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 of ensuring a reliable frequency response in certain scenarios after outages.**

***Index Terms*—Deloading of renewable generation, frequency dynamics, unit commitment, system frequency response model.**

I. 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]. 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 [2].

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 relative 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 [3]. 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 [4]. 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 [5]. Current under frequency load shedding (UFLS) schemes disconnect certain amounts of loads if the frequency or frequency derivative exceeds certain thresholds [6]. 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 [7]. In [8], various reserve allocation methods are compared and a practice to assess immediate wind primary reserve is presented. [9] analyses different inertia and frequency regulation approaches for RES, which includes 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 ([10]) even though increasing the pitch dynamics may increase maintenance costs due to increased mechanical wear-and-tear. By deloading, wind turbines are technically able to provide reserves by working below their maximum power point tracking (MPPT) operation [11], by adjusting appropriately rotor

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speed. Typically, the deloading rate is less than 20% of the available wind power, depending on the circumstances [12]. An extensive review of the deloading of wind turbines in power systems is presented in [13], and different control methods are compared.

II. 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 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 [14]. In [15] 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 [15], 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. 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 (also presented in [16]). The rest of the paper is organized as follows. In section III, the methodology used is explained. In section IV, the description of the case studies and the scenarios are presented. In section V and section VI, the obtained results for la Palma and Tenerife under no UFLS and under the current UFLS schemes are analyzed. Conclusions are drawn in section VII.

III. 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 IV.

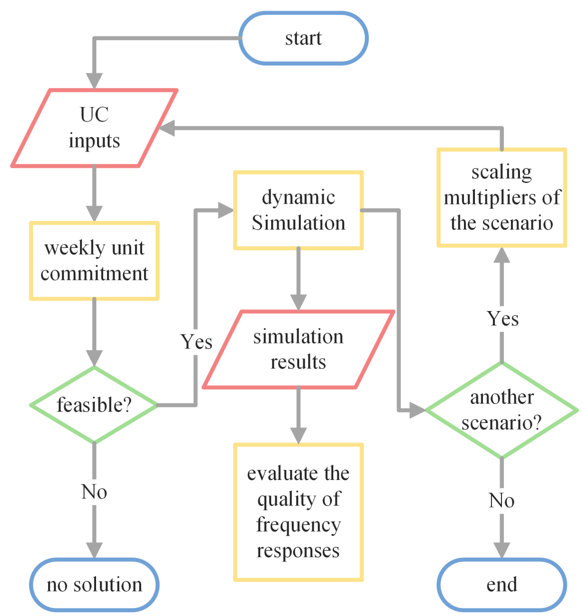

Fig. 1. Flowchart of the methodology.

A. 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 operation cost is minimized by considering technical constraints. For details on the formulation of the UC please refer to [15].

B. SFR Model

The SFR model is 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. Each generating unit 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 can be defined. The overall response of loads can be considered by means of a load-damping factor if its value is known. The complete model is explained in [17].

The inclusion of converter-connected generation can be realized if emulated inertia and parameters of the second-order generating unit model are given. In [17] wind turbines are modeled as thermal units with zero inertia and zero gain 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. 2 and has been applied in different literature studies such as [12] and [18]. This configuration implements the inertia emulation

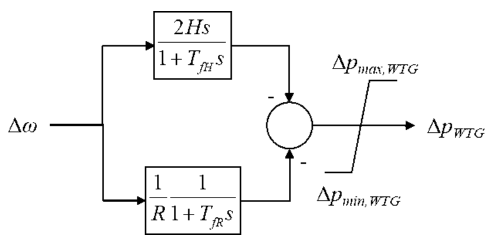

Fig. 2. Control strategy of wind turbines ($H = 3s, R = 0.05, T_{fH} = 0.01$).

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 [19].

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 [20] 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.

C. 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 requirements of Spanish islands in [21]:

- The number of severe cases per state: 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: counts the number of times that the frequency reaches a value under $47Hz$.
- The number of online units in the whole week: 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 [22].

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) [22].

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

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

Where LS is the total UFLS in megawatts and C^{UFLS} is the cost of UFLS in euros. According to [22], the FOR of each type of generator is assumed to be 0.004% for diesel generators, 0.002% for steam generators, 0.0045% for gas generators, and 0.007% for wind turbines. 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 [23] OC is assumed to be 11000€/MWh.

