Contribution of Energy Storage Systems to Long-Term Power System Dynamic Performance

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***Abstract*—This paper discusses the impact of energy storage systems (ESSs) on long-term power system frequency deviations originated by real-time electricity markets with short dispatch periods. The goal of the paper is to evaluate whether and under which conditions ESSs are effective in reducing these frequency deviations. With this aim, the paper first discusses a dynamic market model with inclusion of ESSs. Then, it provides a comprehensive sensitivity analysis of the ESS control parameters based on time domain simulations. Results indicate that ESSs can significantly reduce the long-term frequency deviations. However, the capacities of the ESSs as well as the deadband and droop coefficient of the ESS controllers have to be carefully designed to avoid the outbreak of unexpected dynamic behaviors.**

***Index Terms*—Power system dynamic performance, energy storage systems, automatic generation control, real-time electricity market.**

I. Introduction

Energy storage systems (ESSs) are considered as the *holy grail* of power systems. This is because ESSs can be used for many power system applications, including the safe integration of intermittent renewable energy sources (RES), primary and secondary frequency control, voltage support, and rate of change of frequency control, just to mention some [1]. Reference [2] studies the contribution of ESSs in the Portuguese power system. This work shows that the use of ESSs improve the integration of RES and avoid the need to use low efficient thermal power plants. Reference [3] presents a method for optimal sizing of ESSs in order to provide inertial and primary frequency support. Reference [4] studies the optimal sizing of ESSs for voltage regulation and peak load shaving. In [5], the authors study the impact of battery ESSs on low frequency oscillations of power systems. Reference [6] presents a model predictive control approach to manage the real-time photovoltaic power production.

In this paper, we are interested in studying the impact of ESSs on long-term frequency dynamics. With this aim, we consider real-time electricity markets as the main drivers of long-term frequency fluctuations. This assumption is motivated by the observation that, in recent years, electricity markets worldwide are using shorter and shorter dispatch periods as a way to increase the flexibility of power systems, i.e. by capturing the sub-hourly variability of RES [7]. For example, the European electricity markets are switching from 1 hour time resolution, to that of 15 minutes [8]. In fact, to fully utilize the flexibility of electricity markets, the latter should switch to an even finer time resolution, e.g., 5 minutes [9]. In future markets, it is also expected that the electric demand will play a major role by effectively responding to the wholesale electricity prices, e.g. demand response. In an ideal scenario, the demand and generation can be used to manage the real-time balance of the power system by responding to prices. A market model that represents such a scenario was proposed by Alvarado in [10]. In [11], it is shown that Alvarado's model can be represented as a sort of automatic generation control (AGC). Reference [11] also shows that the market AGC (MAGC) may lead to large frequency deviations or power system instability if no conventional AGC is installed in the system.

A. Contributions

This work provides the following contributions:

- Present a comprehensive analysis of the effectiveness of ESSs and its control parameters in mitigating long-term power system frequency deviations caused by real-time electricity markets.
- Show that, while ESSs can significantly reduce the frequency deviations, two parameters of the ESS primary frequency control, namely, deadband and droop, have to be carefully designed to avoid undesirable fluctuations of the frequency.

B. Paper Organization

The paper is organized as follows. Section II presents the hybrid model of power systems used for time domain analysis. Section III provides a formal analogy between a conventional AGC and MAGC as well as shows the origin of the long-term frequency deviations. Section IV describes the ESS model utilized in this work. Section V studies the impact of ESSs on the long-term power system frequency deviations. Finally, conclusions and future works are given in Section VI.

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This work was supported by Science Foundation Ireland, by funding T. Kërçi and F. Milano under project ESIPP, Grant No. SFI/15/SPP/E3125; and M. A. A. Murad, I. Dassios and F. Milano under project AMPSAS, Grant No. SFI/15/IA/3074.

