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Assessment of Primary Frequency Control through Battery Energy Storage Systems

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Abstract

This article focuses on the impact of the primary frequency control that can be provided by Battery Energy Storage Systems (BESSs) on the transient response of electric grids. A procedure based on the Fourier transform is used for synthesizing a realistic frequency signal based on the variations of load consumption and generation. The impact of BESSs is evaluated with respect to the storage capacity installed and the regulation strategy adopted and then compared with the regulation provided by conventional sources. The impact of a variable-droop strategy on the dynamic response of the grid and the BESSs State of Charges (SOCs) is also evaluated. A novel index to quantify the performance of the BESSs is proposed and discussed. The case study is based on a detailed dynamic model of the all-island Irish transmission system.

Keywords: Battery energy storage systems, Fourier transform, frequency control, renewable energy.

1. Introduction

1.1. Motivations

The recent successful operation of a 100 MW BESS installed in South Australia indicates that BESSs are very well suited for Primary Frequency Control (PFC) due to their fast response [1]. In several European systems, BESSs

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6 already participate to the PFC service [2] and National Grid in UK has started
7 a new service called “enhanced frequency response” that requires a power re-
8 sponse in less than 1 second [3]. This paper addresses the open question of
9 how to assess the performance of BESSs that provide PFC compared to con-
10 ventional primary frequency controllers during normal grid dynamic conditions.
11 Such an appraisal appears particularly relevant if ancillary services are rewarded
12 proportionally to their effectiveness, as recently recommended by FERC [4].

13 *1.2. Literature Review*

14 There are several studies on the impact of BESSs on primary frequency con-
15 trol. The contribution of BESSs to frequency stability after a contingency is
16 discussed in [5, 6, 7, 8, 9]. The use of BESSs to regulate the frequency within
17 a microgrid is studied in [10, 11]. A third group of studies focuses only on the
18 BESSs without considering their impact on the grid. In these works various
19 strategies, e.g. variable droop, energy arbitrage and participation to balancing
20 markets, are utilised in order to optimize BESS profit and SOC management in
21 addition to frequency regulation. In [12, 13, 14], BESSs regulate their SOC by
22 considering the instantaneous frequency. BESS power output can be adjusted
23 using a different droop, changing the set point when the frequency is in the
24 deadband or considering an over-response from the battery. Heuristic meth-
25 ods [12, 13] or fuzzy control logic [14] is used to control the BESS response.
26 Moreover the use of market schedules and participation in intra-day and bal-
27 ancing markets is considered to avoid over and under charging values [13] and to
28 perform energy arbitrage [14]. More efficient approaches considering dynamic
29 programming are used in [15, 16]. Multi-services provision [17] and the presence
30 of other resources like loads or PV is studied in [18, 19] by using optimization
31 approaches (e.g. model predictive control) in order to maximize the frequency
32 reserve capacity of the BESS. In UK and Central Europe, BESSs are already
33 allowed to vary their droop from the nominal value to partially regulate their
34 SOC [3, 13] by considering a small deviation from the nominal point [12]. Since
35 BESSs capacity devoted to provide PFC service to the grid is expected to in-

crease [1], Variable Droop (VD) strategies are thus expected to play a relevant
role.

Multi-hour/day simulations to study the BESSs impact on the grid are considered in [20, 21, 22, 23, 24]. In [20], the impact of a BESS on a small power system is evaluated with field tests by changing the parameters of PFC. The improvement of the frequency signal is estimated by computing the grid frequency standard deviation when BESS is on or off, but not explicitly simulated. In [21], a specific control algorithm that takes into account droop control and SOC management for the BESS is implemented and its effect on the frequency signal is simulated. However, no index is used to quantify this improvement. In [22, 23, 24], the focus is on secondary frequency control, where BESSs are introduced in the simulations to improve the stability of the grid, and their performance is compared to Conventional Generation (CG).

The evaluation of the performance of the frequency control through BESSs is closely linked to the creation of realistic frequency scenarios. In [22, 23, 24], measurement data from several load profiles and photovoltaic power plants are used, while the power exchanged at the tie lines and frequency reserves are estimated. These approaches cannot guarantee a realistic signal, unless a huge and diversified database of measurements is used, which is impractical for large scale power systems. In [21], a system equivalent model is used to reproduce a recorded frequency signal only if real time grid data parameters and variables can be accurately estimated.

The definition of realistic scenarios requires a precise characterization of all components and controllers of the grid. A taxonomy of the frequency variations in Europe is presented in [25]. These are divided into: (i) stochastic frequency deviations due to the fast variations of loads and renewable sources, (ii) deterministic frequency deviations caused by the ramps of CG following their market scheduling [26]. CG undergoes an hourly or sub-hourly unit commitment, which leads to a long term mismatch with respect to the net load [27]. In order to reproduce a realistic signal it is necessary to simulate both typologies of frequency deviations and verify the resulting variability of the frequency signal

67 with real-world data.

68 *1.3. Contributions*

69 The contributions of this paper are as follows:

- 70 • quantify the impact of the primary frequency control provided by BESSs
71 and compare it to CG contribution through the use of a novel quantitative
72 index. It is also studied the impact of a VD control strategy used by
73 BESSs.
- 74 • a novel procedure, whose preliminary version appeared in [28], to generate
75 realistic synthetic frequency scenarios.

76 *1.4. Organization*

77 The remainder of the paper is organized as follows. Section 2 presents the
78 stochastic models included in the grid, whereas Section 3 describes the adopted
79 frequency control of the BESS. Section 4 outlines the procedure to create real-
80 istic scenarios. Section 5 describes various indexes, included the proposed one,
81 to evaluate the performance of the control provided by BESSs and other energy
82 resources. Section 6 describes the case study and discusses simulation results.
83 Finally, Section 7 provides conclusions and outlines future work.

84 **2. Modelling of Stochastic Processes**

85 In normal dynamic conditions, frequency variations are mostly determined
86 by the unbalance between total produced and consumed power [29]. This un-
87 balance is caused by the variations of loads, wind power plants and conventional
88 generators ramping to change set point. Power variations are stochastic and,
89 thus, a proper mechanism to emulate randomness has to be put in place to
90 obtain realistic results from simulations. We provide below a short description
91 of the devices involved in the creation of the power disturbances considered in
92 this work.

93 *2.1. Conventional Generation*

94 The PFC of conventional power plants is shown in Fig. 1. f_{nom} is the nominal
 95 frequency of the grid, while f is the instantaneous frequency value, p_{pfc} is the
 96 power requested by primary frequency control, p_{ord} is the power reference set
 97 point of the turbine and R [pu(Hz)/pu(MW)] is the droop of the controller.
 98 The lead-lag block represents the turbine governor dynamics and p_m is the
 99 mechanical output of the turbine. By changing the time constants it is possible
 100 to simulate different CG technologies like steam, gas and hydro power plants.
 101 The model is detailed enough for transient stability studies, where frequency
 102 variations remain well bounded and the focus is the overall response of the
 103 system. As explained in Section 4, p_{ord} is subjected to ramps of maximum
 104 amplitude $|\Delta p_{\text{max}}|$ with time period Δt_{CG} ranging from few minutes up to
 105 one hour in order to mimic the power variations yielded by net load following
 106 dispatching. In such a way, we reproduce slow power fluctuations around the
 107 net load. An example of such fluctuations is shown in Fig. 2.

