Evaluation of the Impact of the Size of Storage Devices in Grid-Connected Microgrids

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***Abstract*—Storage devices play an essential role in increasing the flexibility of microgrids. In addition to improving the security and the resiliency of the microgrids, and in turn facilitating the handling of energy generated from intermittent sources, storage devices also allow microgrids to take tactical decisions to improve their efficiency or to increase their revenues. Demand side management, load following, and switching between an island mode and a grid-connected mode are typical examples of applications that are better enabled by the presence of storage devices. In this context, the objective of this paper is to explore how the size of storage devices affect the efficiency of microgrids, and their ability to gain revenues in a competing market. Results obtained in realistic Monte Carlo simulations on the IEEE 39-bus system are provided and discussed for this purpose.**

***Index Terms*—Microgrid, storage devices, energy management systems, distributed energy resources.**

I. INTRODUCTION

A. Motivation

In recent years, the power system community has dedicated a significant effort to design the most convenient way in which the Microgrids (MGs) should be operating. This is a very challenging task, as it requires the ability to take into account uncertain variables, namely, the load and the energy generated by renewable sources in a future horizon. In this context, energy storage devices (ESDs) have an essential role. This paper will discuss the effect of the size of ESDs in the operation of MGs, and propose a dynamic analysis able to define which ESD size gives the best trade-off between economical and technical constraints.

B. Literature Review

A microgrid is defined as any aggregation of DERs, including both dispatchable and intermittent (e.g., wind or photovoltaic plants) power plants, loads and storage devices. Usually, MGs operate at low-voltage level, are connected to distribution networks, and their main feature is to be able to operate both in a connected or disconnected mode (i.e., islanded mode) from the outer ac grid [1], [2]. The Energy Management System (EMS) is the intelligent core of the MG, and is responsible of taking tactical decisions, for instance deciding whether it is more convenient to operate in islanded mode or not.

The possibility to decompose traditional power systems into a number a semi-independent MGs is expected to improve the resiliency of the grid; simplify the control hierarchy; and to lead to a more efficient, up to fully decentralized, regulation of the power grid [3], [4]. At the time of writing this paper, however, the transition from the conventional power grid to a population of interconnected, or grid-connected, MGs is still at an exploratory level, and the power community has just started investigating the possible challenges and consequences of such new topological schemes [5]–[8]. Previous work of the authors (e.g., see [9]–[12]) analyses the effects of a large population of grid-connected MGs, for instance in terms of the impact on the frequency of the power system.

As indicated in the motivation above, ESDs play a crucial role in such a transition process. Without ESDs, in fact, the ability of the EMS to balance load and generation is limited to postponing controllable loads to more favourable windows of time, or other similar demand side management actions. On the other hand, the inclusion of ESDs enables more complex actions, for instance, MGs can connect to or disconnect from the grid based on the conditions of the electric energy market. With this regard, a typical EMS approach is to store energy when the price is low, and to sell it back in the market when the price is higher. A review of energy storage applications in power distribution networks can be found in [13].

C. Contribution

This work further develops the line of research of [9]–[11] and focuses on the specific impact of the size of the ESDs, with the aim of identifying the minimum size of storage devices that is required to preserve a given flexibility of MGs (e.g., in terms of their ability to compete in the market) while the impact on the system frequency stability is maintained below a given safety level. This result is obtained through a stochastic decentralized control of the EMS of the MGs. While in the previous works the authors had assumed that MGs would always have enough capacity to provide ancillary services at any moment in time, in this paper we shall drop this assumption to better investigate the importance of ESDs.

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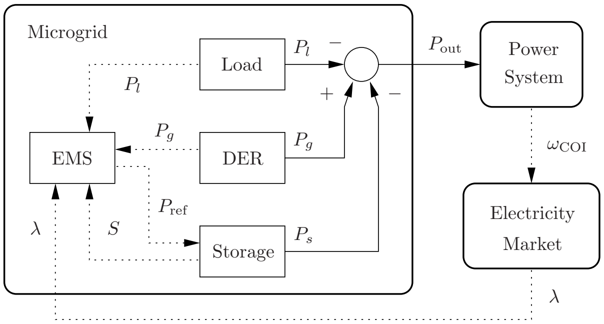


Fig. 1: Structure of the connection between the MGs.

