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Battery energy storage system for frequency support in microgrids and with enhanced control features for uninterruptible supply of local loads

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ABSTRACT

This paper proposes a battery energy storage system (BESS) to support the frequency control process within microgrids (MG) with high penetration of renewable energy sources (RES). The solution includes features that enhance the system's stability and security of supply. The BESS can operate connected to MG or islanded and the transition between the two states is seamlessly coordinated by an original method. The BESS active power response is governed by an improved frequency controller on two layers, namely primary and secondary. It responds to frequency deviations by combining a conventional droop control method with a virtual inertia function to improve the system's stability. The proposed BESS may also compensate the power of the local loads, so that the MG frequency transients can be reduced and, depending on the remaining inverter capacity, voltage support in the point of common coupling with the MG may be provided. If the MG power quality degrades in terms of the voltage and frequency, the BESS and the local load are disconnected from the MG and continue operating islanded. The BESS is reconnected to the MG after a smoothly resynchronization of the local voltage with the MG, without disturbing the local loads supply. Simulation and experimental results assesses the proposed control solutions.

1. Introduction

In the current context of globally promoting the integration of renewable energy sources (RES) in small, medium and large-scale power systems, with the power grids expanding and becoming more complex, the development of new technologies for better RES integration and utilization is a current concern worldwide. Many countries are focusing to achieve the RES targets, to reduce the greenhouse gas emissions and to make the societies less energy-consuming [1]. However, the RES power variations and their unpredictable nature decrease the grids' reliability by making them more sensitive to voltage and frequency stability issues, the power reserve estimation becomes more difficult and the security of supply can be affected. Therefore once the RES penetration level increases the related standards are continuously revised [2].

Within this context, a new power system structure has emerged, namely the microgrid (MG), which was initially developed to supply remote consumers with electricity. A MG consists of one or more micro-generators (of the same type or different) and consumers, defining all the equipments and infrastructure required to operate a small-scale power system [3]. The MG is meant to be mainly supplied by RES, whereas specific control devices (e.g. energy storage systems) maintain the required power quality. Despite of the potential benefits, the development of MGs suffers from technical difficulties, lack of standardization, economical challenges, and administrative and legal barriers [4,5]. Recently, the smart grid (SG) evolved towards a new concept, where the MG represents the main building block [6,7]. Multiple MGs, linked through power and communications lines, can be seen in the SG as the equivalent power generators in the conventional power systems. The MG can operate islanded, feeding power to the local consumers from the in site power generators, or it can be interconnected with other grids.

The power quality issues in an autonomous MG are rather similar to those from a classical power system (voltage, frequency, security of supply). The main MG weakness comes from the limited power supply capacity, especially when the RES penetration level is high. The majority of technical resources are based on power electronics converters, which are the critical distinguishing feature of the MGs, along with intelligent control and communication [8,9]. Besides the generators, storage elements and other equipments needed for a normal operation, the MG may also include a centralized control system (the equivalent of a grid dispatcher), known as the microgrid central controller (MGCC) [10,11]. All the decisions regarding the MG resources handling are fulfilled by

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the MGCC, which provides the appropriate commands for each MG unit.

The frequency control process represents a main component within the control system of a MG. Giving the fact that the MG is characterized by small rigidity in comparison with the classical grid, the RES generators and the loads power variations are the main sources of instability. Ensuring an adequate power quality largely depends on maintaining the grid frequency within a certain range (e.g. ±2%), regardless of the generation and consumption levels. Unlike the voltage, which is a local power quality parameter of a network, and which usually depends on the reactive power flow, the steady-state frequency of a certain synchronous area represents a global indicator of the active power balance between the generation and consumption (including the system losses). The unpredictable RES power variation decreases the system's stability and security, making the power reserve estimation a difficult task [12]. While in the large power grids the pumped hydro power plant represents the most efficient energy storage solution, in the case of MGs combining battery energy storage systems (BESS), smart loads, gensets and implementing a hierarchical control of the resources provide a solution to the frequency control challenges [13–16]. Due to the rapid active power response, the BESS may compensate the fluctuations produced by RESs, and the generation rate constraints of conventional generators [17,18]. The energy storage resource may come from stationary units based on different battery technologies (e.g. lead-acid, vanadium redox flow, etc.) [19,20], or from electric vehicles as recent studies suggest [21,22].

In the classical grids, the frequency control is accomplished on three time-dissociated levels, namely primary, secondary and tertiary, deployed successively in order to both regulate the frequency and to ensure an optimal loading of the generating units according to the requirements in each control area [23]. Recent studies suggest that the frequency control in MGs should follow a similar structure [24], involving the real-time dispatching of multiple generators, energy storage systems and active loads.

