Local Effects of Grid-Forming Converters Providing Frequency Regulation to Bulk Power Grids

Antonio Zecchino, Francesco Gerini, Yihui Zuo,
Rachid Cherkaoui, Mario Paolone
Distributed Electrical Systems Laboratory (DESL)
Ecole Polytechnique Fédérale de Lausanne, EPFL
Lausanne, Switzerland
{antonio.zecchino, francesco.gerini, yihui.zuo,
rachid.cherkaoui, mario.paolone}@epfl.ch

Elena Vagnoni
Technology Platform for Hydraulic Machines
Ecole Polytechnique Fédérale de Lausanne, EPFL
Lausanne, Switzerland
{elena.vagnoni}@epfl.ch

Abstract—The progressive displacing of conventional generation in favor of renewable energy sources requires restoring an adequate capacity of regulating power to ensure reliable operation of power systems. *Battery Energy Storage Systems* (BESSs) are considered to be promising assets to restore suitable frequency regulation capacity levels. BESSs are typically connected to the grid with power-converters, able to operate in either grid-forming or grid-following modes. This paper quantitatively assesses the impact on the local distribution grid of BESSs providing frequency regulation to bulk power systems. Specific metrics are proposed to compare the performance of grid-forming and grid-following control. Experimental results are obtained taking advantage of a 720 kVA/500 kWh BESS connected to the 20 kV distribution grid of the EPFL campus. The quantitative evaluation based on suitably proposed metrics confirms the superior performance of grid-forming strategy, compared to grid-following one.

I. INTRODUCTION

Integrating renewable energy sources in the European energy supply mix has long been ascertained as a fundamental step for the decarbonisation of the electric sector. Moving towards this direction raises multiple challenges for power systems, including the need for regulating power and flexibility services provision to mitigate the massive integration of non-dispatchable and stochastic resources. In this respect, converter-interfaced *Battery Energy Storage Systems* (BESSs) are considered as perspective assests for grid frequency regulation in view of their large ramping rates, high round-trip efficiency and commercial availability [1], [2], [3]. BESSs interface with the grid through four-quadrant power converters [4], typically controlled to provide grid ancillary services ranging from frequency regulation up to energy management [5]. As known, there are two main approaches to control converter-interfaced BESSs: *Grid-Forming* (GFR) and *Grid-Following* (GFL). Nowadays, the majority of converter-interfaced resources are controlled as

GFL sources, as this operating mode is considered to be sufficiently efficient [6], [7]. Nonetheless, future grids may require GFR devices to provide more frequency and voltage regulation, stability and black-start capabilities, all services that are nowadays offered primarily by synchronous machines [8], [9]. Furthermore, recent studies have proved GFR control strategies to outperform GFL in terms of frequency regulation performance in low-inertia power grids [10]. The impact of GFR converters on the dynamics of a reduced-inertia grid has been investigated in [11], which quantitatively proved the good performance of GFR units in limiting the frequency deviation and in damping the frequency oscillations in case of large contingencies. The existing scientific literature lacks of studies on the assessment of the performance of GFR units in supporting the frequency containment process of large interconnected power grids. In fact, studies on the GFR units synchronizing with AC power grids are mostly limited to either simulation [11], [10], [12] or to experiments on ideal slack buses with emulated voltage [13], [14]. The latter are capable of identifying the fundamental characteristics of the GFR controls, as well as to optimize optimal control parameters [13]. However, they can not assess the dynamic interaction between power grids and the GFR units. Simulations-based studies have been investigating the impact of large-scale GFR or GFL units on frequency containment of low-inertia power grids[10], [12], where the power rating of the controlled element (i.e. the BESS) is comparable to the one of the power system. Nevertheless, in bulk power grids, the influence of a single frequency control provider can hardly be detected through frequency measures at the transmission level. An alternative approach is to measure the influence of units providing frequency regulation services on the local distribution grid. In this respect, the scope of this paper is to experimentally assess the performance of GFR and GFL control for converter-interfaced BESS by measuring with accurate *Phase Measurement Units* (PMUs) the influence of the two control strategies on the local distribution grid. The

experimental campaign is conducted by taking advantage of a grid-connected 720 kVA/500 kWh BESS connected to the 21 kV distribution feeder on the EPFL campus.