D. Organization

This paper is organized as follows: Section II briefly recalls the models that are required in our simulations to investigate the impact of storage devices. Section III provides some preliminary results that we have obtained and that motivate the present work and then presents the results obtained from the current analysis. Finally, Section IV summarizes the contributions of the paper.

II. MODEL

In this paper, we shall model each MG using stochastic differential equations, taking into account loads, DERs and storage units, coordinated by an EMS. The EMS is in particular responsible of choosing the most convenient active power set point of each MG (i.e., how much power each MG may want to buy or sell from the outer electrical grid [3]). Figure 1 shows the connections of the MG with the power system and the electricity market, where S is the state of charge of the storage device; P_s is the power generated or absorbed by the storage device (where $P_s > 0$ corresponds to charging); P_g and P_l are the generated active power and the power absorbed by local loads, respectively, of the MG; λ is the price of electricity; P_{out} is the overall power exchanged with the outer power grid; and ω_{COI} is the frequency of the center of inertia, that we consider here as a proxy to discuss the stability of the power system.

This paper builds on previous work of the authors, namely, [9]–[12]. In particular, we use here the same models of the single elements that are required to simulate the interactions between the MGs: this includes the model of the power system; the model of the electricity market; and of the single MGs. The interested reader may refer to [9] for a detailed description of the specific models.

III. SIMULATION RESULTS

In this Section we present the results obtained from several simulations with the IEEE 39-bus system [14]. All simulations are based on Dome, a Python-based software tool for the transient stability analysis of power systems [15]. We first show some results obtained in a previous work to explain the general context and to motivate the work in this paper.

A. Preliminary Results

In [9] the authors had observed that a non-coordinated number of MGs connected to the distribution grid, that try to maximize their own revenues by trading electrical energy in the market may cause stability issues to the power grid. For this purpose, the authors had further designed deterministic and stochastic control strategies to mitigate the impact of MGs on the power stability, namely, by asking the MGs to provide frequency regulation services when the frequency got close to dangerous values. Accordingly, a fraction of active power was in fact used by MGs to provide ancillary services rather than increasing their revenues.

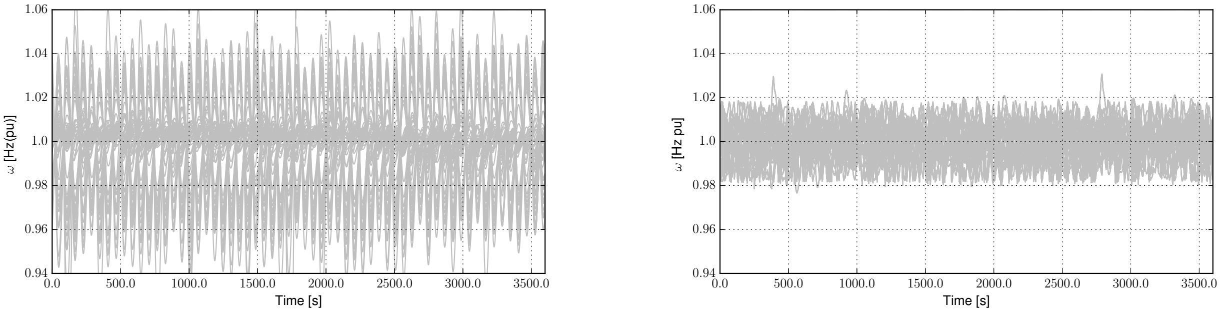
The previous comments may be graphically summarized by figures 2.a and 2.b. In particular, Figure 2.a shows the values of the frequency of the center of inertia in 500 Monte Carlo simulations with 36 MGs connected to the IEEE 39-bus system. The depicted results correspond to the case when the MGs operate in a non-coordinated and non-controlled fashion, trying to maximize their revenues at every point in time. Clearly, this may lead to undesired oscillations of the frequency (expressed in pu). On the other hand, Figure 2.b shows all the realizations of the frequency, in other 500 Monte Carlo simulations, when the MGs are required to provide frequency regulation services when the frequency gets close to undesired values (here it was assumed that the allowed range of frequency variation was between 0.98 and 1.02 Hz pu).