II. Hybrid power system model

Power systems are large and multi-time scale systems [12]. They can be modeled as a set of nonlinear hybrid differential algebraic equations (HDAEs) [13], as follows:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}, \boldsymbol{z}) \,, \\ \mathbf{0}_{n_y,1} &= \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{u}, \boldsymbol{z}) \,, \end{aligned} \tag{1}$$

where $\boldsymbol{f}$ are the differential equations, $\boldsymbol{g}$ are the algebraic equations, $\boldsymbol{x}$, $\boldsymbol{x} \in \mathbb{R}^{n_x}$ are the state variables, e.g. generator rotor speeds, and $\boldsymbol{y}$, $\boldsymbol{y} \in \mathbb{R}^{n_y}$, are the algebraic variables, e.g. bus voltage angles; $\boldsymbol{u}$, $\boldsymbol{u} \in \mathbb{R}^{n_u}$, are the inputs, e.g. load forecast, generator bids; and $\boldsymbol{z}$, $\boldsymbol{z} \in \mathbb{N}^{n_z}$, are the discrete variables, e.g. status of the machines.

Equations (1) represent the conventional model of power systems for transient stability analysis. They include dynamic models of synchronous machines, turbine governors (TGs), automatic voltage regulators, ESS, power system stabilizers and the discrete model of the AGC and MAGC. We outline below the discrete model of the AGC and MAGC as well as the model of the ESS. Further information on all other models can be found in [13].

It is important to note that theory on stability analysis of nonlinear hybrid dynamical systems is extremely limited. Furthermore, interactions between continuous dynamics and discrete events can lead to non-intuitive behavior [14]. The best approach for studying the stability of these systems is to solve time domain simulations. This is also the approach utilized in this work.

III. AGC and Market-Based AGC

Transmission systems operators (TSOs) use the secondary frequency control or AGC to manage the real-time balance between power generation and demand [15]. The AGC is a centralized controller installed in the control centers of TSOs. Its function is to update the power set-points of conventional power plants at fixed time intervals. In general, this interval is in between 2-4 seconds [16]. A standard control scheme of the AGC is shown in Fig. 1. The measured signal is the frequency of the center of inertia ($\omega_{\rm CoI}$) which is compared with a referenced one ($\omega^{\rm ref}$). The goal of the AGC is to reduce the frequency steady-state error to zero. With this aim, it includes an integrator with gain K_o. The output Δp is discretized at fixed times (e.g., every 4 seconds) and sent to the TGs of the synchronous generators proportional to their droops (R_i).

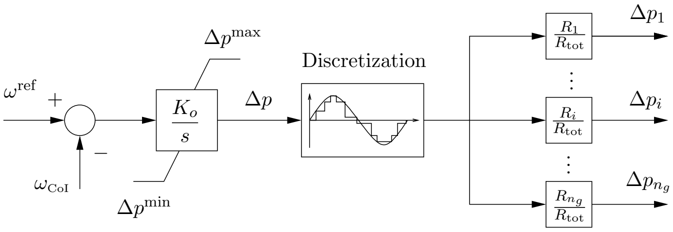

Fig. 1: AGC control diagram.

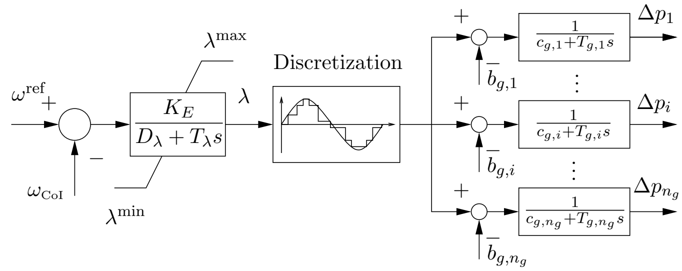

Fig. 2: MAGC control diagram.

