

5.4 Scenario Defenition

The impact of wind penetration levels on providing spinning reserve is analyzed by contemplating different scenarios of increasing installed capacity, in sample weeks of each season (winter, spring, summer, and autumn). Scenario I denotes the current amount of installed wind capacity. For scenarios II to IV, the initial amount is multiplied by 2, 5, and 10, respectively. All the seasons and scenarios are considered for forecasted electricity demand for the years 2020, 2025, and 2030 to acknowledge the economic and technical impacts of each scenario in near future. For each scenario, three cases with different capabilities of providing spinning reserve by RES are defined.

- **Case A:** This case is the current practice of operators in Spanish islands where RES can provide neither spinning reserve nor inertia. The total reserve should be provided by thermal units. This case serves as a reference case.
- **Case B:** wind and solar sources provide up spinning reserve. A constant deloading factor of 10% is applied for the entire time horizon to available wind power. So, in each hour, 10% of available wind generation is deloaded and specified as up reserve. Emulation of inertia is also included.
- **Case C:** The possible amount of deloading is defined as a coefficient between 0 and 15% of available wind generation. The UC optimization problem will decide the optimal amount of deloading in each hour. Emulation of inertia is also included.

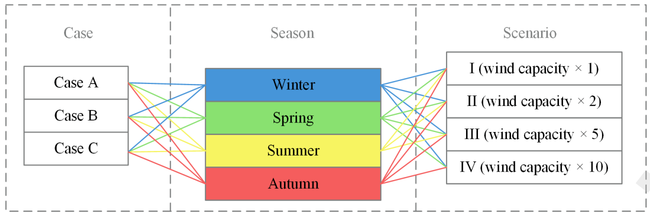

Figure 6: Considered states.

Figure 6 shows all of the considered states. Weekly unit commitment is solved for 3 different cases (A, B, and C), 4 sample weeks of different seasons (winter, spring, summer, and autumn), and 4 wind penetration scenarios (I, II, III, IV) for each year; composing 48 weekly UCs for each year. This approach is employed for three different years: 2020, 2025, and 2030. For each island, a total of 144 weekly UC simulations have been completed. For each hour of the 144 weekly UC, the outage of every generator including WTGs is simulated with the SFR model.

6 Results for La Palma

When the simulations are executed without UFLS schemes, the weekly KPI and the total weekly operation cost for the different scenarios and cases for the La Palma island are shown in Table 4. Weekly KPIs have been averaged over the four seasonal sample weeks. In addition, it shows in the dynamic simulations under current UFLS schemes, the expected weekly cost of UFLS for the different scenarios and cases. For a better analysis of the results, data from table 4 are depicted in fig. 7, where average weekly results for 4 seasons are shown. Different cases are specified above each bar. The number of scenarios is stated in the bottom corner. Obtained results for the years 2020, 2025, and 2030 are separated with dashed lines. Above zero is the total cost in k€ and below zero is the number of severe cases.

In fig. 7, blue bars represent the weekly UC dispatch cost plus the expected cost of UFLS. Yellow bars represent the number of severe cases under no UFLS schemes. Case A is considered as the base case, then the incremental or decremental percentage of the KPIs is inscribed in the table and in the graphic, compared to the base case. It should be noted that as the KPIs under no UFLS scheme (except for the number of online units) are correlated, only the number of severe cases is represented in fig. 7.

As shown in [23], the weekly operation cost of thermal generation is less for the cases with deloading capability. In case A, the UC solver is forced to turn off big units, even though they are cheaper, to avoid reserve violation. When deloading is considered, wind generators have the capacity of providing up reserve in the system. As a result, the economic dispatch changes, and the number of online units decreases because some thermal units that in case A are

Table 4: Results for La Palma.