While even from visual inspection it is clear that the fluctuations of the frequency may be restrained within (any) desired range, results had been obtained under the strong assumptions that all MGs had enough capacity to provide ancillary services at any moment in time. Clearly, this was a strong, and somewhat unrealistic, assumption. Accordingly, in the next subsection we drop the previous assumption, and investigate what happens for different values of the storage size, and whether an optimal value can be identified.

B. Simulations

This section compares the impact on the dynamic response of the IEEE 39-bus system with inclusion of 12 MGs with different as ESD capacities. Table I lists the parameters of the 12 MGs and the corresponding buses to which they are connected. The parameters $\bar{p}_g$ and $\bar{p}_l$ refer to the average active power generated by the DERs, and consumed by the loads, respectively. T_c represents the discharge time of the ESDs, and in the remainder of this paper we shall use it to indirectly denote the capacity of an ESD, as we assume that the power rate of the ESD is the same for all MGs and in all scenarios.

We analyze the impact of the size of the ESD by performing 100 Monte Carlo simulations of 10 different scenarios with decreasing values of T_c (each scenario corresponds to a certain percentage of the nominal value considered in Table I). The comparison is then performed in terms of the impact on the stability of the grid (i.e., the standard deviation of the frequency of the centre of inertia of the system), and in terms of the revenues of each MG. These quantities are computed as follows,



(a) Without controller

(b) With frequency control

Fig. 2: Frequency trajectories, over all the realizations, of the 39 bus system.

$$\omega_{\mathrm{COI}} = \frac{\sum_{i=1}^{r} H_i \omega_i}{\sum_{i=1}^{r} H_i} \ , \tag{1}$$

$$R_i(t) = \int_0^t P_{\mathrm{out_i}}(\tau)\lambda(\tau) d\tau \ . \tag{2}$$

TABLE I: Microgrid parameters

MG	Bus #	$\bar{p}_g$ pu(MW)	$\bar{p}_l$ pu(MW)	σ_{net} pu(Hz)	T_c s
1	18	0.88	0.54	0.025	3600.0
2	3	0.77	0.20	0.040	3600.0
3	15	0.80	0.10	0.030	3600.0
4	17	0.40	0.20	0.020	3600.0
5	21	0.20	0.10	0.013	3600.0
6	28	0.20	0.40	0.040	3600.0
7	24	0.36	0.84	0.010	3600.0
8	17	0.20	0.50	0.020	3600.0
9	11	0.20	0.30	0.010	3600.0
10	5	0.10	0.80	0.010	3600.0
11	7	0.80	0.10	0.030	3600.0
12	12	0.40	0.40	0.025	3600.0

TABLE II: Controller performance

Discharge Time s	Storage Capacity pu(MWh)	σ_ω pu(Hz)	$\bar{R}(t)$ pu($)
0	0	0.022	0.679
360	0.1	0.015	0.712
720	0.2	0.013	0.847
980	0.3	0.006	0.888
1340	0.4	0.006	0.902
1800	0.5	0.006	0.945
2160	0.6	0.006	0.989
2520	0.7	0.006	1.000
2880	0.8	0.006	1.000
3240	0.9	0.006	1.000
3600	1.0	0.006	1.000

