

Automatic under-frequency load shedding mal-operation in power systems with high wind power penetration

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Abstract

Countries with a **limited** interconnection capacity suffer substantial frequency variations after large incidents so they use automatic under-frequency load shedding schemes to arrest the frequency decay. Some of these countries such as Portugal, Spain and Ireland also have very high wind penetrations. This can cause additional frequency excursions due to generation time variability but also to the fact that variable speed wind turbines **do not** add **directly** their inertia to the power system. Thus several transmission system operators have announced new grid codes requiring wind turbines to provide frequency response.

In some scenarios, however, wind energy support may be detrimental **to frequency control** because it generates an extra energy that reduces decay and derivative but that cannot be maintained over time. These lower values of frequency decay and derivative are currently expected after a reduced incident or when conventional generation, which can maintain the extra generation, provides frequency support, so lead to low or no load shedding. This paper has studied, in particular, the effect of wind generation emulating inertia. A re-

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duction of frequency derivative is achieved, which looks positive at first, but in some cases leads to initial smaller load shedding than the incident requires. A reduced frequency derivative triggers less under-frequency relays as if there were a significant amount of conventional generation that is online. However, this generation has been substituted by wind generation emulating inertia, and as it can maintain extra generation over time, the frequency continues to decay until the shedding of the next load step. As a result there is an excessive frequency deviation and an incorrect load shedding for the magnitude of the initial disturbance. In order to prevent this problem, automatic under frequency load shedding settings may need readjustment when a large amount of wind generation provides frequency support.

Keywords: wind energy, under-frequency load shedding, frequency control, power system simulation

1. Introduction

Wind energy has reached penetrations over 10% in several European countries, particularly Denmark, Portugal, Spain, Ireland and Germany [12]. However, the way these countries deal with wind integration is significantly different. On the one hand, Denmark, whose penetration is by far the highest, has an extraordinary exchange capacity with its neighbouring power systems, around 100% of its peak load, that permits to deal with wind variability. In the case of high wind energy production, Denmark is able to export its overproduction to Germany, that belongs to the Synchronous grid of Continental Europe (former UCTE), or Norway and Sweden, that belong to the Nordic Synchronous Area (former Nordel). Conversely, a sudden reduction of wind generation can be mitigated by importing energy from the aforementioned countries. Moreover, this strong interconnection with other power systems supports Denmark in case of an incident that could cause a massive disconnection of wind turbines.

On the other hand, Ireland until September 2012, Portugal and Spain have had a very limited transmission capacity. The Republic of Ireland was only

interconnected with Northern Ireland via a double circuit tie line with a total transmission capacity of 1320 MW, limited to 760 MW due to existing constraints. At the end of September 2012, a 500 MW HVdc link with the United Kingdom was opened, raising the exchange capacity up to 27.3% of the 2011 peak load.

Portugal and Spain are relatively well interconnected to each other and belong to a common electricity market. Although in the case of transmission restrictions each country may have different prices (market splitting), both countries can be considered as a single system, which will be referred to as Iberian system in the following. The Iberian system is synchronously interconnected with France and Morocco. The thermal capacity of the interconnection is only 8.7% –the net transfer capacity (NTC) is around 5%– of the 2011 peak load, being 6% with the Continental Synchronous Area and the remaining 2.7% with Morocco. More detailed data about the exchange capacity of the aforementioned countries are shown in Table 1, which collects data from [11].

With a **limited** interconnection capacity below 10%, the Iberian system can be considered as an electricity “island”. Quasi-islanded systems require static sources of reserve, such as interruptible load, pumped storage hydroelectricity (PSH) and load shedding to reduce frequency variations, being the latter the only way to prevent frequency collapse following a large incident [19]. However, as installed wind capacity has reached considerable figures in those systems, the almost negligible capability to adapt energy exchanges to wind production has forced their system operators to order wind generation curtailment at certain times of high wind penetration [1] and even the installation of new wind capacity has been affected by the exchange limitation. Hence, future wind energy development depends to some extent on the possibility to increase the transmission capacity. A greater number of storage units is also helpful for this purpose. An HVdc link between Spain and France and new PSH units are currently under construction.