			SFR with no UFLS				UC simulations	SFR with UFLS
			online units in whole week (#)	severe cases (#)	min frequency violations (#)	frequency violation (%)	weekly operation cost (K€)	weekly Cost of UFLS (K€)
scenario I	2020	A	1329	202	199	15	575	0.35
		B	1358 (+2%)	175 (-13%)	169 (-15%)	12.4 (-17%)	-1%	-13%
		C	1289 (-3%)	179 (-11%)	175 (-12%)	13.6 (-9%)	-2%	-4%
	2025	A	1467	166	144	9.8	657	0.37
		B	1477 (+1%)	151 (-9%)	127 (-12%)	8.6 (-12%)	-1%	-9%
		C	1420 (-3%)	286 (+72%)	224 (+56%)	15.8 (+61%)	-2%	22%
	2030	A	1452	295	215	14.8	726	0.53
		B	1533 (+6%)	255 (-14%)	192 (-11%)	12.5 (-15%)	0%	-12%
		C	1544 (+6%)	202 (-32%)	141 (-34%)	9.1 (-38%)	-1%	-16%
scenario II	2020	A	1294	229	217	16.8	527	0.37
		B	1165 (-10%)	271 (+18%)	257 (+19%)	22.1 (+32%)	-3%	-6%
		C	1206 (-7%)	280 (+22%)	283 (+30%)	23.5 (+40%)	-5%	1%
	2025	A	1438	188	178	12.4	610	0.37
		B	1373 (-5%)	182 (-3%)	159 (-11%)	11.6 (-6%)	-3%	-5%
		C	1487 (+3%)	109 (-42%)	113 (-37%)	7.6 (-39%)	-6%	-18%
	2030	A	1452	243	187	12.9	671	0.46
		B	1460 (+1%)	176 (-28%)	140 (-25%)	9.6 (-26%)	1%	-15%
		C	1516 (+4%)	165 (-32%)	122 (-35%)	8 (-38%)	-3%	-15%
scenario III	2020	A	1308	22	11	0.8	393	0.21
		B	1077 (-18%)	111 (+405%)	132 (+1100%)	12.3 (+1357%)	-5%	-15%
		C	1051 (-20%)	192 (+773%)	209 (+1800%)	19.9 (+2265%)	-11%	32%
	2025	A	1374	85	81	5.9	469	0.27
		B	1288 (-6%)	73 (-14%)	83 (+2%)	6.4 (+9%)	-4%	-25%
		C	1215 (-12%)	107 (+26%)	128 (+58%)	10.5 (+79%)	-8%	12%
	2030	A	1266	266	247	19.5	531	0.44
		B	1308 (+3%)	117 (-56%)	108 (-56%)	8,3 (-58%)	-44%	-40%
		C	1302 (+3%)	154 (-42%)	145 (-41%)	11.1 (-43%)	-50%	-25%
scenario IV	2020	A	1241	4	4	0.3	327	0.25
		B	807 (-35%)	12 (+200%)	13 (+225%)	1.6 (+389%)	-44%	-85%
		C	781 (-37%)	37 (+825%)	45 (+1025%)	5.8 (+1660%)	-50%	-58%
	2025	A	1232	96	90	7.3	396	0.33
		B	913 (-26%)	50 (-48%)	57 (-37%)	6.2 (-15%)	-39%	-73%
		C	818 (-34%)	86 (-10%)	97 (+8%)	12.2 (+67%)	-44%	-52%
	2030	A	1206	212	205	17	447	22
		B	937 (-22%)	91 (-57%)	99 (-52%)	10.6 (-38%)	-32%	-62%
		C	965 (-20%)	94 (-56%)	109 (-47%)	11.3 (-34%)	-36%	-51%