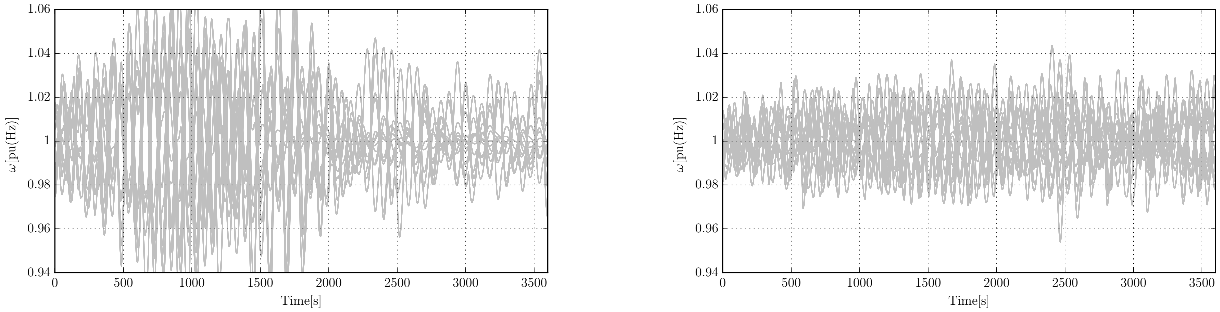
In (1), ω_i and H_i are the frequency and the moment of inertia of the i-th synchronous machine, respectively; and r is the number of conventional generators in the grid. In (2), λ is the market clearing price of electrical energy in $/MWh. In the following, the revenue values R_i are normalized with respect to the largest one, since the absolute values depend on the choice of the market model and not on the proposed control scheme and thus, only the relative values are meaningful.

Figure 3 and Table II summarize the obtained results. The control system is able to maintain the frequency in the desired interval [0.98, 1.02] as long as the discharge time is greater than 720 s (i.e., starting from the 20% case shown in Figure 3.c). Below this threshold the control system is not able to regulate the frequency within the prescribed range. The reason for this is that without the flexibility of a (large enough) ESD, the MGs can not simultaneously internally balance the consumed and the generated energy, and at the same time provide ancillary frequency regulation services to the power grid.

Table II also shows that the revenues of the MGs remain constant when the discharge time of the ESD is greater than 2520 s, while it decreases when smaller values of the capacity are available. The explanation of this result is that a minimum size of the ESD is required to achieve certain revenues (e.g., to store energy when its price is low, and sell it back when its price is larger). However, when the storage device is large enough, then a saturation value is achieved, and no more revenues are gained.

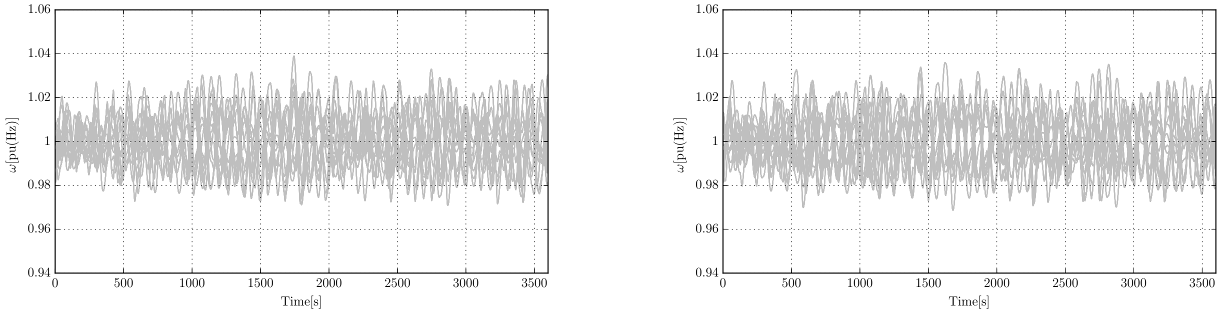
It is also interesting to note that for intermediate values of the capacity of the ESD, the frequency is regulated in a satisfactory manner (see second column of Table II), but optimal values of revenues are not achieved. This is due to the fact that the controller is designed to prioritize frequency regulation rather than individual revenues.

To summarize the previous discussion, it is possible to conclude that there are two critical values for the storage capacities (given the proposed control strategy). A minimum value of the ESD is necessary to provide basic frequency regulation services that are critical to maintain the power frequency within a safe range. At the same time, there is an upper bound of the size of the ESD after which no extra