Variable-speed wind turbines have no inertial response so **the power system inertia is reduced when they displace conventional generators**. After an incident,

Table 1: Peak load (MW) and thermal capacity (MVA) in 2011 for selected countries.

	Denmark	Ireland	Portugal & Spain		
Peak load	6231	4610	52788		
	Germany	2676	N.I. 760	France	3142
Thermal	Norway	850	U.K. 500	Morocco	1430
capacity	Sweden	2752			
	TOTAL	6278	1360		4572

lower inertia causes an increase in the rate of change of frequency (RoCoF) that could affect the frequency relays, including those of the automatic under-
50 frequency load shedding (AUFLS) scheme [2].

Some already announced grid codes try to prevent large frequency variations by requiring wind turbines to provide some form of frequency response[8, 9, 14, 22, 27]. In the Iberian system, a proper recovery is critical to avoid the risk of losing the interconnection with France, which would make the initial incident
55 worse by leaving the system completely isolated.

Although many studies have proved the benefits of frequency response by wind turbines [17, 4, 21, 25, 28], only [17] considers load shedding. Interaction between wind energy and load shedding has been recently studied but only for small systems. **In this kind of systems, energy storage is a cost-effective option to reduce load shedding [6] or a simple PC with very short calculation time can provide adaptive adjustments or limitations in normal operation to frequency relays, spinning reserve, load reconnection, or wind generation [7]. In [15], the interaction of wind and load shedding is studied in detail but only from the intermittency point of view.**
60

This paper studies the impact of increasing wind penetration on larger power
65 systems equipped with AUFLS, **when provide frequency support.** The model of the power system used in the simulations is described in Section 2. The different studied scenarios are presented in Section 3, and the effects of increasing wind penetration on load shedding in the different scenarios are presented in Section 4.

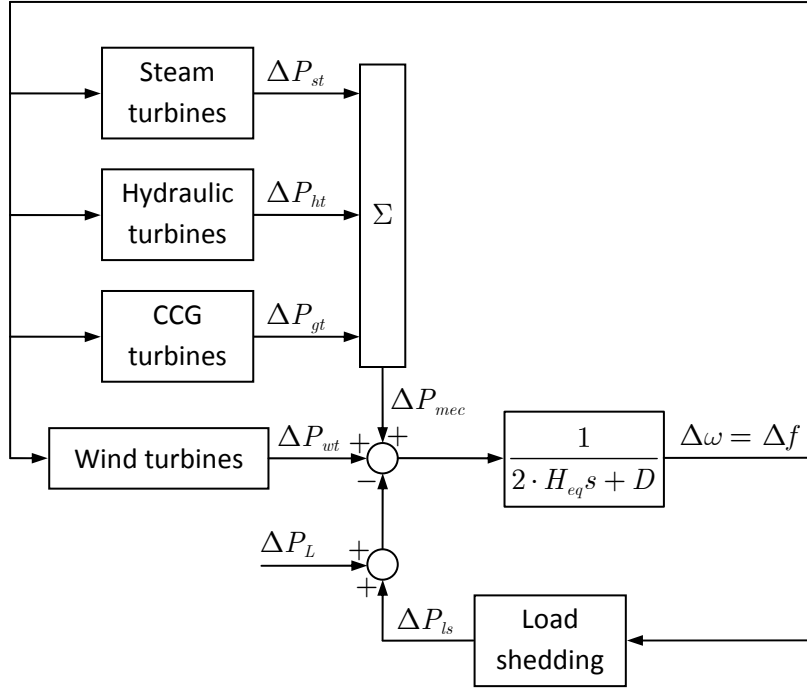


Figure 1: Schematic of power system model.