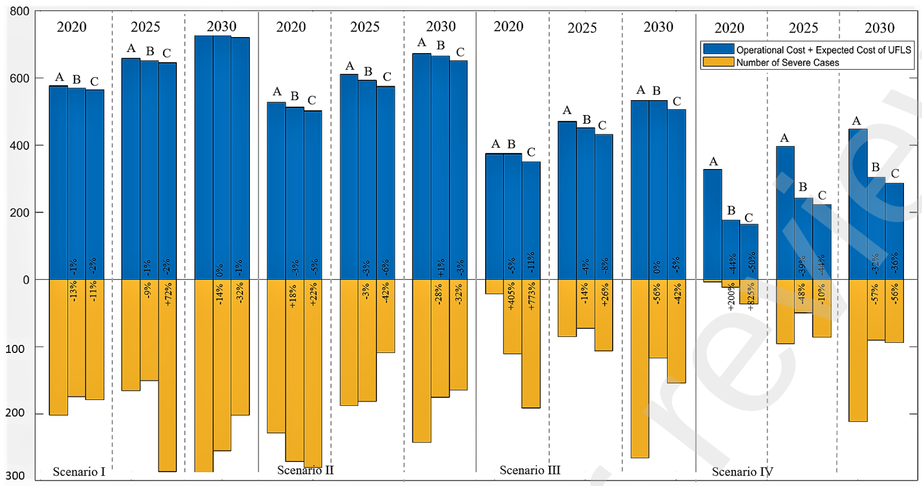

Figure 7: The average weekly results of 4 seasons in La Palma island.

only connected to cover the reserve requirements can now be disconnected. In case B and C, less spillage occurs which leads to a decrement in weekly cost, compared to the base case. In some of the hours of case B more power than the amount to cover the reserve requirements is deloaded. In these circumstances, it is more cost-efficient to deliver more power to the grid and reduce or cut the deloading and as a result, the total operation cost of case B increases with respect to case C.

6.1 Analysis of Simulations Without UFLS Schemes

When UFLS schemes are not activated, there is a high number of severe cases and frequency violations. The comparison of the metrics between these cases yields a clear picture of how and when the provision of inertia and reserve by RES improves or worsens the dynamic frequency behavior of the system. Results show that for the current demand (the year 2020), the frequency response only improves for the cases with deloading capability (cases B and C) if the wind penetration is low (Scenario I). For instance, in 2020 the number of severe cases for case B diminishes 13% for Scenario I, and increases +18%, +405%, and +200% with respect to base case A for scenarios II, III, and IV respectively. As with low demand in a small island like La Palma the number of online units is very low, and the outage of one of them has a big impact on the frequency response of the system. If the wind generation increases, fewer conventional units are connected and when the considered wind outage occurs, the impact on the frequency response is considerable. It is important to highlight that comparing different cases implies comparing different economic dispatches, as the online units for the same demand and wind penetration vary from one case to another. Figure 8 shows the frequency response of the system in hour 69 of one sample week (summer) with the current demand and low wind penetration scenario (scenario I). Each response represents the frequency response of the

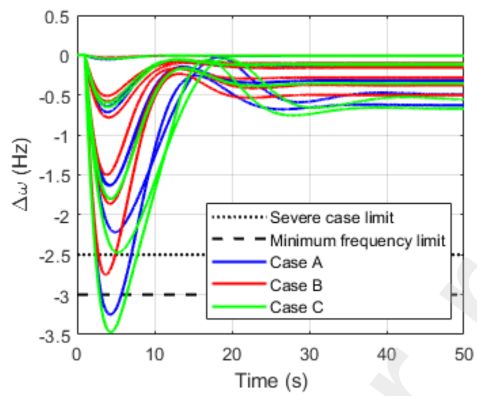

Figure 8: Frequency response in hour 69 of summer in La Palma 2020, scenario I for case A, B and C under no UFLS.

system to the outage of one of the online units. The outage of every thermal unit, as well as the loss of 10% of RES, is shown. The legend specifies the amount of power that is lost in each contingency of the generators dispatched by the UC in cases A, B, and C. This graphic illustrates how the frequency response can improve for the cases with deloading, especially if the deloading factor is constant (case B). This figure also shows the limits for severe cases and minimum frequency. UFLS schemes are essential in this case to avoid the violation of the frequency ranges required by the Spanish regulation.