108 *2.2. Load*

Load models are assumed to be voltage-dependent, i.e., exponential or ZIP
 models, and either static or dynamic voltage recovery [30]. The reference power
 consumption of a load, say p_{load} , is defined as the sum of two components:

$$p_{\text{load}} = p_{\text{det}} + p_{\text{sto}} , \quad (1)$$

109 where p_{det} is the “deterministic” consumption which is assumed to vary linearly
 110 between assigned values in a given period, e.g. 15 minutes; p_{sto} is a stochastic

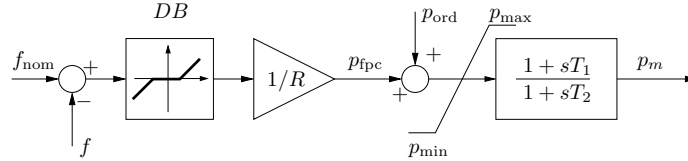


Figure 1: simplified model of the primary frequency control and turbine of conventional power plants. Note that all quantities in the figure are in pu.

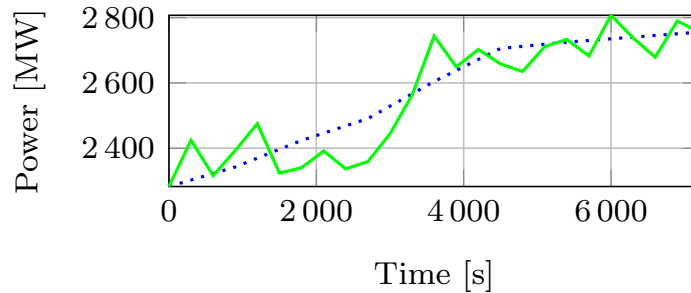


Figure 2: example of noise that reproduces slow fluctuations. The blue dotted line represents the net load, while the green solid line represents the net load plus CG fluctuations.

111 fluctuation that models volatility. p_{sto} is defined as a Gaussian distribution
 112 with a given standard deviation σ_{Load} . Stochastic variations are computed with
 113 a given period Δt_i . Fig. 3 shows an example of load profiles.

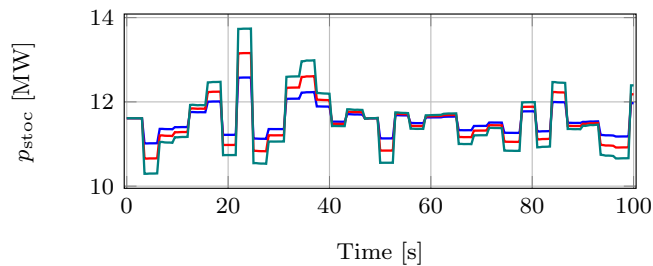


Figure 3: examples of p_{sto} profiles using $\Delta t_i = 3$ s and various standard deviations, namely 2.5, 4 and 5.5%.

114 *2.3. Wind Generation*

Wind generators are modelled as doubly-fed induction generators (Type C). The turbine is fed by wind speed time series, which are defined as the sum of two components: wind speed stochastic component $w_{\text{s,sto}}$ [m/s] and $w_{\text{s,ramp}}$ [m/s] component modelled as linear wind speed ramps with a certain time period. The stochastic component is modelled as a set of Stochastic Differential Equations (SDEs) based on the Ornstein-Uhlenbeck Process [31], also known as mean-

reverting process. The equations for the wind speed ω_s can be written as follows:

$$w_s = w_{s,\text{ramp}} + w_{s,\text{sto}} , \quad (2)$$

$$\dot{w}_{s,\text{sto}} = \alpha(\mu_w - w_{s,\text{sto}}) + b_w(\sigma_w)\xi_w , \quad (3)$$

115 α is the mean reversion speed that dictates how quickly the $w_{s,\text{sto}}$ tends to the
 116 given mean value μ_w (in our case 0). ξ_w is the white noise, formally defined
 117 as the time derivative of the Wiener process. This process is controlled by
 118 adjusting α and the standard deviation σ_w of the wind stochastic part which
 119 affects the b_w component. Fig. 4 shows three sample wind stochastic profiles
 120 obtained by changing the σ_w and α parameter.

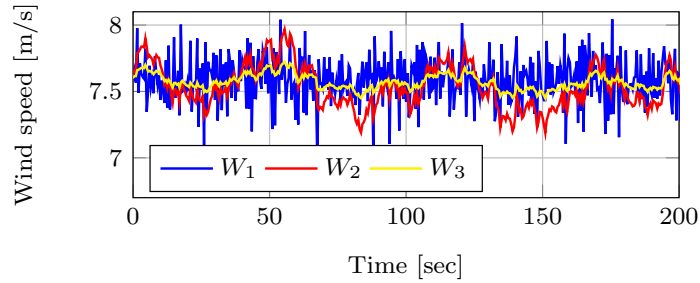


Figure 4: $w_{s,\text{sto}}$ profiles. W_1 ($\alpha = 10$, $\sigma_w = 0.17$); W_2 ($\alpha = 0.1$, $\sigma_w = 0.17$); W_3 ($\alpha = 0.1$, $\sigma_w = 0.06$).

121 3. BESS Control

122 In this study, we consider the BESS model defined in [32]. The power pro-
 123 duced by the battery is transferred to the grid through a current source con-
 124 verter. The converter includes the PI controllers that regulate the active and
 125 reactive powers at the point-of-connection with the ac grid. Overall the BESS
 126 responds within a second after a Δp request. The reference active power is
 127 defined by the PFC control. Two PFC characteristics are considered in this
 128 study, namely fixed and variable droop control strategy. The latter is a novel
 129 contribution of this paper.

130 *3.1. Fixed Droop (FD)*

This control is implemented as a fixed power/frequency curve, as commonly in use for CG. The droop (R) of CG plants is usually set at 0.04 or 0.05 pu considering a 10% regulation band of the generator nominal power, as specified in the Irish grid code [33]. Depending on these parameters, a certain frequency error Δf_{\max} causes the full provision of the regulation band. In general the droop for a CG and a BESS unit is computed as follows [34]:

$$R_{\text{CG}} = \left| -\frac{\Delta f_{\max}}{f_{\text{nom}}} \cdot \frac{1}{PFC_{\text{band}}^{\text{CG}}} \right|, \quad (4)$$

$$R_{\text{BESS}} = \left| -\frac{\Delta f_{\max}}{f_{\text{nom}}} \cdot \frac{1}{PFC_{\text{band}}^{\text{BESS}}} \right|, \quad (5)$$

where PFC_{band} represents the regulator band in pu (in this study, we set $PFC_{\text{band}}^{\text{CG}} = 0.1$ pu(MW) and $PFC_{\text{band}}^{\text{BESS}} = 1$ pu(MW)). Taking Δf_{\max} equal for both resources and dividing equation (5) by (4), we obtain the relationship which correlates both the droops:

$$R_{\text{BESS}} = R_{\text{CG}} \cdot \frac{PFC_{\text{band}}^{\text{CG}}}{PFC_{\text{band}}^{\text{BESS}}} = R_{\text{CG}} \cdot 0.1. \quad (6)$$

131 For each value of the CG droop one obtains a corresponding BESS droop
 132 which saturates its regulation band at the same frequency deviation of the CG
 133 resources.