70 Conclusions are summarized in Section 5.

2. Power system description

A single bus bar model of the Spanish peninsular system, depicted in Fig. 1, has been developed in Simulink to analyse the frequency response of different incidents. The generation consists of four different technologies, comprising
75 steam, hydraulic, combined cycle gas (CCG) and wind turbines. Conventional generation rotates synchronously, adding inertia to the power system so its mechanical powers add to the total mechanical power P_{mec} . On the other hand, all wind turbines have been considered to work at variable speed and, therefore, they have no frequency response with the conventional control. Their generated
80 power P_{wt} is considered as electrical power with opposite sign to the demand P_L . The model also incorporates AUFLS including PSH, which produces a load

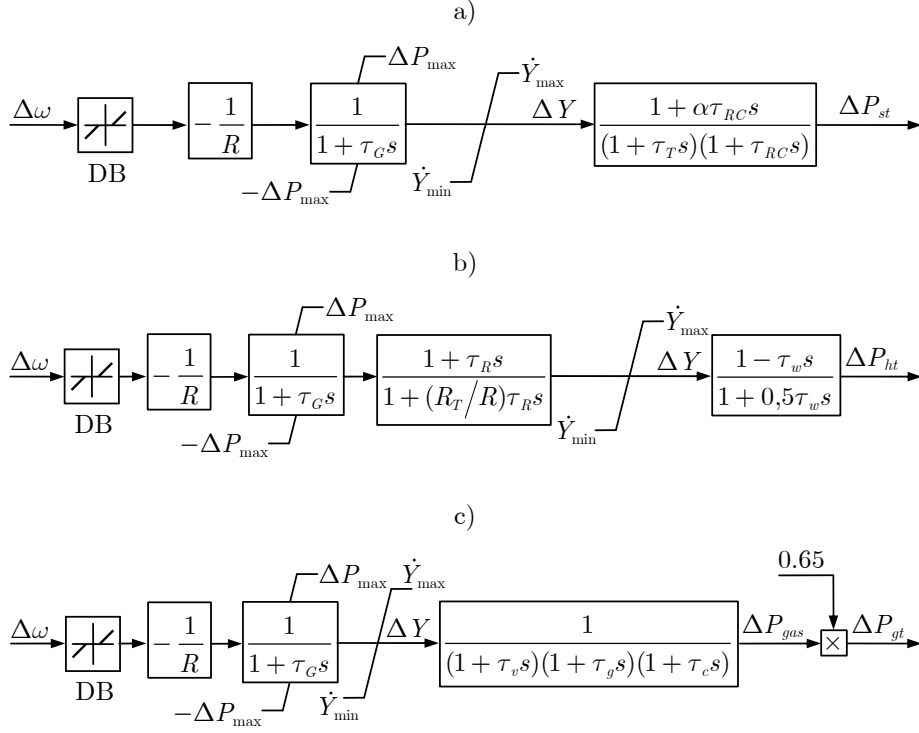


Figure 2: Models of a) steam, b) hydraulic, and c) combined cycle gas turbines.

disconnection ΔP_{ls} in case of frequency decay. All the variables are considered as small deviations from normal operation.

Models of these characteristics, which only consider a uniform frequency
85 across the system, have been proved valid for island systems over many years [23, 18].

A deviation in generation or load will lead to a deviation in frequency following the power system dynamics. A first order transfer function includes the power system inertia constant H_{eq} and the self-regulation of load (also known
90 as load-damping constant) D . The parameters of all the power system elements are provided in the Appendix.

2.1. Conventional generation

Commonly accepted models based in [16] have been used for the steam and hydraulic turbines. The CCG turbine model is based on [24]. Fig. 2 shows the schematic of the a) steam, b) hydraulic and c) CCG turbine models. In a CCG turbine, only the gas turbine provides frequency support, in contrast to the assembled steam one. Therefore, the gas turbine output is multiplied by 0.65, which is its share of the total CCG turbine output. All turbines include a governor with the same characteristics, including dead band DB, droop $-1/R$, time constant τ_G and maximum power increase ΔP_{\max} .

2.2. Wind energy

The total wind power plants are considered as an aggregate model based on a variable speed wind turbine. With additional controls, this kind of wind turbines can provide frequency control [5], including inertia emulation and even primary control when there is energy storage [26]. Spain experienced significant development of wind industry later than other countries with longer wind energy tradition such as Denmark or Germany. Hence, doubly-fed induction generator (DFIG) is the predominant technology.