In [11], the authors provide a formal analogy between the AGC and the real-time electricity market model (or MAGC) proposed in [10]. The control diagram of the MAGC is depicted in Fig. 2. One can notice the similarities between Fig. 1 and Fig. 2. The input of both controllers is the same, namely, the difference between $\omega_{\rm CoI}$ and $\omega^{\rm ref}$. Next, the MAGC includes a low-pass filter (LPF) that has a similar goal with that of the AGC, namely, to filter the high-frequency oscillations. Then, the output of the LPF, λ (electricity price), has the same fuction, although different physical meaning, as the output of integrator, Δp. The output of the MAGC is also updated at regular intervals and discretized as that of the AGC. Finally, the price signal λ is sent to each TG of the synchronous generators proportionally to their bids. The interested reader can find more information about the analogy between AGC and MAGC in [11].

A. Illustrative Example of the Dynamic Behaviour of the MAGC

If the system includes only the MAGC controller (i.e., no AGC is installed in the system), then large MAGC time intervals lead to power system instability. For illustration purposes the discretization-driven instability is shown in Fig. 3 using a modified IEEE WSCC 9-bus system and a MAGC time interval of 120 seconds. In this work, all simulations are carried out using the python-based power system analysis software tool Dome [17]. The contingency is a 10% instantaneous load increase (approximately 32 MW) at $t = 1s$.

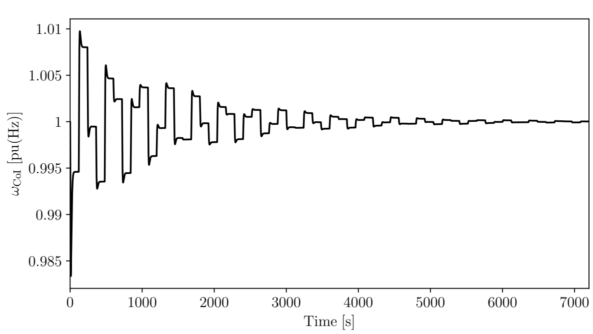

Fig. 3: Transient response of $\omega_{\rm CoI}$ following 10% instantaneous load increase.

Figure 3 shows that the contingency causes large frequency deviations during the first 1,500 seconds. These deviations are unacceptable in practice. After a few hours the frequency oscillations damp. Note that the high frequency oscillations can be avoided if one uses big time constants (i.e, T_λ) or very small gains (i.e., K_E). However, in these cases, the MAGC is very slow (not effective) and is unable to improve the dynamic response of the system because it does not change the set-points of the machines.

IV. Energy Storage Systems

ESSs are expected to play an important role in improving the power system dynamic performance by smoothing the variable output of RES [18]. This is because they are able to store energy, keep it stored, and eventually release it whenever the power system needs it, e.g. a sudden demand increase [19]. The goal of this paper is to investigate the effectiveness of the ESSs in mitigating the long-term oscillatory behavior of the frequency caused by the electricity market. With this aim, we assume that ESSs do not participate in the electricity markets, i.e. are not part of the MAGC in Fig. 2, but instead are paid for the frequency containment support that they provide.

Here, we utilize the simplified ESS model presented in [20]. The ESS frequency control diagram is depicted in Fig. 4. In this case, the input of the controller is the difference between the measured (ω) and reference frequency ($\omega^{\rm ref}$). The frequency is measured through a phase-locked loop device. Next, the ESS control scheme includes a deadband and a LPF in order to make the controller less sensitive to small frequency deviations and filter out noises, respectively. Then, it includes a PI regulator with K_p being the proportional gain, and K_i being the integral gain. In the control scheme shown in Fig. 4, the droop coefficient is obtained indirectly through the integral deviation coefficient H_d. For $H_d = 0$ the controller is a PI and hence the droop coefficient is $R = 0$, whereas for $H_d \neq 0$, the controller becomes a lead-lag filter, with droop coefficient $R = H_d/(K_i + K_p H_d)$. Finally, the ESS is represented by an anti-windup first-order lag filter with time constant T_{ESS}.