The paper is structured as follows: Section II presents the characteristics GFR and GFL, Section III analyses the state-of-the-art metrics used to compare GFR and GFL control and proposes a new metric, to better capture local effects of the two control strategies. Section IV presents and discusses the experimental results. Finally, Section V summarizes the results and concludes the paper.

II. CONVERTER CONTROLS

As mentioned in Section I, GFR and GFL controls are the two approaches currently used to control converter-interfaced BESSs [8], [15]. For the sake of consistency, this section reports the description of GFR and GFL controller proposed by [8].

GFR units are based on a power converter which controls magnitude and angle of the voltage at the *Point of Battery Coupling* (PBC). As a consequence, the knowledge of the fundamental frequency phasor of the grid voltage at the PBC is not strictly necessary. Fig. 1a presents a general structure of the GFR control, where the modulated voltage angle is linked with the converter active power, while the voltage magnitude is regulated by taking into account of voltage or/and reactive power reference.

GFL units are based on a power converter which controls the currents injection to adjust the active and reactive power injection. To this end, the injected current is controlled with a specific phase displacement with respect to the grid voltage at the PBC. Consequently, the fundamental frequency phasor of the grid voltage at the PBC is needed at any time to correctly calculate the converter reference currents. Fig. 1b shows the classical structure of the GFL control, where the grid voltage angle $\tilde{\theta}_g$ is estimated thanks to a *Phase Locked-Loop* (PLL) and used by the Park's transformation. The outer control loops can adjust the amplitude and angle of the current reference currents to inject required amount of active and reactive power. Grid-supporting GFL converters can be applied to adjust active and reactive power set points under frequency or voltage deviations

III. QUANTIFICATION OF FREQUENCY REGULATION

A. State-of-the-Art Metrics

To evaluate the impact of the frequency regulation provided by BESSs to low-inertia grids, [10] proposes the hereby listed metrics:

- Frequency *Probability Density Function* (PDF), where the standard deviation of the grid-frequency statistical distribution is observed to assess the capability of the control strategy in limiting the frequency deviations from the nominal value.
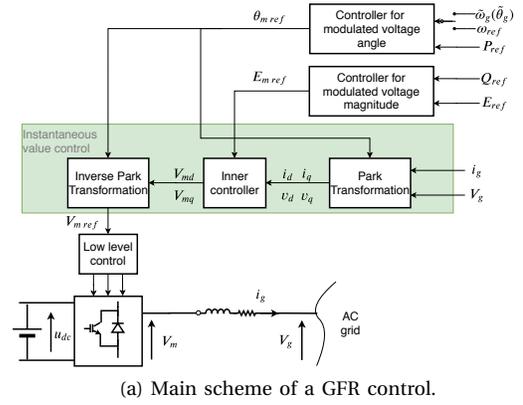
(a) Main scheme of a GFR control.
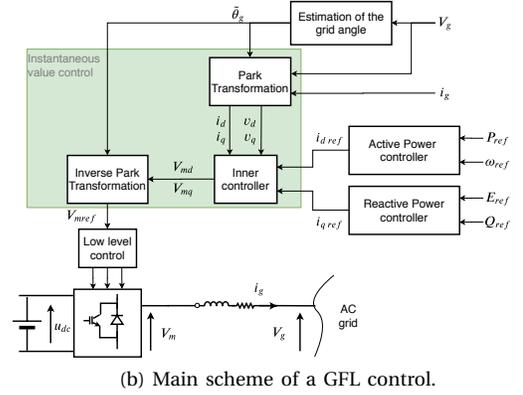
(b) Main scheme of a GFL control.

Fig. 1. Main schemes of GFR and GFL controls [8].

- *Integral Frequency Deviation* (IFD):

$$\text{IFD} = \sum_{i}^{M} \sum_{k=1}^{N} |f_{k,i} - f_0| \tag{1}$$

where M is the number of measurement units, N is the total sampling number of frequency measurements for each load, $f_{k,i}$ is the frequency measured by the measurement unit i at sample k and f_0 is the nominal frequency, i.e. 50 Hz.

Both frequency PDF and IFD establish a relation between grid-frequency measurements and control actions of the converter-interfaced BESS. Nevertheless, it is not possible to measure the influence of a small frequency control provider to the bulk power grid, as the frequency can be considered independent from the single action of a small power converter. Therefore, frequency PDF and IFD can not be considered as reliable metrics.