A DFIG model based on [3] has been used in the simulations. Besides, [3] also includes the characteristics of both frequency controls for commercial use offered by General Electric, inertia emulation and active power control. A supplementary control strategy for DFIGs that is specific for mitigating the impact of **limited** inertia can be found in [13]. Only inertia emulation has been considered **in this work because in the event of under frequency**, wind turbines can provide this control with relatively ease and, **contrary to active power control**, do not need to operate continuously deloaded. **Several grid codes consider deloaded operation of wind turbines, although in practice they are not required to continuously spill wind just in case their upward regulation is required at some point due to under frequency. In the absence of grid restrictions, wind turbines are allowed to produce their maximum power and may be required to provide only downward regulation in the event of over frequency. Thus exclusively the**

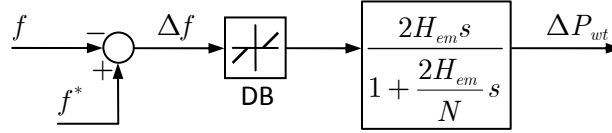


Figure 3: Inertia emulation control.

effect of no deloaded wind turbines providing upward regulation through inertia emulation has been studied.

The inertia emulation control is depicted in Fig. 3 and consists in a derivative
 125 gain that is twice the inertia H_{em} to emulate. Three different values of the
 derivative gain have been considered 5, 10 and 15 s, which emulate reasonable
 values of inertia, 2.5, 5 and 7.5 s respectively. An N times faster filter has
 been also added in order to minimize the mechanical impact on the drive train.
 Control engineering recommends values of N between 5 and 20 for derivative
 130 filters, depending on the noise of the signal. Frequency measurements in the
 simulations are quite smooth so the maximum value ($N = 20$) has been chosen.

2.3. Exchange capacity

According to the figures shown in section 1, the Iberian system has a very
 limited interconnection capacity. In the event of a contingency in the tie-lines
 135 connecting Spain to France, the interconnection capacity becomes almost negli-
 gible. Moreover, primary regulation from the rest of countries cannot contribute
 to the Iberian system stability as much as it should because it would trip the
 few interconnection tie-lines. As a result, no exchange capacity has been taken
 into account in the simulations, which consider contingency scenarios. Thus
 140 power system has been considered as completely isolated.

2.4. Automatic under-frequency load shedding

The design of an AUFLS scheme depends on many issues, including the
 largest expected incident, the minimum permissible frequency and the values of
 inertia constant and load-damping constant. AUFLS schemes are implemented

145 in various steps. Each step is tripped at different frequency values and sheds a certain load portion.

The scheme used in the simulations is based in the information provided in the Spanish operating procedure 1.6, which only includes data about frequency drops and amount of load shed. According to [16], a scheme based on
150 frequency drop alone is generally acceptable for incidents up to 25%. Greater incidents could cause unnecessary tripping of load so selectivity should be increased by taking into account the RoCoF [29]. Ontario Hydro uses different frequency trend relays whose RoCoF are set to 0.4, 1.0, 2.0 and 4.0 Hz/s [16]. The protection criteria of the Spanish transmission system operator state that
155 the coordination of frequency relays of all generation units and the load shedding must be sensitive to the RoCoF. The exact frequency derivative values are not given for the peninsular system but they are perfectly known for one of the Spain's non peninsular systems. The AUFLS relays of this system are set to 0.5 or 1.0 Hz/s depending on the frequency excursion. These values are consistent
160 with those used in Ontario Hydro except for the first value, which differs in 0.1 Hz/s. A lower value seems appropriate for larger systems where a lower RoCoF is expected, as is the case of our system.

As a result, the AUFLS settings used in the simulations are shown in Table 2, which include two steps of PSH. Each one represents 0.05 p.u. as the installed
165 capacity of PSH in Spain is around 10% of its off-peak demand.

The trip time of the AUFLS has been considered 220 ms, which corresponds to the sum of 6 cycles (120 ms) for detection plus 100 ms for the time from the relay signal sent to circuit breaker operation.

2.5. System inertia constant and self-regulation of the load

170 The inertia constant of a power system depends on the characteristics of the generating units that are online at each instant of time. Inertia constant is around 3 s in hydraulic turbines whereas it is between 4 and 7 s in steam turbines. Variable wind turbines are non-synchronous generators which have no inertial response so the higher the wind penetration, the lower the power system

Table 2: Automatic under-frequency load shedding scheme.