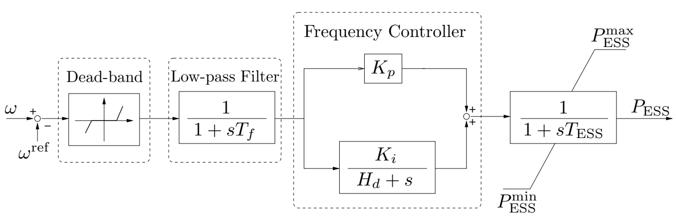

Fig. 4: The frequency control scheme of an ESS.

V. Case Study

This section discusses the effectiveness of the ESSs in mitigating the frequency oscillations caused by the discretization of the MAGC controller shown in Fig. 3. As mentioned above, a MAGC time interval of 120 seconds is used as a worst case scenario. Next, ESS devices are connected to different buses of the system and their impact on the long-term frequency deviations is duly discussed. Three scenarios are considered, as follows:

- Without ESSs limits;
- With ESSs limits; and
- Comparison of the impact of droop and deadband parameters.

All scenarios above are compared with the base case, i.e. without ESSs (see Fig. 3).

A. ESSs without Capacity Limits

This first scenario discusses the effect of ESSs on long-term power system dynamics without considering capacity limits of the ESS. This scenario is relevant for micrograms where the storage capacity can be relatively large with respect to the total installed power capacity. For simulation purposes, $H_d = 0.7$ is used and the deadband is set to zero. Figure 5 shows the transient response of $\omega_{\rm CoI}$ for three scenarios, namely, with one ESS connected at bus 9, three ESSs connected at buses 7, 8, and 9, and when no storage is included in the system.

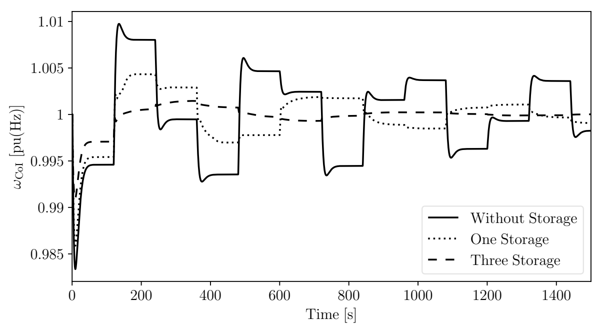

Fig. 5: Transient response of $\omega_{\rm CoI}$ following a 10% instantaneous load increase without ESSs limits.

Simulation results indicate that the ESSs help reduce the frequency variations caused by large MAGC time intervals and, hence, considerably improve the dynamic performance of the system. Moreover, the case with three ESSs leads to significantly lower frequency variations as compared to the case with one ESS. This result indicates that, from the dynamic point of view of the system, it is better to install ESSs in different locations of the network rather than installing them in one location.

B. ESSs with Capacity Limits

This section considers the same system and contingency as in the previous scenario, but taking into account the ESS capacity limits. In particular, each ESS device is now assumed to have a 10 MW capacity. Thus, the case with three ESSs represents almost the 10% instantaneous load increase (32 MW). Figure 6 depicts the transient response of $\omega_{\rm CoI}$. The case with three ESSs leads to a similar dynamic behaviour where no limits are considered (Fig. 5). Whereas the case when one ESS is connected in the system is unable to solve the problem caused by the MAGC discretization. These results indicate that, as expected, the performance of the ESSs is greatly impacted by its capacity.

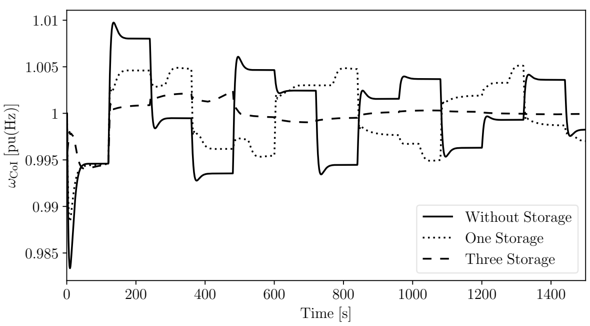

Fig. 6: Transient response of ω_{CoI} following a 10% instantaneous load increase with ESSs limits.