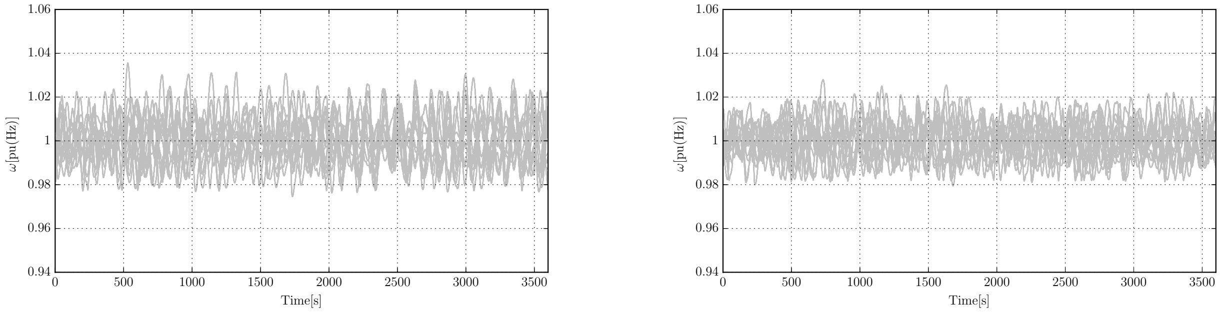
(a) 0% of the nominal storage

(b) 5% of the nominal storage



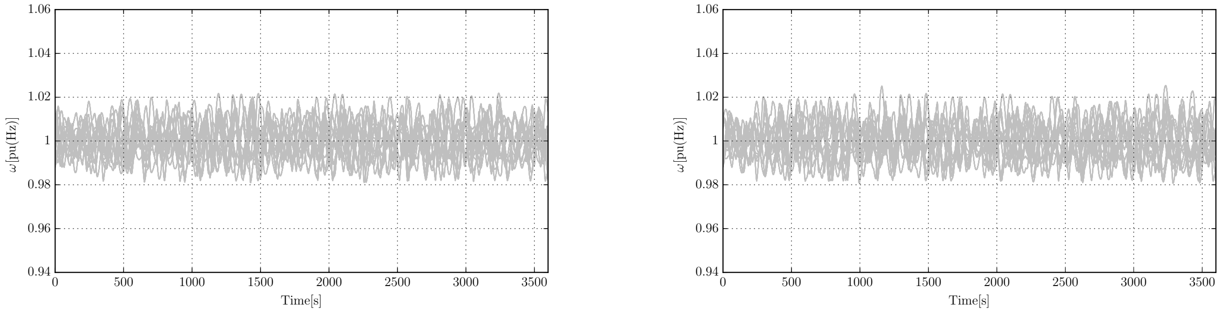
(c) 10% of the nominal storage

(d) 15% of the nominal storage



(e) 20% of the nominal storage

(f) 50% of the nominal storage



(g) 75% of the nominal storage

(h) 100% of the nominal storage

Fig. 3: Realizations of the center of inertia of the frequency.

advantages are obtained by the MGs. While this observation appears to have a general interpretation, the exact values of such two thresholds can not be generally determined but depend on the specific case study. In particular, their values depend on the size of the MGs, on their topological position in the power grid, and on the way their EMS works. For instance, [10] shows that the strategy of the EMS has a great impact on the stability of the power grid itself, as MGs that work in island mode have a very small impact in the frequency of the system.

IV. CONCLUSIONS

This paper follow previous work of the authors in the analysis of the interaction of grid-connected MGs. While most of their previous work neglected the importance of the size of the storage device, this paper illustrates its impact as the size varies from small, or zero, capacity to a large one.

In particular it was noticed that it is possible to determine two critical values. Below a lower bound of the ESD, the MGs fail to provide frequency regulation services that are essential to maintain the frequency of the grid within a safe range of operation. Above an upper bound of the ESD, on the other hand, the revenues of the MGs saturate to a constant value, and no more advantages are achieved. For intermediate values of the capacity of the ESD, the frequency is well regulated, but lower earnings are obtained by the MGs, as less flexibility is obtained when the storage is smaller.

While the authors believe that the previous discussion can be easily generalized, still the computation of the two critical values may strongly depend on some specific assumptions (e.g., on the Energy Management System of the MGs that may be designed to make the MGs compete, or cooperate, or work autonomously in island mode, within the same power grid). Thus, future work will focus in trying to generalize the previous observations in a more comprehensive framework.

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