134 *3.2. Variable Droop (VD)*

135 Frequency fluctuations distribute symmetrically around f_{nom} and follow a
 136 normal distribution or a binomial one if a deadband in governors controller of CG
 137 is present [35]. Therefore, the PFC of the battery usually works on average 50%
 138 in under-frequency and 50% over-frequency periods with a zero mean energy.
 139 However, using a FD frequency control characteristic, due to the internal losses
 140 of the battery the SOC is expected to gradually decrease to 0. At the same
 141 time, long over-frequency periods could make the BESS reach maximum SOC,
 142 limiting its regulation capacity. The proposed VD strategy tries to avoid such
 143 extreme SOC conditions by introducing an asymmetry in the frequency control
 144 of the BESS.

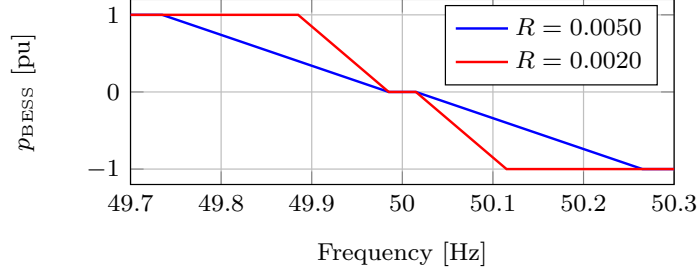


Figure 5: Power limits example for the VD frequency control.

		Low SOC_i → High SOC_i				
		SOC_1	...	SOC_{ave}	...	SOC_n
\uparrow $\Delta f_{e,j} > 0$ $\Delta f_{e,j} < 0$ \downarrow	$\Delta f_{e,1}$	$R_{1,1}$...	R_{ave}	...	$R_{n,1}$
	\vdots	\vdots		\vdots		\vdots
	$\Delta f_{e,m}$	\vdots		\vdots		\vdots
	$\Delta f_{e,m+1}$	\vdots		\vdots		\vdots
	\vdots	\vdots		\vdots		\vdots
	$\Delta f_{e,2m}$	$R_{1,2m}$...	R_{ave}	...	$R_{n,2m}$

Figure 6: VD lookup table scheme.

145 As shown in Fig. 5, we assume that the droop is variable and bounded by two
 146 values, namely R_{max} and R_{min} . These values are limited by system stability and
 147 resources technical considerations. Usually TSOs request droop values between
 148 2 and 8% [36], typical values are 4 and 5%.

149 The VD is implemented through the use of a two dimensional lookup table,
 150 where the droop value depends on the instantaneous frequency error $\Delta f_e =$
 151 $f_{nom} - f$ and the SOC. The droop values are divided in five different areas (see
 152 Fig. 6): (i) in the red areas the values are close to R_{max} , (ii) in the blue areas
 153 the values are close to R_{min} and (iii) in the green area (which correspond to
 154 a column vector) the droop values are all equal to the average droop R_{ave} , at
 155 half distance between R_{max} and R_{min} . The values of the table are therefore
 156 constructed symmetrically in such a way that the BESS is expected to avoid

157 excess discharge or charge keeping its SOC close to SOC_{ave} level. As an example,
158 if SOC is high and Δf_e is positive then the BESS discharges with a low droop
159 to reach SOC_{ave} , whereas if Δf_e is negative it charges with a high droop to slow
160 down the SOC increase.

161 Note that, in order to regulate the SOC the best choice would be to set
162 the droop values equal to R_{max} in red areas and R_{min} in blue areas. However,
163 to avoid sudden droop changes and less effective frequency regulation, droop
164 values gradually approach R_{max} and R_{min} .

165 A better SOC regulation is achieved by setting the SOC_i values close to
166 SOC_{ave} and taking small values of $\Delta f_{e,j}$. Better SOC management is also
167 expected if the distance between the maximum and minimum droop R_{max} and
168 R_{min} is large.

169 The VD strategy here proposed cannot achieve a perfect SOC regulation
170 being a decentralized technique, nevertheless it is useful to improve the SOC
171 dynamics with respect to a FD strategy and it is used in this study to make the
172 BESS droop change realistically during the simulations and analyse the impact
173 of VD strategies on the grid frequency stability.

174 4. Generation of Realistic Scenarios

175 Our aim is now to reproduce realistic frequency fluctuations in order to
176 properly quantify the BESS contribution to the PFC. The reference scenario,
177 considered below, is a time series of the frequency measured by the authors at
178 University College of Dublin. The data represents 330 days of measurements
179 with a sampling rate of 10 Hz.

180 A Discrete Fourier Transform (DFT) is applied to define the harmonic con-
181 tent of the frequency measurements. The goal is to synthesize and then simulate
182 a dynamic base case scenario (S1) with a harmonic content similar to the real
183 frequency data sampled in the lab. The implemented procedure is valid to
184 replicate the harmonic amplitudes of six hours of real frequency signal. Of all
185 the thousands of harmonics computed through the DFT, only the first 800 are

186 considered, which represent more than the 98% of the variance of the signal for
 187 all the days considered (as computed by applying Parseval’s Theorem). The
 188 frequency signal is therefore a ”slow” signal in that the first harmonics (charac-
 189 terized by longer periods) hold more importance than the shorter period ones.
 190 For example, in Fig. 7 we show the harmonic profiles related to the six hour pe-
 191 riod going from 6:00 to 12:00, the mean μ and the standard deviation σ of each
 192 harmonic for all days considered. All the profiles are similar. The grid frequency
 193 signal is therefore quite variable in time domain but much more similar in the
 194 harmonic content. Therefore, to reproduce similar harmonic amplitudes of the
 195 real data assures that the synthetic signal behaves realistically. Similar results
 196 hold for the other three time ranges (00:00-6:00, 12:00-18:00, 18:00-24:00).