C. *Impact of Droop and Deadband*

Deadband and droop coefficient are two relevant parameters that can reduce the sensitivity of a controller to small frequency variations and noise. In the context of this work, we are interested to understand what is the impact of these control parameters on the overall dynamic performance of the system. With this aim, four cases are considered, as follows:

1) Zero droop and without ESSs limits.
2) Zero droop and with ESSs limits.
3) Non-zero droop and without ESSs limits.
4) Non-zero droop and with ESSs limits.

When non-null values are utilized, a deadband value of $db = 0.0006$ pu(Hz) and $H_d = 0.7$ are used. Furthermore, only the case when three ESSs connected at buses 7, 8, and 9 is considered below.

1) Zero droop without ESSs limits: Figure 7 shows the trajectories of the ω_{CoI} for three scenarios, namely, without storage, with storage and without deadband, and with storage and with deadband. The aim is to evaluate the impact of the deadband on the frequency error when ESS capacity limits are not considered. Interestingly, the case with a non-null deadband leads to a worse dynamic behaviour compared to the case without. This result leads to conclude that it is better not to include a deadband on the frequency error.

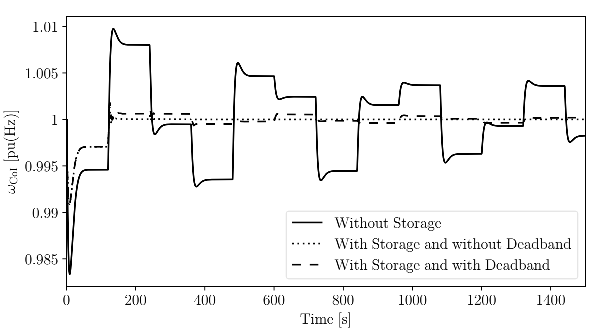

Fig. 7: Transient response of ω_{CoI} following a 10% instantaneous load increase with zero droop and without ESSs limits.

2) Zero droop with ESS capacity limits: The results of this scenario are shown in Fig. 8. If the ESSs limits are taken into account and the droop is set to zero ($H_d = 0$), the inclusion of the ESSs does not necessarily improve the dynamic behaviour of the system. Moreover, introducing or not a deadband on the frequency error does not improve the overall dynamic response of the system. These results indicate that a PI controller is not the most adequate set up to mitigate the long-term frequency variations caused by the market.

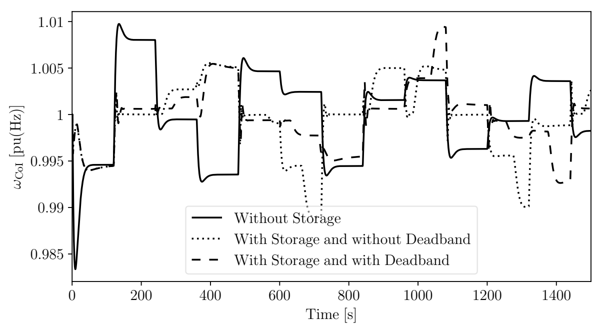

Fig. 8: Transient response of ω_{CoI} following a 10% instantaneous load increase with zero droop and with ESSs limits.

3) Non-zero droop without ESS capacity limits: This scenario considers a system setup similar to that discussed in Section V-C1 except for the value of the integral deviation coefficient that is assumed to be $H_d = 0.7$. Figure 9 shows that the frequency deviations for this scenario are similar to those obtained in Fig. 7. Also in this case, the inclusion of the deadband on the frequency error leads to a worse dynamic behaviour of the system as compared to the case without deadband.