It is also worth mentioning that in the year 2020, the number of severe cases is always better for case B (fixed deloading factor) than for case C (variable deloading factor). This proves that the deloading factor that is optimal from the UC economic point of view (case C) is not necessarily optimal for the frequency response enhancement. In fact, case C can improve or worsen the frequency response of the system with no clear correlation with the demand and the wind penetration (for instance, in 2030 case C improves case B in scenarios I and II, and worsens in III and IV). Since the UC schedules a minimum spinning reserve requirement neglecting frequency dynamics, wind generation is only deloaded in the hours that thermal generation up reserve is not enough. When a contingency occurs, it has less power to serve as reserve and can result in a worse frequency response. Figure 9 shows the frequency response of the system in hour 69 of the summer week with the current demand (the year 2020) and a high wind penetration scenario (IV). For each case, the frequency response of every committed unit is presented. For instance, there are five green responses because, for case C, 5 thermal units were scheduled. The figure shows also the thresholds of severe frequency response (47.5 Hz for more than 3 seconds) and minimum allowable frequency (47 Hz). It can be seen that variable deloading does not

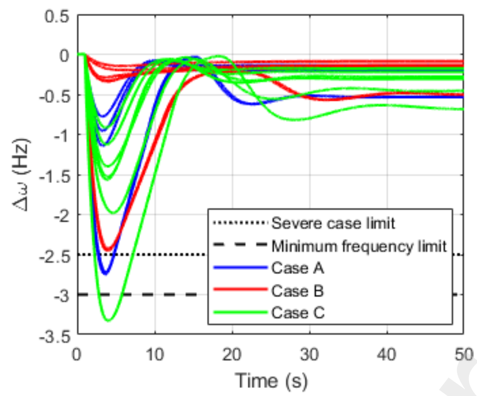

Figure 9: Frequency response in hour 69 of summer in La Palma 2020, scenario IV for cases A, B and C under no UFLS scheme.

improve the response, since a violation of the minimum frequency and thus a severe case only occurs for case C. When the demand increases (the years 2025 and 2030) more online units are connected, and their outage does not have such a high impact on the frequency response. It can be seen that a fixed deloaded capability (case B) always improves base case A, for every wind penetration scenario (Scenarios I, II, III y IV). In the increased demand scenarios of 2025 and 2030, for high wind penetration scenarios (III and IV), case C worsens the dynamic response with respect to case B.

6.2 Analysis of Simulations Under Current UFLS Schemes

When the UFLS scheme is considered, table 4 outlines that a better dynamic performance translates into less load shedding and in this way less UFLS system cost. However, due to the low values of FOR of generators, the total expected cost of UFLS is negligible compared to the system operations cost. For example, the total operation cost for the year 2020, scenario I and case A, is 575 k€ while the expected UFLS cost is 0.35 k€. When checking the total system cost (dispatch operations cost + expected UFLS cost in fig. 7) case B outperforms case A regarding the operation cost, and case C outperforms case B.

Even though reserve provision in actual demand scenarios (the year 2020) might be counterproductive, in future scenarios it allows increasing RES penetration. In addition, it becomes clear that neglecting the dynamic response when considering reserve provision in the UC model leads to an overestimate of the benefits of providing reserve. In order to improve the dynamic performance of the system and in this way reduce the UFLS, it is advisable to implement a fixed deloading percentage of RES in wind generators and not a variable deloading as decided by the UC only. However, from a strictly economical point of view with the assumed cost of load shedding, a variable deloading factor is advisable since the expected cost of UFLS is not significant compared to the operational cost. It seems also quite interesting that in order to capture both the minimum system cost and best frequency dynamic behavior, system operators of real systems should move to the use of UC models that include frequency-related constraints (more on this in [33]).

7 Results for Tenerife

The seasonal average weekly KPI and the total operation cost for different scenarios and cases for Tenerife island without UFLS scheme are shown in table 5 and in fig. 10 (which follows the same pattern as fig. 7).