B. New metrics

To characterize the local effect of a converter-interfaced BESS providing frequency regulation and to identify the difference between the GFR and GRL controls, we proposed new metrics based on PMUs measurements performed locally, i.e., on the distribution feeder where the BESS is installed. The frequency measures at the *Point of Common Coupling* (PCC) of the distribution feeder, as well as the phase angle differences between the voltage controlled by

the converter unit and the PCC voltage are taken into consideration to derive the following metrics:

- *Relative Rate-of-Change-of-Frequency* (rRoCoF):

$$rRoCoF = \left| \frac{\Delta f_{PCC}/\Delta t}{\Delta P} \right| \qquad (2)$$

where Δf_{PCC} is the difference between one grid frequency sample and the next (once-differentiated value) at the bus where the BESS is connected to, ΔP is the once-differentiated BESS active power, and Δt is the sampling interval.

- *Relative Phase Angle Difference Deviation* (rPADD):

$$rPADD_k = \left| \frac{\Delta\theta_k - \Delta\theta_0}{\Delta P_k} \right| \qquad (3)$$

quantifying the change in the phase-to-neutral voltage angle difference $\Delta\theta_k$, measured by two PMUs installed on nodes at different voltage level of the local feeder, versus the case with null delivered active power $\Delta\theta_0$.

The relative RoCoF metric measures the RoCoF regulation at PCC. Since the RoCoF is weighted by the delivered active power of the BESS, it can be used to compare the local performance of GFR versus GFL converter in large interconnected electrical systems. On the other side, for the rPADD computation, the benefit of using metrics based on voltage phase angle is two-fold: (i) changes in the phase angle estimation are directly linked with frequency deviations from nominal frequency [16] and (ii) it can indicate the ability of the connected unit in sustaining local voltage by controlling its angle. The metric is normalized by the delivered active power of the converter-interfaced unit to ensure its independence from the grid condition and the power rating of the converter-interfaced unit.

IV. EXPERIMENTAL CAMPAIGN

A. Experimental Setup

1) Feeder Characteristics: for the experimental campaign, a 20 kV distribution network equipped with a BESS is considered. The experimental configuration shown in Fig. 2 consists in a group of buildings of the EPFL campus characterised by a 140 kW base load, hosting 95 kWp root-top PV installation and a grid-connected 720 kVA/500 kWh Lithium Titanate BESS. The BESS bidirectional real power flow is denoted by P, and G is the composite power flow seen at the PCC. The aggregated building demand is denoted by L and, by neglecting grid losses [17] , it is estimated as $L = P - G$. For both buildings and BESS, positive values denote injection towards the PCC, while negative denote consumption. The measuring systems is composed by three PMUs, i.e. PMU 2, PMU 1 and PMU 0, installed respectively on 0.3 kV, 20 kV and 50 kV side of the feeder. Two transformers connect the different voltage levels of the feeder. Their nominal voltage and power, as well as their short circuit voltage expressed in percent are shown in Fig. 2.
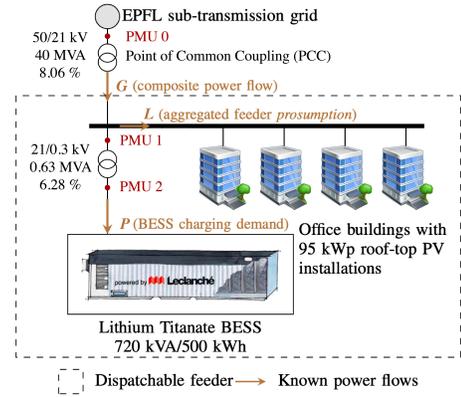
Fig. 2. Experimental setup of the EPFL campus MV grid hosting the utility-scale 720kVA/500 kWh BESS.

2) Controller Characteristics: the BESS converter is capable of synchronizing with the grid in both GFL and GFR control modes. In GFR mode the converter controls the voltage angle to provide frequency regulation by means of an internal control loop directly establishing a droop relation between the grid frequency and the active power to be delivered. In GFL mode, the active power set-point for frequency regulation is computed in an external loop, as a function of the grid frequency deviation (from 50 Hz). In particular, the maximum feasible droop, i.e. 1.44 MW/Hz, is selected for the experiments and implemented in both GFR and GFL modes to maximise the BESS response.