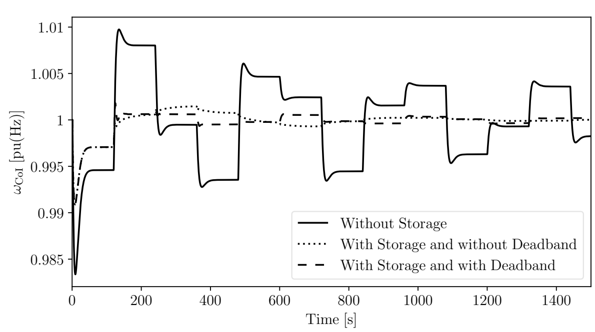

Fig. 9: Transient response of ω_{CoI} following a 10% instantaneous load increase with non-zero droop and without ESSs limits.

4) Non-zero droop with ESS capacity limits: This last scenario considers ESS controllers with a non-zero droop and with and without a deadband in a scenario where ESS capacity limits are binding. Results shown in Fig. 10 allow concluding that, also in this scenario, the inclusion of the deadband deteriorates the dynamic behaviour of the system.

Figure 11 shows the effect of the deadband on the active power of an ESS. When deadband is not null, the ESS reaches its active power limit, which gives raise to a sort of *bang-bang* phenomenon. These results indicate that depending on the set-up of the real-time electricity market, the values of the droop and deadband of the ESS frequency controller have to be carefully chosen.

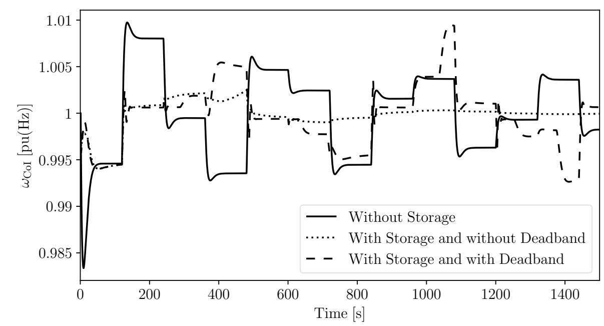

Fig. 10: Transient response of $\omega_{\rm CoI}$ following a 10% instantaneous load increase with non-zero droop and with ESSs limits.

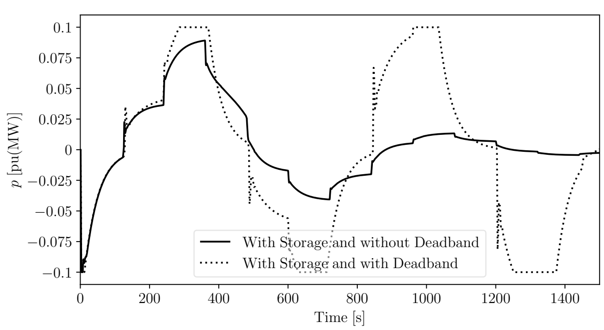

Fig. 11: Transient response of ESS active power following a 10% instantaneous load increase with non-zero droop and with ESSs limits.

VI. Conclusions

This paper evaluates the ability of ESSs to mitigate long-term power system frequency deviations caused by quasi-real-time electricity markets. The main conclusions of the paper are twofold. First, it is shown that ESSs play an important role in reducing the frequency deviations caused by the market. Second, it is shown that two parameters of the ESS frequency control, namely, the droop coefficient and the deadband on the frequency error, have to be carefully chosen in order not to deteriorate the overall dynamic performance of the system. In particular, simulation results indicate that the inclusion of the deadband may have a negative impact for ESSs with small capacity, and thus, when ESS energy limits are binding. The paper also shows that long-term dynamics of ESS can lead to surprising results when coupled with other dynamics of the grid. In this vein, future work will further investigate long-term dynamics driven by ESS controllers, e.g. load levelling and shifting.

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