Load shed	Relay settings
50% PSH	
25% PSH	49.5 Hz
25% PSH	49.5 Hz + 0.4 Hz/s
50% PSH	
25% PSH	49.3 Hz
25% PSH	49.3 Hz + 0.4 Hz/s
15% load	
4% load	49.0 Hz
5% load	49.0 Hz + 0.4 Hz/s
6% load	49.0 Hz + 1.0 Hz/s
15% load	
4% load	48.7 Hz
5% load	48.7 Hz + 0.4 Hz/s
6% load	48.7 Hz + 1.0 Hz/s
10% load	
5% load	48.4 Hz
5% load	48.4 Hz + 0.4 Hz/s
10% load	
5% load	48.0 Hz
5% load	48.0 Hz + 0.4 Hz/s

175 inertia constant [17].

A study of the Spanish system [20] obtained the minimum values of the inertia constant that guarantee stability after a three-phase fault during peak and off-peak load. The results were 3.6 s for peak demand and 1.3 s for off-peak demand. The latter value is so low that is only possible with massive amounts of non-synchronous generation substituting conventional generation, which can only happen during off-peak hours. The former supposes a higher amount of conventional generation that is online, which at off-peak hours implies operation at minimum technical load offering spinning reserve. This scenario is more realistic today so it will be used to simulate the behaviour of the power system. If the steam generation is considered to have a penetration of 40% and inertia of 6 s, hydro generation to have a penetration of 15% and inertia of 3 s and CCG generation to have inertia of 4 s, then the wind penetration is around 25%, which is considered a significant value.

180 The self-regulation of the load has been considered to be 0.5 p.u. since the European Network of Transmission System Operators for Electricity (ENTSO-E) establishes that in the Continental Synchronous Area it is assumed to be 1%/Hz [10].

3. Studied scenarios

Two scenarios have been studied. One represents peak hours whereas the other represents off-peak hours. In each scenario, three different wind penetrations have been considered, low (LW), medium (MW), and high (HW), corresponding to 10, 30, and 50%, although 50% is only achievable during off-peak load. While production of steam and hydraulic turbines remains constant throughout the day, being 35 and 15% respectively, the CCG turbines adapt their production depending on the wind penetration.

200 Incidents considered for each scenario are based on the reference incident and the observation incident described by ENTSO-E for the Continental Synchronous Area. The reference incident is the maximum instantaneously oc-

ccurring power deviation between generation and demand in both positive and
 205 negative direction, which according to [10] is defined to be 3000 MW. Obser-
 vation incidents are separated into two levels. The first level is reached when
 the sudden loss of generation or load exceeds 600 MW whereas the second level
 implies that the incident exceeds 1000 MW. In the Spanish system the refer-
 ence incident supposes a power deviation of approximately 7% of peak demand
 210 and approximately 15% of off-peak demand. The observation incident supposes
 a power deviation of approximately 3% of peak demand. The two considered
 scenarios are as follows.

- **Peak load (S1).** PSH units are not operating and the reference incident
 assumes a power deviation of 7% so considered incidents will be of this
 215 magnitude or lower.
- **Off-peak load (S2).** PSH units are operating and the reference incident
 supposes a power deviation of 15%.

4. Results

Initially, all scenarios are in steady state with constant 50 Hz frequency
 220 until $t = 5$ s, when an incident occurs causing a frequency drop. The frequency
 variation has been measured with the following indicators:

- maximum dynamic frequency deviation, Δf_{\max} (mHz). According to
 ENTSO-E it must be lower than 800 mHz from the nominal frequency
 in response to the reference incident.
- 225 • quasi-steady state frequency deviation, Δf_{qss} (mHz). According to ENTSO-
 E it must be lower than 180 mHz from the nominal frequency in response
 to the reference incident.
- RoCoF at certain frequency X, \dot{f}_X (mHz/s). Part of the shedding relays
 trip depending on this value.
- 230 • load shed, ΔP_{ls} (%). It is the amount of load or PSH that is shed.