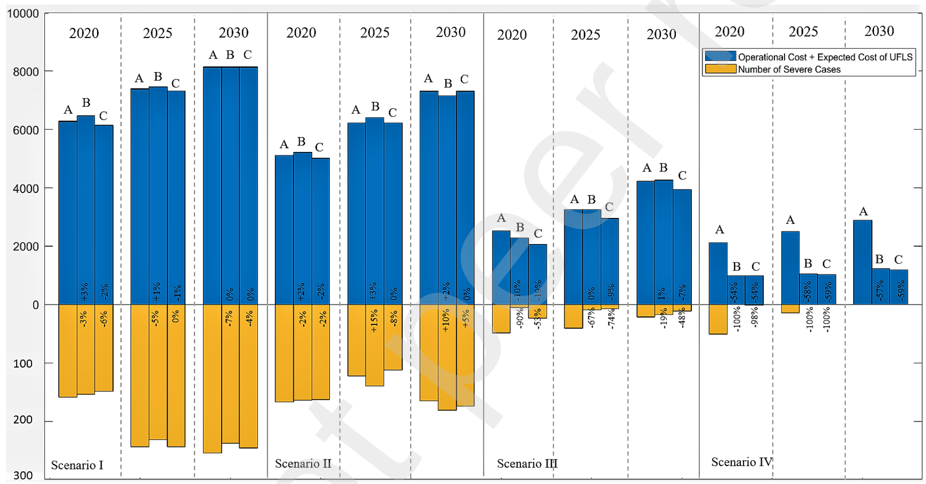

Figure 10: The average results of 4 seasons in Tenerife island.

For a bigger island like Tenerife, the main qualitative conclusions obtained for La Palma are verified only for high wind penetration scenarios. For low wind penetration scenarios (I and II), deloading (fixed or variable) might not be advisable both from an economic or a dynamic frequency quality point of view. For instance, in Scenario II and the year 2030, case B increases the number of severe cases by 10% and the total system cost by 2%, while case C increases the number of severe cases by 15% not being able to reduce the total system cost. For future wind scenarios, case B always diminishes the number of severe cases with respect to case A, and case C can improve or not frequency quality with respect to case B. For future high demand and wind scenarios (scenario IV, years 2025 and 2030) RES frequency regulation removes all severe cases meaning that UFLS is not activated.

Figure 11 shows the frequency response of the system in the first hour of a summer week with high demand (the year 2030) and a high wind penetration scenario (scenario III). It shows that deloading (either fixed deloading -red- or

Table 5: Results for Tenerife.

			SFR with no UFLS				UC simulations	SFR with UFLS
			online units in whole week (#)	severe cases (#)	min frequency violations (#)	frequency violation (%)	weekly operation cost (K€)	weekly Cost of UFLS (K€)
scenario I	2020	A	1604	159	147	9.2	6274	7.02
		B	1629 (+2%)	154 (-3%)	144 (-2%)	8.8 (-4%)	3%	-9%
		C	1625 (+1%)	149 (-6%)	145 (-1%)	8.9 (-3%)	-2%	-3%
	2025	A	1706	244	236	13.8	7388	11.07
		B	1738 (+2%)	232 (-5%)	215 (-9%)	12.4 (-11%)	1%	-13%
		C	1729 (+1%)	244 (+0%)	230 (-3%)	13.3 (-4%)	-1%	-3%
	2030	A	2005	255	234	11.7	8136	10.09
		B	2069 (+3%)	238 (-7%)	225 (-4%)	10.9 (-7%)	0%	-14%
		C	2072 (+3%)	246 (-4%)	220 (-6%)	10.6 (-9%)	0%	-10%
scenario II	2020	A	1403	167	166	11.8	5109	8.01
		B	1402 (+0%)	165 (-2%)	163 (-2%)	11.6 (-2%)	2%	-9%
		C	1401 (+0%)	163 (-2%)	163 (-2%)	11.6 (-2%)	-2%	-3%
	2025	A	1644	122	107	6.5	6233	4.65
		B	1602 (-3%)	140 (+15%)	129 (+21%)	6.3 (+24%)	3%	36%
		C	1562 (-5%)	112 (-8%)	98 (-8%)	8.1 (-4%)	0%	24%
	2030	A	1788	165	146	8.2	7305	8.25
		B	1723 (-4%)	181 (+10%)	159 (+9%)	9.2 (+9%)	2%	1%
		C	1773 (-1%)	174 (+5%)	154 (+5%)	8.7 (+5%)	0%	-1%
scenario III	2020	A	1179	49	15	1.3	2534	0.31
		B	834 (-29%)	5 (-90%)	5 (-67%)	0.6 (-53%)	-10%	-89%
		C	809 (-31%)	23 (-53%)	24 (+60%)	3 (+133%)	-19%	-48%
	2025	A	1309	27	25	1.9	3246	1.06
		B	1108 (-15%)	9 (-67%)	9 (-64%)	0.8 (-57%)	0%	-71%
		C	1094 (-16%)	7 (-74%)	7 (-72%)	0.6 (-66%)	-9%	-87%
	2030	A	1416	21	21	1.5	4231	1.08
		B	1297 (-8%)	17 (-10%)	17 (-19%)	1.3 (-12%)	1%	-74%
		C	1283 (-9%)	11 (-48%)	11 (-48%)	0.9 (-42%)	-7%	-60%
scenario IV	2020	A	1150	51	17	1.5	2131	0.33
		B	674 (-41%)	1 (-100%)	0 (-100%)	0 (-100%)	-54%	-100%
		C	672 (-42%)	0 (-98%)	1 (-94%)	0.1 (-90%)	-54%	-98%
	2025	A	1282	14	9	0.7	2499	12
		B	681 (-47%)	0 (-100%)	0 (-100%)	0 (-100%)	-58%	-100%
		C	684 (-47%)	0 (-100%)	0 (-100%)	0 (-100%)	-59%	-100%
	2030	A	1266	0	0	0	2881	9
		B	716 (-43%)	0	0	0	-57%	-100%
		C	701 (-34%)	0	0	0	-59%	-96%