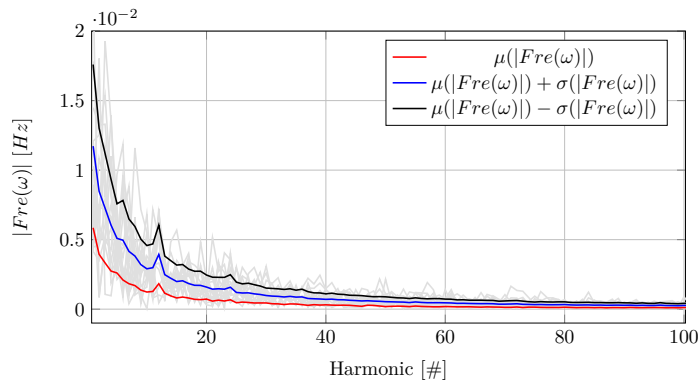


Figure 7: harmonics amplitudes related to the six hour period 6:00-12:00.

197 In order to reproduce real data harmonics, we make use of power stochastic
 198 profiles from generation and consumption. These processes are divided in two
 199 groups following the taxonomy presented in the literature review, as follows:

- 200 • *Fast Stochastic Processes (FSP)*. The stochastic processes of load con-
 201 sumption and wind speed discussed in Section 2 are used to replicate the
 202 events that cause stochastic frequency fluctuations in the grid (typically
 203 with period lower than 2 minutes).
- 204 • *Slow Stochastic Processes (SSP)*. Two noises are used to model determin-

205 stochastic frequency deviations: SSP1 which models wind and CG ramps and
206 SSP2 which models the long term mismatch between net load and con-
207 ventional generation due to the market structure of the system. SSP1 are
208 noises up to 10 minutes, while SSP2 are up to one hour. We refer to these
209 deviations as slow frequency variations.

210 To tune the parameters of each component of FSP and SSP, a precise map-
211 ping between stochastic processes and excited frequency harmonics is defined
212 and stored in a database. This is obtained by varying the parameters values,
213 simulating the grid and then computing and recording the resulting harmonic
214 amplitude. To separate the effect of each stochastic process, one perturbation at
215 a time is considered, being null all other stochastic processes. The parameters
216 used to variate the stochastic processes are the ones described in Section 2 and
217 are a total of 7.

218 In particular, for the load model, a variety of time periods Δt_i (going from
219 0.5 to 2 seconds) and standard deviations σ_{Load} (going from 2 to 15%) values
220 are considered. σ_w is the only parameter to be changed to vary the stochasticity
221 of the wind component with α fixed to 0.1. For the SSP, time steps and power
222 ramps are chosen from uniform distributions with specified limit values. In the
223 case of SSP1, time steps Δt_{CG} go from 2 to 10 minutes, while for SSP2 the
224 period goes from 13 to 60 minutes. In the case of power variations, requested
225 ramps are both negative or positive, with a maximum $|\Delta p_{\text{max}}|$ which goes from
226 10 MW up to 70 MW for both SSP noises.

227 Figures 8 and 9 show several harmonic profiles obtained from the simulation
228 of FSP and SSP noises. As expected, The former noises excite short period
229 harmonics, while the latter give rise exclusively to long period harmonics.

230 Finally, the stochastic processes of loads, wind speeds and CG power set
231 points are summed together and the resulting profile, say p_{tot} , is thus identified
232 by a given unique set of parameters that define the four stochastic processes.
233 The harmonic contents of the frequency trajectories obtained with p_{tot} are then
234 compared with the real data through the estimation of an error ϵ_f , which is

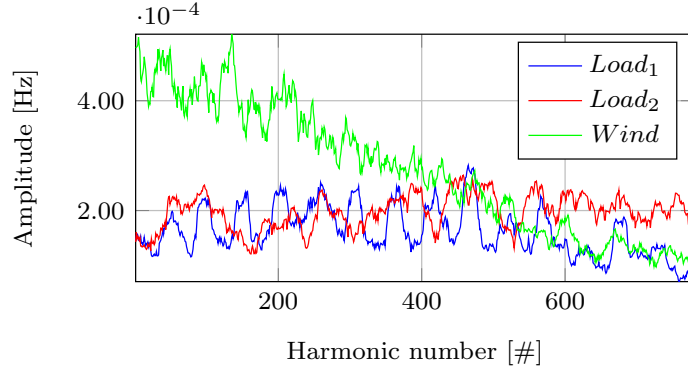


Figure 8: examples of harmonic obtained with load and wind stochastic processes. $Load_1$ ($\Delta t_i = 1s$, $\sigma_{Load} = 2\%$); $Load_2$ ($\Delta t_i = 0.5s$, $\sigma_{Load} = 2\%$); Wind ($\sigma_w = 3\%$).

235 defined as follows:

$$\epsilon_i = \begin{cases} |(Y_{sim_i} - (Y_{real_i} - std_i))|, & \text{if } Y_{sim_i} < (Y_{real_i} - std_i), \\ (Y_{sim_i} - (Y_{real_i} + std_i)), & \text{if } Y_{sim_i} > (Y_{real_i} + std_i), \\ 0, & \text{if } (Y_{real_i} - std_i) < Y_{sim_i} < (Y_{real_i} + std_i) \end{cases} \quad (7)$$

$$\epsilon_f = \frac{\sum_{i=1}^{N_{harm}} \epsilon_i}{\sum_{i=1}^{N_{harm}} Y_{real_i}} \quad (8)$$

236 where ϵ_i is the error at the harmonic i ; Y_{sim_i} is the value of the simulated
 237 frequency data at the harmonic i ; Y_{real_i} is the mean of all real data at the
 238 harmonic i ; std_i is the standard deviation of the real frequency data at the
 239 harmonic i ; N_{harm} is the number of harmonic used.

240 If this error falls within the desired tolerance, the procedure ends, otherwise
 241 relevant noise parameters are increased or decreased according to their impact
 242 on the signal harmonics. In such a way the procedure creates a scenario in which
 243 frequency does not emulate a specific real day data, but it tries to recover the
 244 average variability of real measurements. The synoptic scheme that illustrates
 245 the procedure is shown in Fig. 10.

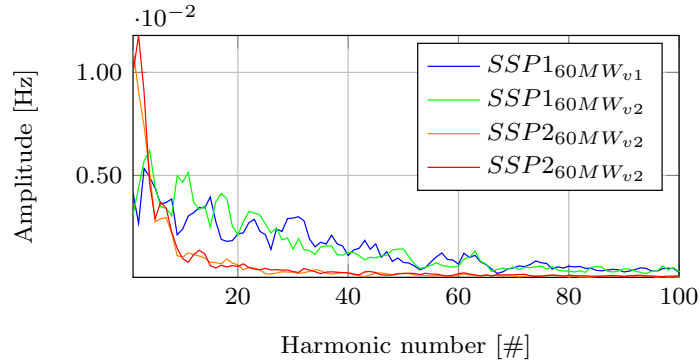


Figure 9: examples of harmonic groups obtained with the SSP1 and SSP2 noises. $v1$ and $v2$ refer to different noise profiles with equal $|\Delta p_{\max}|$ value. Δt_{CG} is equal to 3-7 minutes for SSP1 and 13-50 minutes for SSP2.

246 5. Indexes

247 This section describes a variety of indexes that allow evaluating the impact
 248 of stochastic processes and the effectiveness of the PFC provided by BESSs and
 249 CG.