IV. Case Studies and Scenarios

This paper builds on the economic analysis of [15] 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.

A. Case Studies

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. Details about these two islands can be found in [24].

B. 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 the 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.
- **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 (the same percentage is used in [25] and [26] among the others).
- **Case C:** The possible amount of deloading is defined as a coefficient between 0 and 15% of available wind generation (similar to [27]). The UC optimization problem will decide the optimal amount of deloading in each hour.

Figure 3 shows all of the considered states. Weekly unit

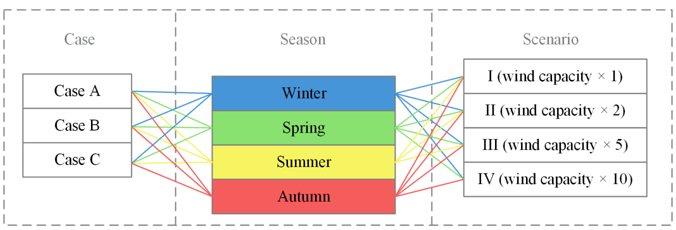

Fig. 3. Considered states.

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.

V. Results for La Palma

The weekly KPIs and the total weekly operation cost for the different scenarios and cases for the La Palma island are shown in Table I (results of 2025 aren't included for brevity).

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.

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.

Figure 4 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

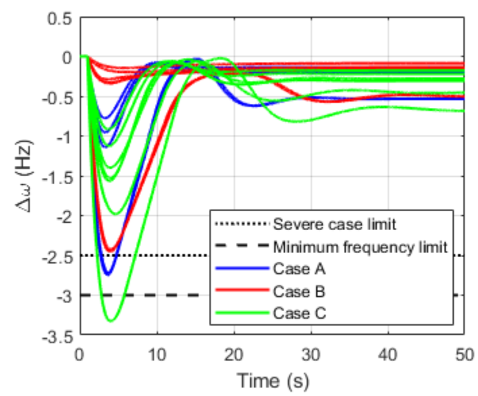

Fig. 4. Frequency response in hour 69 of summer in La Palma 2020, scenario IV for cases A, B and C under no UFLS scheme.

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 improve the response, since a violation of the minimum frequency and thus a severe case only occurs for case C.

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) case B outperforms case A regarding the operation cost, and case C outperforms case B.

VI. Results for Tenerife

The seasonal average weekly number of severe cases and the total operation cost for different scenarios and cases for Tenerife island are shown in table II (results of 2025 aren't included for brevity).

TABLE I
RESULTS FOR LA PALMA.

			SFR with no UFLS				UC	SFR with
			online units (#)	severe cases (#)	min frequency violations (#)	frequency violation (%)	operation cost (K€)	UFLS cost (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%
	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%
	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%
	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%
	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%

TABLE II
RESULTS FOR TENERIFE.

			SFR with no UFLS				UC	SFR with
			online units (#)	severe cases (#)	min frequency violations (#)	frequency violation (%)	operation cost (K€)	UFLS cost (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%
	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%
	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%
	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%
	2030	A	1266	0	0	0	2881	9
		B	716 (-43%)	0	0	0	-57%	-100%
		C	701 (-34%)	0	0	0	-59%	-96%

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 5% 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 may or may not improve the 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 5 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 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

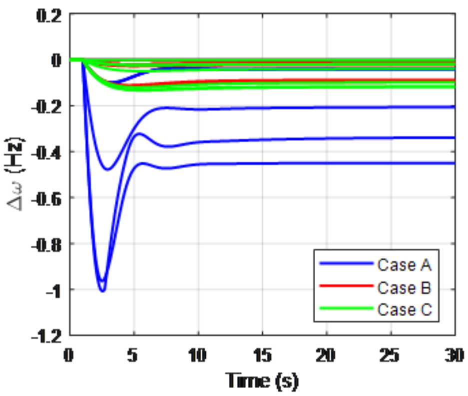

Fig. 5. the frequency response in the first hour of summer in Tenerife 2030, scenario III for case A, B, and C.

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. 5, none of the frequency limits are exceeded.

VII. 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 and Tenerife 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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