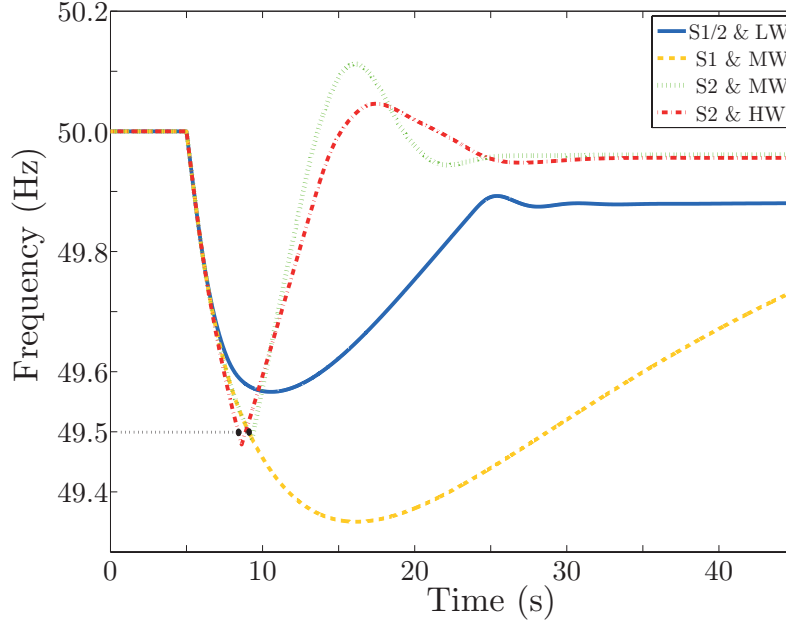


Figure 4: Frequency in S1 and S2 after a 3% incident when there is no wind energy contribution to frequency control.

4.1. No wind energy contribution to frequency control

First, both scenarios 1 (S1 & S2) have been simulated when wind energy does not contribute to frequency control. These simulations are representative of the current situation of the Spanish power system. Wind energy has displaced some conventional generation but there is still sufficient online to maintain system inertia equal to 3.6 s. The obtained frequency deviations after a 3% incident are shown in Fig. 4 and all indicators are given in Table 3.

With low wind penetration (LW), the frequency drop is identical in both scenarios because the frequency deviation is below 500 mHz and hence no load is shed. However, with medium wind penetration (MW), the frequency drop clearly differs. In S1 no load is shed either since the frequency drops 650 mHz, i.e. less than 1 Hz, whereas in S2 a part of the PSH (25%) is shed and the frequency drops less, 512 mHz. With high wind penetration (HW), which is

Table 3: Frequency deviation characteristics and load shed when there is no wind energy contribution to frequency control.

3% INCIDENT					
Scenario	Δf_{\max}	$\dot{f}_{49.5}$	$\dot{f}_{49.0}$	ΔP_{ls}	Δf_{qss}
S1 or S2 & LW	-434	-	-	-	-115
S1 & MW	-650	-	-	-	-134
S2 & MW	-512	-0.05	-	25% PSH	-38
S2 & HW	-521	-0.10	-	25% PSH	-44

7% INCIDENT					
Scenario	Δf_{\max}	$\dot{f}_{49.5}$	$\dot{f}_{49.0}$	ΔP_{ls}	Δf_{qss}
S1 & LW	-1065	-	-0.30	4% load	-115
S1 & MW	-1109	-	-0.33	4% load	-134
S2 & LW	-602	-0.41	-	50% PSH	-83
S2 & MW	-621	-0.42	-	50% PSH	-96
S2 & HW	-670	-0.42	-	50% PSH	-118

only possible in S2, both the frequency deviation and the amount of shed PSH
245 are similar. Only 25% of the PSH is shed because the RoCoF at 49.5 Hz ($\dot{f}_{49.5}$),
highlighted with two black dots in Fig. 4, is below 0.4 Hz/s¹.

With a 7% incident, the obtained frequency deviations increase, as Table 3
shows. In S1 the frequency reaches 49 Hz and 4% of the load is shed whereas in
S2 frequency drop is lower because PSH is available at 49.5 Hz, and the whole of
250 this step (50%) is shed. All quasi-steady state frequencies are below 180 mHz.

Finally, a 15% incident has been simulated in S2 and the results show that
shedding of the whole PSH (100%) and 4% of load is required to achieve the
frequency recovery with all penetrations. The quasi-steady state deviation is
only 51 mHz.