250 5.1. Impact of the stochastic processes on the system dynamic response

To quantify the contribution of each stochastic process to the overall frequency fluctuations, we consider the sum variance law of the frequency signal which defines the variance of a signal composed by N stochastic independent variables as:

$$\sigma_{\text{TOT}}^2 = \sum_{i=1}^N \sigma_i^2 . \quad (9)$$

To compare the impact of each process, it is convenient to consider a normalized variance per process, namely:

$$\sigma_{i,\text{pu}}^2 = \frac{\sigma_i^2}{\sigma_{\text{TOT}}^2} , \quad (10)$$

in such a way, from Equ. (9), we can write:

$$1 = \sum_{i=1}^N \sigma_{i,\text{pu}}^2 . \quad (11)$$

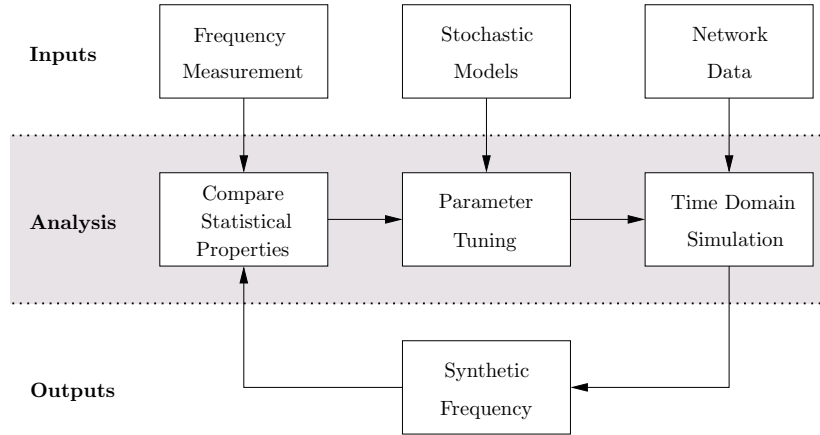


Figure 10: Procedure to generate realistic scenarios.

251 *5.2. Impact of BESSs on frequency fluctuations*

This index provides a measure of the relative improvement to the dynamics response due to the BESSs. It is defined as:

$$h_B = 1 - \frac{\sigma_B}{\sigma_o} , \quad (12)$$

252 where σ_B is the standard deviation of the frequency of the system with inclusion
 253 of BESSs and σ_o is the standard deviation of the frequency for the same scenario
 254 but without BESSs.

255 *5.3. Effectiveness of the PFC*

This novel proposed index evaluates the effectiveness of the frequency control provided by any resource included in the system. Considering a resource k , the index is defined as:

$$e_k = \frac{E_k^+ + |E_k^-| - (E_{o,k}^+ + |E_{o,k}^-|)}{E_k^{\text{ref}}} , \quad (13)$$

where

$$E_k^{\text{ref}} = \int_o^T \frac{P_{\text{nom},k}}{R_k(r)} |\Delta f(r)| dr . \quad (14)$$

256 R_k [pu] is the droop of the resource which, for the BESS regulated with VD, is
 257 a time-dependent quantity, $P_{\text{nom},k}$ [MW] is the nominal power of the resource

258 and $|\Delta f(r)|$ [Hz] is the frequency error including the deadband. E_k^{ref} represents
 259 the integral of the exact real-time power profile requested by the PFC service in
 260 a given period T , E_k^+ represents the actual energy produced by the resources for
 261 $\Delta f > 0$, whereas E_k^- is the energy produced for $\Delta f < 0$ in the same period T .
 262 The condition $E_k^+ + E_k^- < E_k^{\text{ref}}$ generally holds as E_k^+ and E_k^- account for the
 263 delays of the primary frequency control dynamics. $E_{o,k}^+$ and $|E_{o,k}^-|$ represent the
 264 energy produced for $|\Delta f| < db$ where db is the deadband of the controller. These
 265 energies work against the PFC requirements and thus reduce the effectiveness
 266 of the frequency control.

267 According to the above definition, $e_k = 0$ if the resource does not partic-
 268 ipate to PFC, $e_k \ll 1$ if the resource is slow and not able to follow the PFC
 269 reference signal and $e_k = 1$ for an ideal frequency control with instantaneous
 270 time response.

271 6. Case Study

272 This case study discusses the performance of the BESS PFC described in
 273 Section 3 and its impact on various scenarios based on the procedure discussed
 274 in Section 4. With this aim, we make use of the Irish transmission system [37].
 275 Table A.5 in the appendix summarizes the main elements of the grid. The CG
 276 active installed capacity in S1 is 4347 MW while wind active installed capacity
 277 is 2123 MW. In S2 and S3 CG capacity is decreased by 25%.

278 All simulations are solved using Dome [38], a Python and C-software based
 279 tool that allows simulating large scale power systems modelled as a set of
 280 stochastic differential algebraic equations. Relevant components are modelled
 281 in detail such as a high voltage network topology, a 6-th order machine model
 282 of the synchronous generator, frequency and voltage regulators etc.

283 6.1. Scenarios Construction

284 Three scenarios, S1, S2 and S3, are considered. In Appendix A we report
 285 the static and dynamic parameters of the CG PFC.

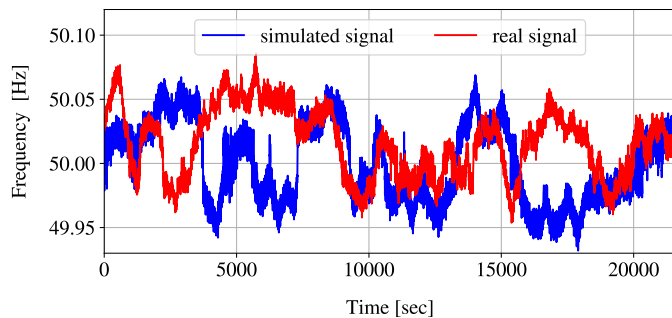


Figure 11: comparison between real and simulated (S1) frequency

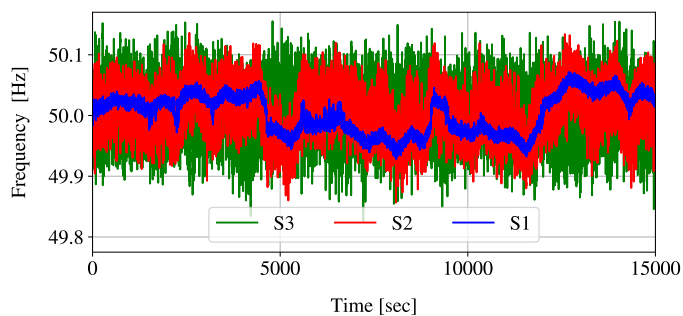


Figure 12: frequency profiles examples for the three considered scenarios.