The use of BESS for frequency supporting in power systems is a highly debated topic in the literature, with special attention being provided to the autonomous MGs with RES. In [13] a centralized frequency controller, coordinating a BESS and a dump load, regulates a wind–diesel system, where the BESS ensures the MG loads supply during energy shortage periods. Another control strategy for MGs based on short-term energy storage systems is reported in [25], where the frequency control process is hierarchically organized on two layers. The energy storage systems support the MG frequency and voltage during the primary control, after which they are unloaded during the secondary level. Similarly, [26] analyzes the primary frequency supporting using BESS for complex autonomous MG with RES-based and fossil fuel generators, from the optimal storage capacity point of view. The control of power electronics – based MGs is more flexible and the integration of BESS is easier as all the inverters can be unitary controlled. In this case, the two-level voltage and frequency control can also be successfully implemented [27].

On this line, the paper proposes a BESS structure that mainly provides frequency support in MGs supplied by either inverter-based or conventional generators, but including supplementary functions for improving the MG stability and security of supply.

2. The proposed BESS

Fig. 1 shows the proposed BESS structure, including the hardware part (Fig. 1a) and the control system (Fig. 1b). A single-phase voltage source converter (VSC) controls the power transfer between a battery bank and the AC microgrid. A grid filter ($L_f - C_f$) mitigates the current harmonics produced by the VSC high-frequency switching. The BESS is placed near a sensitive consumer (or a cluster of consumers), after which a switch (K_g) can detach the BESS and loads of the MG. The point of common coupling (PCC) with the MG is defined at the output leads of K_g and the impedance of the MG feeder is represented by Z_G.

The proposed control part, illustrated by the block diagram from Fig. 1b, includes interlinked subsystems that accomplish the following two main tasks:

- BESS control in MG-connected mode (hereinafter called *MG-mode*);
- BESS control in islanded mode (hereinafter called *I-mode*).

The MG can operate either autonomously or interconnected to a larger grid (e.g. public grid). This paper is focused mainly on the autonomous MG operation, but the proposed system can be easily adapted for grid operation too. Thus, the *MG-mode* state means that the BESS is connected to the autonomous MG, whereas the *I-mode* characterizes the BESS operation disconnected from the MG. By this approach, a complex system may operate with multiple sectionalized zones, which is one feature of a flexible MG [3].

As Fig. 1 shows, the control scheme is developed behind an inner current control loop, which further provides the VSC output voltage references used to generate the PWM signals. The adopted current controller is based on sinusoidal signal integrators (SSI) [28], also known as second-order generalized integrators [9], implemented in the natural stationary reference frame. Fig. 2 shows the current controller block diagram, where, besides SSI_1 that acts on the fundamental current component, multiple SSI regulators accomplish the harmonic compensation for the odd harmonic current components (3,5,7,...). The transfer function of the P-SSI current controller is provided in (1). The voltage controller in *I-mode* has a similar structure, as will be described in Section 2.3.

In *MG-mode*, two outer frequency and voltage controllers provide the active (P_G^*) and reactive (Q_G^*) power references, which further are used to generate the grid current reference i_G^* as in (2). The orthogonal grid voltage components $v_{G\alpha}$ and $v_{G\beta}$ needed in (2) are generated by means of a SSI filter tuned at the grid frequency, as shown in Fig. 3 [28]. The SSI filter transfer function is expressed by (3) and the two orthogonal voltages results as in (4). Fig. 3 illustrates the filter frequency response (Bode diagram) for $k_F = 130$ and $f_G = 50$ Hz, values for which the cut-off frequencies of the direct ($v_{G\alpha}$) and orthogonal ($v_{G\beta}$) voltages are 75 Hz and 62 Hz respectively.

$$G_{RI}(s) = k_{pI} + \frac{2k_{iI}s}{s^2 + (2\pi f_G)^2} + \sum_{h=3,5,7,\ldots} \frac{2k_{hI}s}{s^2 + (2\pi h f_G)^2} \tag{1}$$

with k_{pI} is the proportional gain; k_{iI} and k_{hI} integral gains for the fundamental and harmonic components.

$$i_G^* = \frac{P_G^* v_{G\alpha} + Q_G^* v_{G\beta}}{v_{G\alpha}^2 + v_{G\beta}^2} \tag{2}$$

$$G_{F-\text{SSI}}(s) = \frac{2k_F s}{s^2 + 2k_F s + (2\pi f_G)^2} \tag{3}$$

$$\begin{aligned} v_{G\alpha} &= G_{F-\text{SSI}}(s) \cdot v_G \\ v_{G\beta} &= G_{F-\text{SSI}}(s) \cdot \tfrac{2\pi f_G}{s} \cdot v_G \end{aligned} \tag{4}$$

In *MG-mode*, a conventional phase-locked-loop (PLL), presented in Fig. 4, provides the synchronization signals for the inverter control system. The PCC voltage phase (φ_{oG}) is tracked by means of a closed loop with a PI controller (PI_G) acting upon canceling the phase deviation between the real and estimated voltage phases. The PLL provides as additional signals, the RMS voltage (V_G) and