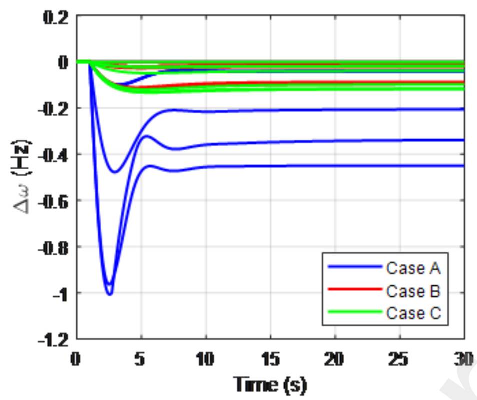

Figure 11: the frequency response in the first hour of summer in Tenerife 2030, scenario III for case A, B, and C.

optimal -green-) clearly improves the frequency response of case A represented by blue lines. Because of its big size, Tenerife has more units connected than smaller islands, and the contingency of each of them has a smaller impact on the overall frequency response. The number of severe cases, minimum frequency violation, and frequency violation percentage are better than in La Palma, and in fig. 11, none of the frequency limits are reached. It can be concluded that the size of the island power system is essential for the frequency response. More online units participating in the recovery of the system translates into a lower impact on the frequency dynamics. From the analysis of simulations run under UFLS schemes, it is clear from table 5, that total expected UFLS cost is also negligible for Tenerife island, and from a strictly economical point of view, variable deloading is best, especially for high wind scenarios (III and IV) and can reduce case A total system cost up to 60%.

8 Conclusion

This paper has evaluated the impact of providing frequency regulation by wind turbines on the system frequency response. Simulations are carried out for La Palma (small size) and Tenerife (medium size) islands with various samples of actual and future scenarios to recognize what technical impacts are expected from enabling RES to provide reserve and frequency regulation. Simulations without UFLS schemes are presented to evaluate the frequency response quality, whereas simulations under current UFLS schemes are conducted to assess the impact on UFLS size and cost. For future scenarios of a small island like La Palma, fixed deloading enhances the frequency quality behavior compared to variable deloading in most scenarios. However, since the expected cost of UFLS schemes is negligible due to typical values of FOR of generators, variable deloading is preferable from a strictly economical point of view. In a bigger island like Tenerife, variable deloading is only recommended for high demand and wind scenarios, since it improves both dynamic response and total system cost.

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