286 The time horizon of the three scenarios is 12 hours, from 6:00 to 18:00.
 287 Load and wind linear slow power profiles are defined based on real-world data
 288 obtained by the Irish TSO Eirgrid, while the mismatch from the net load comes
 289 from the application of the 4 noises presented in Section 4.

290 Each scenario is first simulated without the BESSs. S1 represents the sce-
 291 nario that reproduces the measurement data obtained in the lab. S2 and S3
 292 include higher level of noises and decreasing inertia levels, which lead to greater
 293 and faster frequency fluctuations. In particular, in S2 we increase the FSP noises
 294 and decrease the SSP2 noise, while in S3 the SSP noises are reduced almost to
 295 zero and FSP noises are highly increased.

296 One profile of scenario S1 and a real frequency time series are shown in
 297 Fig. 11. As expected, the synthetic frequency signal retains a similar variability

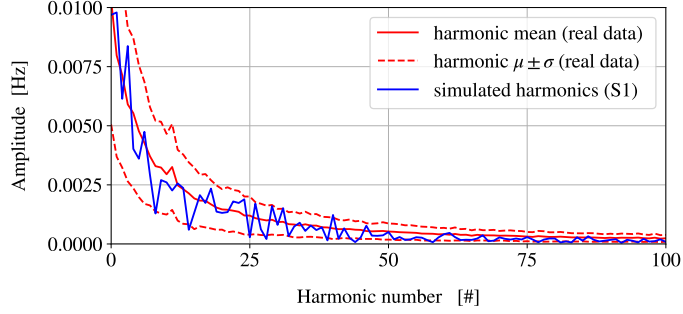


Figure 13: harmonic comparison between simulated and real data for the scenario S1, period 12:00 - 18:00.

298 with respect to the real data. Sample frequency fluctuations of the three sce-
 299 narios are shown in Fig. 12. Table 1 summarizes the standard deviation of the
 300 frequency of the system σ_f , the normalized variances $\sigma_{i,\text{pu}}^2$ of the four stochastic
 301 components and the two S1 errors ϵ_f evaluated by applying Equ. (8). In S1
 302 (real-world scenario) the slow noises (SSP) represent almost 90% of the grid
 303 deviations with more than half coming from SSP2 noises. In S2 and S3, SSP2
 304 noise goes towards zero. The noises parameters which were used to create the
 305 scenarios can be seen in Table B.8 in Appendix B. Note that in both this table
 306 and table 1 values of S2 and S3 were computed as the average between the two
 307 six hours time periods.

308 In Fig. 7 the harmonics of real data and S1 scenario are compared and as
 309 expected from the definition of error ϵ_f , the simulated profile is well bounded by
 310 the real data harmonics standard deviation. Moreover the mean of the signal in
 311 the scenarios is set in accordance with the mean of the 330 real days. For this
 312 reason, frequency signal is slightly under 50 Hz for the first 6 hours and over 50
 313 Hz for the period from 12:00 to 18:00. These frequency mean offsets are very
 314 important in order to capture day frequency dynamics which affect the BESS
 315 SOC profiles.

Table 1: normalized variances and frequency standard deviations for the three stochastic scenarios

Scenario #	σ_f [Hz]	μ_f [Hz]	$\sigma_{i,\text{pu}}^2$				ϵ_f [pu]
			Load	$Wind_{\text{sto}}$	SSP_1	SSP_2	
S1 (6:00-12:00)	0.0308	49.9996	0.09	0.02	0.34	0.55	0.032
S1 (12:00-18:00)	0.0302	50.0038	0.075	0.07	0.34	0.515	0.021
S2 (6:00-18:00)	0.0359	50.0028	0.22	0.12	0.37	0.29	-
S3 (6:00-18:00)	0.0431	50.0021	0.55	0.24	0.16	0.05	-

316 *6.2. BESS Frequency Control*

317 The simulations that include BESSs are divided in two groups: the first
 318 considers exclusively the dynamic behaviour of FD, the second compares FD
 319 and VD control strategies. For the first group, the three scenarios are simulated
 320 by considering four BESS capacities (100, 200, 300 and 400 MW) and three
 321 droop values ($R_{BESS} = 0.005, 0.004, 0.0035$). In the second group, S1 and S2
 322 scenarios are simulated, with 100, 200 and 300 MW of BESSs characterized by
 323 two efficiencies ($\eta_{BESS} = 0.8, 0.9$) and by a power-energy ratio equal to 0.4.

324 With regard to the PFC, two FD droops (equal to 0.004 and 0.0035) are
 325 compared respectively to two VD strategies which are shown in Table 2: (i)
 326 “hard mode”, for which the droop varies in the range $R \in [0.002, 0.005]$, and
 327 (ii) “soft mode”, for which the droop varies in the range $R \in [0.003, 0.005]$. The
 328 tables have been built following the process described in Section 3.2 considering
 329 4 SOC_i and 4 $\Delta f_{e,j}$ points. For both modes $SOC_{\text{ave}} = 60\%$, while R_{ave} is
 330 equal to 0.004 in the hard mode and 0.0035 in the soft mode which are the
 331 values used by the FD strategy. Both setups, especially hard mode, make the
 332 droop to vary significantly during the simulations in order to regulate the SOC
 333 as well as possible.

Table 2: lookup tables for VD “hard” and “soft” control modes. Note that droop is here expressed in % and not in pu to improve readability of values.

Hard mode					Soft mode				
Δf_e	SOC range				Δf_e	SOC range			
[Hz]	50%	55%	60%	70%	[Hz]	45%	50%	60%	75%
0.03	0.20	0.20	0.35	0.50	0.040	0.3	0.35	0.40	0.50
0.0175	0.20	0.25	0.35	0.50	0.020	0.35	0.375	0.40	0.50
-0.0175	0.50	0.45	0.35	0.20	-0.020	0.45	0.425	0.40	0.30
-0.03	0.50	0.50	0.35	0.20	-0.040	0.50	0.45	0.40	0.30

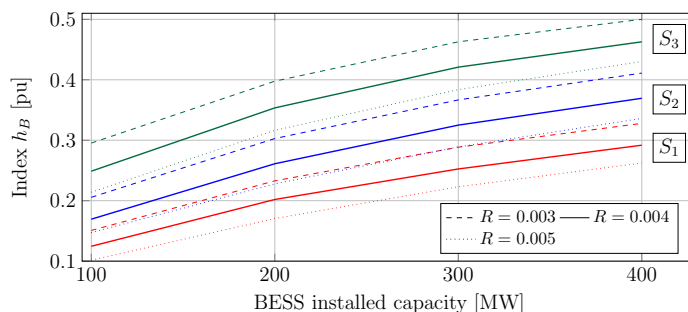


Figure 14: index h_B for the FD control strategy of the BESSs. The droop values is indicated by R . Different colors represents different scenarios.