3) Requirement for PMUs: for the computation of the Relative Integrated Phase Angle Difference Deviation (rPADD), high-accuracy PMUs are required. Knowing the feeder topology, the short-circuit voltage of the two transformers and assuming the line as lossless, it is possible to estimate the angle displacement per unit of delivered power by the BESS as 0.006 degree/kW. Considering a droop of 1.44 MW/Hz and the need of estimating BESS reactions for frequency deviations greater than the typical frequency deadband [18], i.e. 10 mHz [18], the measuring infrastructure must be able to detect angle differences of 0.9 degree. To robustly measure those phase angle differences, the PMU-based distributed sensing with infrastructure deployed in the EPFL campus have been utilized [17], thanks to its accuracy in terms of 1 standard deviation equal to 0.001 degrees (i.e. 18 μrad), 90 times smaller than the minimum angle required for the rPADD computation.

4) Grid condition: as the experimental validation relies on real operating conditions, it is subjected to the uncontrollable variation of the power system frequency of the Continental Europe Synchronous Region, to which the medium-voltage grid of the EPFL campus is connected. For this reason, the experimental campaign has taken place during the transition of the hour, which typically present fast frequency ramps due to mechanisms related to electricity markets [19]. Such frequency ramps have been used to activate BESS to perform considerable active
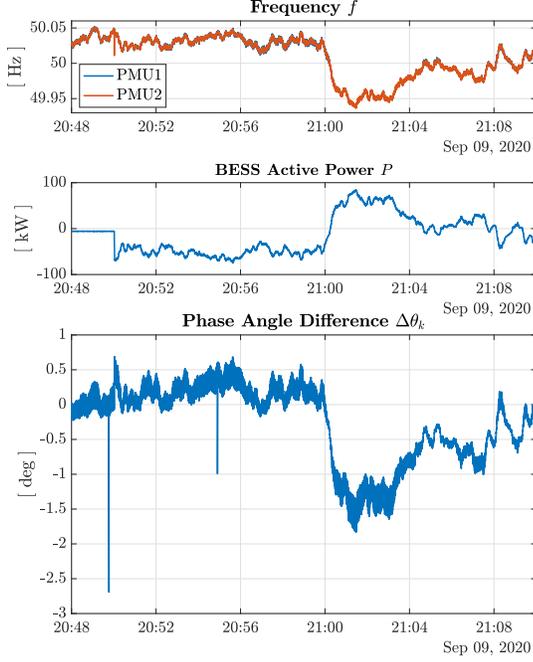
Fig. 3. Experimental test results using the EPFL BESS converter in GFR mode with 1.44 MW/Hz droop.
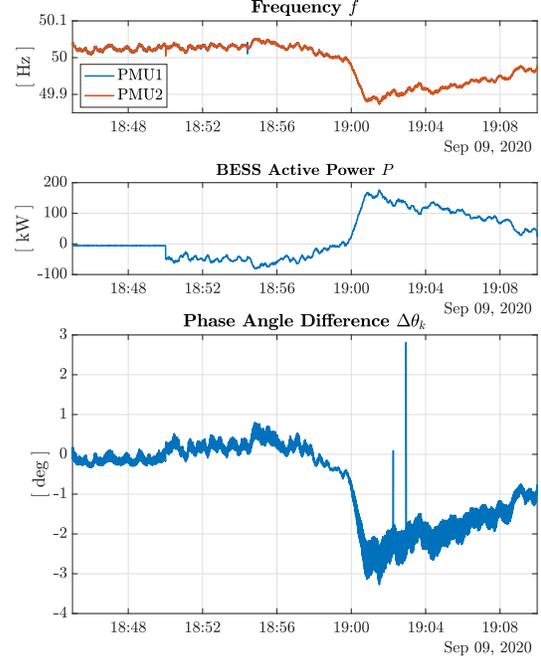
Fig. 4. Experimental test results using the EPFL BESS converter in GFL mode with 1.44 MW/Hz droop

power exchanges P, following the 1.44 MW/Hz droop implemented both in the GFR and GFL controls. Furthermore, the proposed tests have been carried out when the base consumption of the local medium voltage L grid presents a mostly constant profile such that its dynamics are not influencing the local measures on which the metric are based, i.e., during evening and night hours. This allows for assuming $\Delta\theta_0$ to be constant during the experiment, enabling a better identification of the impact of the BESS provided power in the local phase angle displacements.