255 Previously obtained results prove that the AUFLS scheme is correctly de-

¹For a better understanding, frequency magnitudes are considered in their absolute value throughout the text.

Table 4: Frequency deviation characteristics and load shed after a 3% incident when wind energy emulates inertia.

Scenario	$2H_{em}$	Δf_{\max}	$\dot{f}_{49.5}$	ΔP_{ls}	Δf_{qss}
	5 s	-507	-0.03	25% PSH	-38
S2 & MW	10 s	-503	-0.02	25% PSH	-38
	15 s	-490	-	-	-134
	5 s	-513	-0.06	25% PSH	-44
S2 & HW	10 s	-509	-0.04	25% PSH	-44
	15 s	-506	-0.03	25% PSH	-44

signed when power system inertia has a reasonable value and the magnitude of the potential incidents are known. Hence it effectively arrests the frequency and returns it to a value close to normal.

4.2. Wind energy contribution to frequency control

260 The effect of wind turbines providing inertia emulation has been simulated. For a 3% incident, Table 4 shows the frequency variation in S2.

Simulation of S1 is considered not necessary because although wind energy support certainly reduces frequency deviation, in this scenario there are no discernible benefits. A lower frequency drop is only clearly beneficial if load shedding is avoided and Table II shows that no load is shed in S1 without wind energy support.

270 However, PSH shedding is avoided in S2 when wind turbines emulate 7.5 s inertia and the wind penetration is medium. As a counterpart, the quasi-steady state frequency deviation increases from 38 to 134 mHz, which is acceptable because remains below 180 mHz. In the rest of cases wind turbines reduce both maximum deviation and RoCoF but the same amount of load is shed.

275 With a 7% incident, Table 5 shows that not even the emulation of the largest inertia is able to avoid some kind of load shedding. In fact, the amount of shed load does not change but the order does. In S2 the RoCoF at 49.5 Hz is below 0.4 Hz/s so only half the PSH of this step is shed. As a consequence

the frequency continues falling until half the PSH of the next step is shed. The same amount of shed load implies the same quasi-steady state frequency deviation. However, the wrong step order implies larger maximum dynamic frequency deviations.

280 Finally, Table 5 also shows the frequency deviation characteristics when a 15% incident occurs in S2. The amount of shed load depends on the wind energy penetration. With low penetration the amount is the same with and without wind energy support. With medium penetration less load is shed when the emulated inertia is either 5 or 7.5 s because the RoCoF at 49.3 Hz is lower
285 than 0.40 Hz/s so only half of the step is shed. For 5 s Table 5 shows a higher value but after 120 ms of detection the value is lower. The load shedding mal-operation is far worse with the higher wind penetration. The avoidance of some PSH shedding causes higher shedding of consumer load. The avoidable shedding is produced at 48.7 Hz so maximum dynamic frequency deviation significantly
290 increases. By contrast, the quasi-steady state frequency deviation changes to positive due to over-shedding.

Therefore the maximum value of emulated inertia avoids load shedding for a 3% incident but with larger incidents, it leads to AUFLS mal-operation. Thus, it is clearly preferable to emulate inertia of 2.5 s. It is shown in the previous
295 section that this value offers the best results when the power system inertia is minimal.

Load shedding mal-operation is largely due to current schemes having been designed according to the conventional generation mix where a small RoCoF is only possible in two situations, namely when the incident is small or when
300 there is a considerable amount of conventional generation increasing the system inertia and providing primary control to arrest frequency. Wind generation, however, reduces RoCoF while not providing primary control. Frequency is not arrested and continues to decay until more load is shed.