334 6.2.1. FD control strategy

335 Fig. 14 shows the index h_B for the various scenarios. The improvement of
 336 the frequency signal is more relevant for both scenarios S2 and S3 (see Fig. 15
 337 for an example) than for S1. This has to be expected as, in S1, frequency has
 338 smaller standard deviation closer to the deadband value, which limits the impact
 339 of BESSs. For similar reasons, as shown Fig. 14, the h_B index increments tend
 340 to decrease as BESS capacity increases.

341 Table 3 shows the index e_k for the available resources that provide PFC. In
 342 the table, only one value for each scenario and each resource is shown, as e_k is

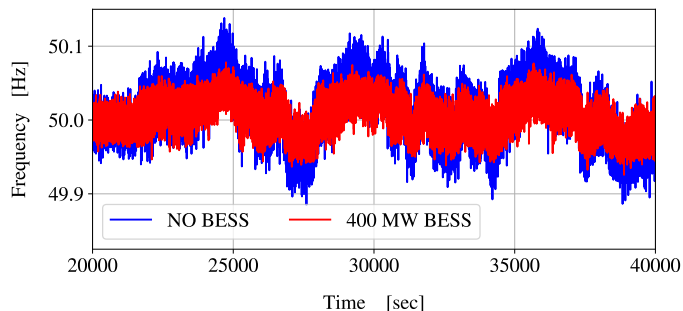


Figure 15: frequency profiles for scenario S2 without BESS and with BESS.

Table 3: index e_k for various scenarios and energy resources

Device	S1	S2	S3
BESS	0.99	0.99	0.97
Steam	0.92	0.78	0.31
Hydro	0.94	0.84	0.44
Gas	0.99	0.98	0.89

343 not greatly affected by the BESS installed capacity and its droop value. Two
 344 parameters mostly influence the index e_k :

345 • *The time response of the resource.* A fast time response of the resource
 346 improves its frequency regulation. As an example Fig. 16 shows the active
 347 power outputs of the BESS and of a conventional steam power plant.
 348 The blu dotted line is the reference PFC signal to be followed by the
 349 two resources. The fast response of the BESS leads to an almost perfect
 350 tracking of the reference signal.

351 • *The harmonic content of the frequency fluctuations.* The index e_k of the
 352 conventional power plants is higher in scenarios S1 and S2 than S3 in that
 353 the frequency signal is slower and easier to follow even for slower resources.

354 The result of the simulations is that in scenario S1, which represents the

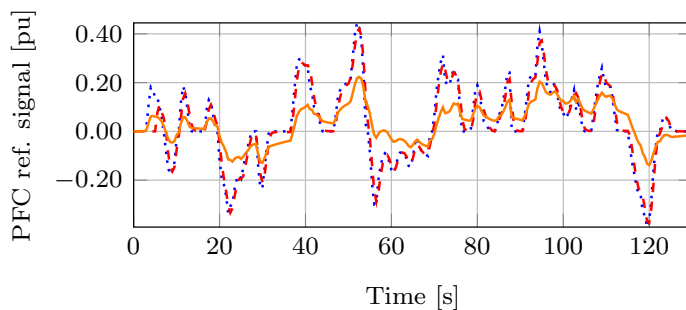


Figure 16: power production of the BESS (dashed red line) and of CG (solid orange line) following a PFC reference signal (dotted blue line).

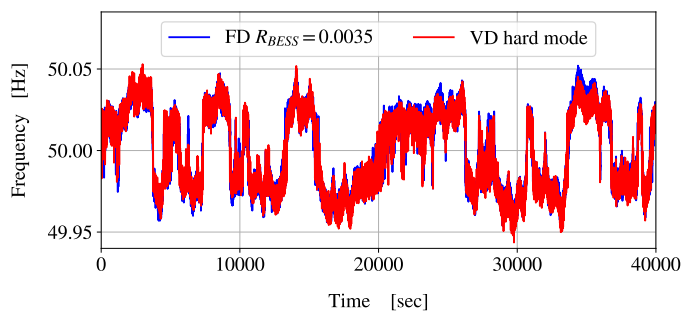


Figure 17: frequency profiles examples with FD and VD strategy ($\eta_{\text{BESS}} = 0.8$) adopted and 200 MW BESS installed.

355 current situation, the performance of the BESSs is comparable with that of
 356 conventional power plants. In S2 and S3, which are characterized by faster
 357 frequency fluctuations, the regulation provided by BESSs have much more value
 358 than CG PFC service.

359 6.2.2. VD control strategy

360 In order to asses the impact of VD strategies, several standard statistical
 361 properties of the frequency signal are used. Note that only the results with
 362 $\eta_{\text{BESS}} = 0.8$ are shown. The cases with $\eta_{\text{BESS}} = 0.9$ provide similar results
 363 and thus are here neglected. In the case of VD strategies, the standard devia-
 364 tion of the frequency signal has a negligible difference in the order of 10^{-4} Hz

Table 4: relevant parameters of simulations related to the case $\eta_{\text{BESS}} = 0.8$

Sim.	Par.	VD_{hard}	$FD_{0.35}$	VD_{soft}	$FD_{0.4}$
$S1_{200\text{MW}}$	$\sigma(\text{fre})$	0.0239	0.02393	0.02444	0.02443
	Skew(fre)	-0.1004	-0.0662	-0.0821	-0.722
	$\mu(\text{SOC})$	0.57	0.58	0.56	0.54
$S1_{300\text{MW}}$	$\sigma(\text{fre})$	0.0223	0.02235	0.02285	0.02286
	Skew	-0.143	-0.118	-0.122	-0.12
	$\mu(\text{SOC})$	0.59	0.61	0.59	0.62
$S2_{200\text{MW}}$	$\sigma(\text{fre})$	0.02595	0.02581	0.02655	0.02648
	Skew	0.143	0.066	0.0938	0.0722
	$\mu(\text{SOC})$	0.63	0.70	0.63	0.69
$S2_{300\text{MW}}$	$\sigma(\text{fre})$	0.02349	0.02342	0.02418	0.02416
	Skew	0.142	0.04	0.131	0.042
	$\mu(\text{SOC})$	0.63	0.66	0.63	0.64

365 with respect to the FD strategies. In Fig. 17 we can visualize the frequency
 366 signal of selected simulations which show great similarity. As shown in Table
 367 4, VD strategies generally enlarge skewness, creating small asymmetries in the
 368 frequency signal. If the initial skewness is negative, the VD strategies will fur-
 369 ther lower this value, while the opposite is true in case the initial skewness is
 370 positive. The difference is bigger in the case of hard mode with respect to soft
 371 mode and when BESS installed capacity is higher, except for the case $S1_{300MW}$.
 372 In general two compensating effects happen as BESS capacity increases: on one
 373 hand, as SOC diverges from the nominal SOC_{ave} value, the droop fluctuates
 374 around R_{ave} . This dynamic is responsible for creating the asymmetries in the
 375 frequency signal and increases its impact as more BESSs are used. On the other
 376 hand, the big BESS capacity makes the frequency less variable and closer to the
 377 deadband limiting the impact of VD strategies.