B. Experimental Results

The experimental assessment of the BESS response are shown in Fig. 3. At the top, the frequency measured by the PMUs and the BESS active power response are provided. The frequency ramp at the hour transition (21:00 CET) are noticeably reflecting on the BESS power ramp. The angle displacement is computed as the angle difference between PMU 1 (21 kV) and PMU 2 (0.3 kV):

$$\Delta\theta_k = \theta_{k,PMU1} - \theta_{k,PMU2} \tag{4}$$

Before the activation of the BESS control at 20:50 CET, the phase angle difference $\Delta\theta_0$ is computed as:

$$\Delta\theta_0 = \theta_{0,PMU1} - \theta_{0,PMU2} \tag{5}$$

The values of $\Delta\theta_0$ and $\Delta\theta_k$ can be inserted in Eq. (3) for the rPADD computation. For the sake of comparison, a similar experimental assessment is conducted in GFL mode and the results are shown in Fig. 4.

To quantitatively assess and compare the two cases with respect to the impact on the local grid frequency, the two relative metrics presented in Section III, namely rRoCoF and rPADD, are considered. rRoCoF is computed over a time window of 60 ms. For the sake of clarity and simplicity of the interpretation, results of the rRoCoF the rPADD computation are reported in terms of *Cumulative Distribution Function* (CDF). Fig. 5 shows the rRoCoF CFD for multiple tests, expressed in [Hz/s/kW]. It is important to observe the vertical trend of the red line, representing the GFR case, implying higher probabilities of having smaller values of rRoCoF. This means that, for a higher number of instances for which the rRoCoF has been computed, it is more likely to have smaller values when controlling the BESS in GFR mode than in GFL mode. This demonstrates that the GFR control can guarantee larger containment of the rate of change of the frequency, compared to the more traditional GFL strategy. These results are in line with what is presented in [10], relatively to the simulation activities on the IEEE 39-bus benchmark grid. Fig. 6 shows the CDF probability of the rPADD of having a given value expressed in [deg/kW]. It is clear that larger values of the index mean larger impact on the local phase angle displacement of the voltages measured at the two different voltage levels. It can be noticed that in this case larger values are found for the GFR case, demonstrating that the implemented GFR control can guarantee larger impact on the local phase angle difference, compared to the more traditional GFL strategy.
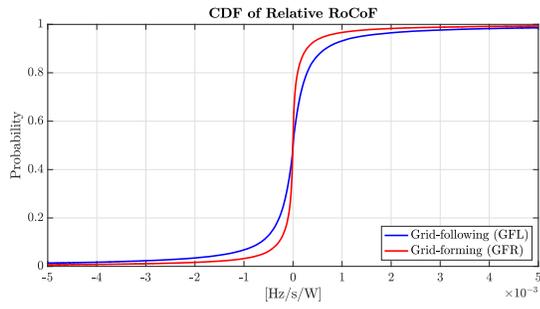
Fig. 5. Cumulative distribution function of the rRoCoF [Hz/s/W] for the experimental tests.
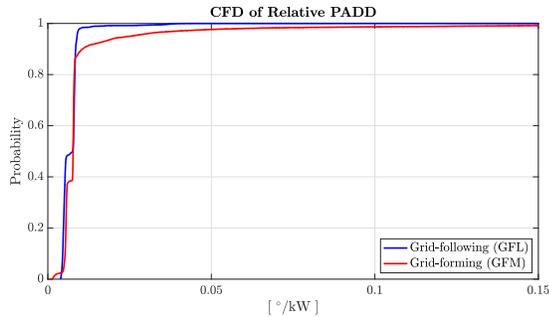
Fig. 6. Cumulative distribution function of the rPADD [deg/kW] for the experimental tests.

V. Conclusion

A novel metric to quantitatively assess the local impact of BESSs providing frequency regulation to bulk power grid has been proposed. Experimental tests confirmed the outcome of the analysis carried out by means of simulation activities on the low-inertia configuration of the IEEE 39-bus emulated grid presented in [10], validating the positive effects of the grid-forming strategy in the control of the local frequency. The upgrade of the PMU-based sensing infrastructure, enabled the assessment of impacts on the local frequency with the BESS control running with maximum possible frequency droop. The proposed metrics (rROCOF and rPADD) can potentially be of use for the quantification of frequency reserve provision to distribution systems. Moreover, both metrics confirmed the superior performance of the grid-forming strategy, characterised by a more contained rROCOF and a larger impact in the local phase angle compared to grid-following mode.

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