Table 5: Frequency deviation characteristics and load shed when wind energy emulates inertia.
7% INCIDENT

Scenario	$2H_{em}$	Δf_{\max}	$\dot{f}_{49.5}$	$\dot{f}_{49.3}$	$\dot{f}_{49.0}$	$\dot{f}_{48.7}$	ΔP_{ls}	Δf_{qss}
S1 & LW	5 s	-1058	-	-	-0.27	-	4% load	-115
	10 s	-1053	-	-	-0.25	-	4% load	-115
	15 s	-1048	-	-	-0.22	-	4% load	-115
S1 & MW	5 s	-1062	-	-	-0.26	-	4% load	-134
	10 s	-1046	-	-	-0.21	-	4% load	-134
	15 s	-1039	-	-	-0.18	-	4% load	-134
S2 & LW	5 s	-732	-0.38	-0.16	-	-	(25% + 25%) PSH	-83
	10 s	-728	-0.35	-0.13	-	-	(25% + 25%) PSH	-83
	15 s	-724	-0.34	-0.11	-	-	(25% + 25%) PSH	-83
S2 & MW	5 s	-731	-0.33	-0.15	-	-	(25% + 25%) PSH	-94
	10 s	-724	-0.28	-0.11	-	-	(25% + 25%) PSH	-94
	15 s	-719	-0.24	-0.09	-	-	(25% + 25%) PSH	-94
S2 & HW	5 s	-732	-0.30	-0.15	-	-	(25% + 25%) PSH	-118
	10 s	-724	-0.23	-0.11	-	-	(25% + 25%) PSH	-118
	15 s	-718	-0.19	-0.08	-	-	(25% + 25%) PSH	-118
15% INCIDENT								
S2 & LW	5 s	-1038	-0.95	-0.92	-0.18	-	100% PSH + 4% load	-51
	10 s	-1032	-0.93	-0.85	-0.15	-	100% PSH + 4% load	-51
	15 s	-1027	-0.92	-0.80	-0.12	-	100% PSH + 4% load	-51
S2 & MW	5 s	-1035	-0.85	-0.62	-0.16	-	100% PSH + 4% load	-57
	10 s	-1193	-0.78	-0.42	-0.25	-	75% PSH + 4% load	-153
	15 s	-1171	-0.74	-0.33	-0.21	-	75% PSH + 4% load	-153
S2 & HW	5 s	-1034	-0.76	-0.44	-0.16	-	100% PSH + 4% load	-68
	10 s	-1305	-0.65	-0.29	-0.22	-0.02	75% PSH + (4% + 4%) load	44
	15 s	-1306	-0.58	-0.23	-0.18	-0.03	75% PSH + (4% + 4%) load	44

5. Conclusion

305 Power systems with limited interconnection capacity are equipped with AU-
FLS to prevent excessive frequency decays. When high wind penetrations are
reached in these systems, the wind turbines are forced to provide frequency
response.

Wind energy inertia emulation is beneficial since the frequency deviation is
310 reduced. However, this fact can only be considered indeed a benefit if some load
shedding is avoided. When the wind turbines emulate a large inertia, there is
no load shedding in the smaller incidents considered in the simulations.

However, with higher emulated inertias the RoCoF is excessively reduced
and some frequency trend relays of the AUFLS do not trigger. As a result,
315 the system frequency continues decaying until the next step, where part of its
load is shed. This leads to both larger frequency deviations and the shedding
of loads that do not correspond to the initial disturbance magnitude. In these
cases, lower values of emulated inertia have been found to give better results.

The results obtained in this work suggest that AUFLS schemes that use
320 derivative frequency may need revision in power systems with high amounts of
wind generation providing inertia emulation.

Appendix

System parameters

Power system: $H_{e}q = 3.6$ s; $D = 0.5$ p.u.

325 **Steam turbines:** $\alpha = 0.3$ p.u.; $\tau_T = 0.3$ s; $\tau_{RC} = 0.3$ s; $\dot{Y}_{\max} = 0.05$ p.u./s;
 $\dot{Y}_{\min} = -0.1$ p.u./s

Hydraulic turbines: $\tau_w = 5$ s; $\tau_R = 5$ s; $R_T = 0.38$ p.u.; $\dot{Y} = \pm 0.16$ p.u./s

330 **Combined cycle gas turbine:** $\tau_v = 0.1$ s; $\tau_g = 0.4$ s; $\tau_c = 0.4$ s; $\dot{Y}_{\max} =$
 0.02 p.u./s; $\dot{Y}_{\min} = -0.02$ p.u./s

Governor: $R = 5\%$; $\tau_G = 0.2$ s; $BM = \pm 20$ mHz; $\Delta P_{\max} = 0.05$ p.u.

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