378 For these reasons the differences in the frequency signal remain small in
 379 the order of 10^{-1} [pu] and the values of skewness are still quite close to 0
 380 and therefore do not represent a big distortion. Finally, in both scenarios, the
 381 kurtosis slightly increase in the order of 10^{-3} [pu].

382 It is therefore clear that little difference exist between VD and FD strate-
 383 gies even if a large BESS capacity is installed. Both strategies are enough to
 384 guarantee stability in the grid during normal dynamic conditions.

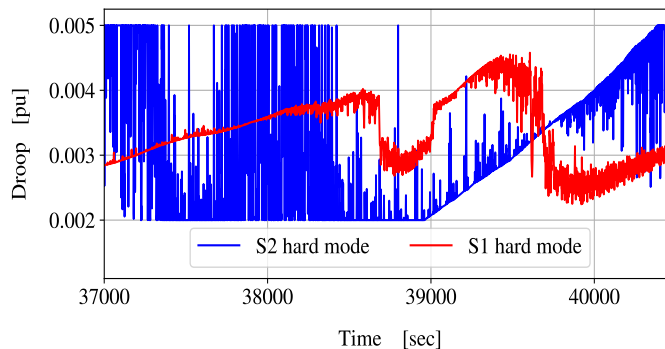


Figure 18: example of droop profiles in S2 with 100 MW of BESS installed and $\eta_{BESS} = 0.8$

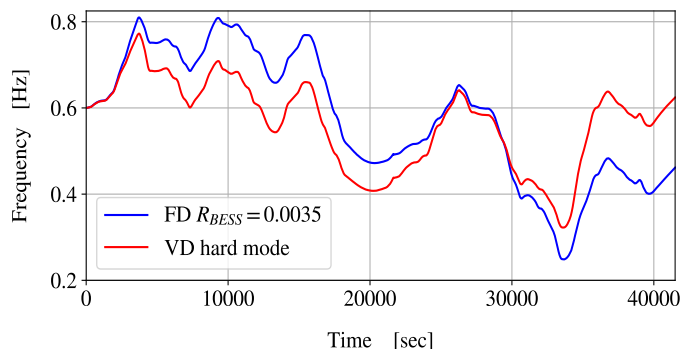


Figure 19: example of SOC profiles in the S1 scenario with 100 MW of BESS installed

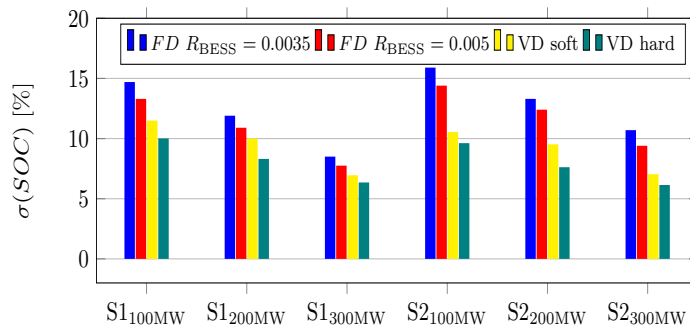


Figure 20: index $\sigma(SOC)$ for various BESS control strategies and capacities with $\eta_{BESS} = 0.8$.

385 For what concerns SOC, in Table 4 the mean SOC value $\mu(SOC)$ of several
 386 simulations is shown. VD strategies, especially for S2, are able to keep the
 387 SOC statistically closer to SOC_{ave} with respect to FD strategies. Fig. 19 shows
 388 as an example two profiles related to the different strategies. As can be seen,
 389 the VD strategy is not able to perfectly regulate the SOC, but manages to
 390 decrease its standard deviation with respect to the FD case avoiding too high
 391 or too low charge levels. Fig. 20 shows the SOC standard deviation for all the
 392 scenarios studied in the case $\eta_{BESS} = 0.8$. The decrease in standard deviation
 393 is slightly better in S2 where the alternation between over and under-frequency
 394 periods is faster, therefore the VD strategy changes values often (as shown

395 in Fig. 18), reaching better performances. The possibility of using a bigger
396 difference between R_{\max} and R_{\min} can further improve the SOC dynamics (e.g.
397 $R_{\min} = 0.002$ and $R_{\max} = 0.008$), but its effect on the frequency must be
398 carefully evaluated.

399 7. Conclusions

400 In this paper we have studied the potential impact of BESSs on the PFC
401 of power systems. Realistic scenarios are generated through a technique that
402 properly reproduces load and generation variations based on the the DFT. Sim-
403 ulation results confirm that BESSs can reduce the fluctuations of the frequency
404 provided that they are properly controlled and enough capacity is installed. The
405 effectiveness of the frequency support is quantified by means of an effectiveness
406 index e_k .

407 The performance of the BESS control depends both on the amount of inertia
408 and the nature of frequency deviations present in the system. If the inertia is
409 high and frequency fluctuations are caused by slow phenomena (as currently
410 happen), the performance of the BESSs is similar to that of fast turbine gover-
411 nors. As inertia decreases and more stochastic fast noises are present into the
412 grid (for example due to the increase of renewable sources) the BESSs are more
413 effective than the conventional primary frequency controllers of synchronous
414 machines (even more than doubling the performance of slow thermal plants).
415 Finally, variable droop control strategy does not seem to impact signal standard
416 deviation and just marginally modify the frequency stability with respect to the
417 fixed droop case, while at the same time improves the BESS SOC management.

418 Future work will be focused on a more rigorous assessment of the impact
419 of variable droop control discussed in the paper by considering more scenarios,
420 parameters and different regulation laws.

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431 **Appendix A. Grid static and dynamic characteristics**

Table A.5: Main elements of the transmission system used

Network	#	Loads and Power Plants	#
AC Power Lines	796	Loads	346
Bus	1479	Conventional Generators	22
Transformers	1055	Wind power plants	472

Table A.6: Parameters of primary and secondary frequency control

Primary Reserve Control	Band [MW]	Reserved [%]	Droop [%]	Deadband [mHz]
S1	421	10	5	15
S2 & S3	302	10	5	15

Table A.7: Parameters of the turbine governors of conventional generators

Time Constant	Steam	Hydro	Gas
T_1 [s]	10	2.5	0.5
T_2 [s]	3	0	0

432 **Appendix B. Noises parameters of the Scenarios**

Table B.8: Stochastic noises parameters values used to create the scenarios

Scenario #	Load		Wind	SSP1		SSP2	
	Δt_i	σ_{Load}	σ_w	Δt_{CG}	Δp_{max}	Δt_{CG}	Δp_{max}
	[s]	[%]	[%]	[min]	[MW]	[min]	[MW]
S1 (6:00-12:00)	0.5	2.75	2.5	3-6	33	13-50	50
S1 (12:00-18:00)	0.5	3	5	4-7	38	15-50	47.5
S2 (6:00-18:00)	0.5	8.5	12.5	3.5-6.5	39	14-50	22.5
S3 (6:00-18:00)	0.5	16	25	4-7	20	14-50	10

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