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State-of-charge-based droop control for stand-alone AC supply systems with distributed energy storage

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ABSTRACT

The droop method is an advantageous technique for stand-alone AC supply systems, allowing for power sharing among various inverters with no need for communication cables. However, in stand-alone systems with multiple distributed energy storage units, the conventional droop methods are unable to control the storage unit state-of-charge (SOC) in order to change simultaneously. Existing techniques endeavor to solve this problem by changing the slope of the *P–f* curve however this solution compromises the power response performance. As an alternative, this paper proposes a new SOC-based droop control, whereby the *P–f* curve is shifted either upwards or downwards according to the battery SOC. The proposed technique makes it possible to select the time constant for the battery SOC convergence and, at the same time, to optimize the power response performance. The paper also shows how the SOC changes when the ratios between the battery capacity and the inverter rated power are different and how the proposed technique can limit the SOC imbalance. Simulation and experimental results corroborate the theoretical analysis.

1. Introduction

For remote locations with difficult access to the power grid, stand-alone systems are more cost effective. In fact, these systems are widely established in mountainous regions and remote villages where they are used for a wide range of applications such as rural electrification, auxiliary power units for emergency services or military applications, and manufacturing facilities using sensitive electronics [1–3].

Distributed generation may be an attractive solution for stand-alone supply systems [4–7]. A frequently adopted and sustainable solution consists in installing photovoltaic (PV) and wind generation with battery energy storage [8–10]. Three configurations are currently in major use for this system: dc microgrids [11], hybrid ac/dc microgrids [12,13], and ac microgrids [14]. Given that most loads are prepared for ac voltage, the ac configuration is probably the most frequently used at the moment. This configuration is shown in Fig. 1, where the wind turbines are connected to the ac grid through ac/ac converters while the batteries and PV generators are connected using dc/ac inverters [15,16].

There are several techniques to implement the global control strategy in this system [17]. On one hand, there is a central control or master–slave approach where a supervisor sets in real time the operation point of each element [18]. The drawback of this approach is that requires a fast communication system between master and microgrid elements [19,20]. Distributed control is another possible technique. In this case, the battery inverters operate as Voltage Source Inverters (VSI) using droop methods. This makes the inverters independent and avoids the need for communication between them, thereby reducing costs and improving reliability [21–24]. For their part, the photovoltaic/wind converters harvest the solar/wind energy and operate as Current Source Inverters (CSI) injecting power to the grid [25,26]. These converters also operate locally since they perform Maximum Power Point Tracking (MPPT) during normal operation and can reduce their power depending on the grid frequency [25,27,28].

Thanks to the droop method, all battery inverters contribute to the grid generation. The real power control is based on the real power–frequency *P–f* curve (or dc voltage–dc current V_{dc}–I_{dc} curve in the case of dc microgrids). The *P–f* curve slope is normally set according to the inverter rated power, in order to share the real powers in proportion to their ratings [29,30]. Although the ratios between the battery capacity and the inverter rated power (C/S_{rat}) should ideally be the same for all battery inverters to ensure that all battery state-of-charges (SOC) change simultaneously, in real

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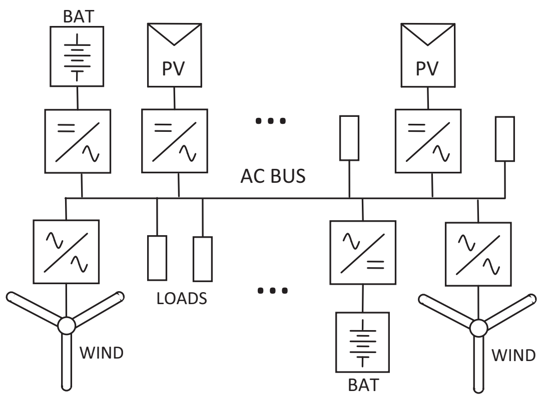

Fig. 1. Stand-alone hybrid system with distributed energy storage and generation.

applications this is not so. The initial C/S_{rat} ratio will never be exactly the same for all battery inverters due to manufacturing variation or inadequate system sizing. Moreover, the battery aging will lead to a capacity reduction which will be more pronounced in some battery banks than in others. The initial SOC can also vary considerably from one battery to another. These situations cause the batteries to operate with different SOCs leading to less than optimal operation.

In [31], a fuzzy control is used for the storage energy control of electric-double-layer capacitors in dc microgrids. The fuzzy control changes the dc voltage reference to balance the stored energy. Similarly, in [32], the control also modifies the dc voltage reference, in this case to balance the battery SOCs. However, these methods are not based on local measurements since information about the energy stored in the other units is required.

In order to maintain the same SOC for all energy storage units without the use of communication circuits, the P–f (V_{dc}–I_{dc}) curve must be changed as a function of the SOC of each storage unit. Some authors have proposed changing the slope of this curve [26,33–38]. In [33], it can be observed how the SOC of two batteries in an ac microgrid tends to reach the same value after a different initial SOC. However, the authors fail to analyze what occurs after that initial transient, when each battery inverter has a different C/S_{rat} ratio. Furthermore, changing the P–f curve slope has an effect on the stability and dynamic performance of the power response [39,40]. This fact prevents the optimization of the power response and results in operating point-dependent damping and dynamics.

This paper proposes a new SOC-based droop control for stand-alone systems with distributed energy storage whereby the P–f curve is shifted either upwards or downwards in line with the battery SOC. As a result, the battery with a higher SOC will either deliver more power or absorb less power until all the batteries reach the same SOC, with no need for communication circuits. Thanks to this curve shifting, the time constant for the battery SOC convergence can be set independently of the power response dynamics, unlike the slope changing method. The P–f curve slope is kept constant, making it possible to optimize the power response performance and to achieve constant damping and dynamics. Furthermore, this method limits the SOC imbalance as required for batteries with different C/S_{rat} ratios, without affecting the system stability.

The paper is organized as follows. Section 2 presents the modeling of the conventional droop method. Section 3 analyzes the SOC-based droop method which modifies the P–f curve slope as a function of the SOC, hereinafter to be called the slope changing method. The power and SOC responses are first studied and then simulation results for a real power profile are presented. Section 4 analyzes the proposed SOC-based droop control, to be called the curve shifting method. Following a similar study to the slope changing method, both techniques are compared. Then, in Section 5, the experimental results for the proposed method are shown. Finally, in Section 6, some conclusions are drawn.

2. Conventional droop method modeling

Fig. 2 represents the stand-alone system shown in Fig. 1, where the renewable-energy generators and loads are modeled together as a current source i_T which demands real power P_T and reactive power Q_T. The battery inverters are connected in parallel through the output impedance, formed by the filter inductance and the line impedance. Since the line impedance is much smaller than the filter impedance, the output impedance can be approximated as the filter inductance, L_i. The inverter rated powers $S_{rat,i}$, battery capacities C_i, and instantaneous value of voltages and currents e_i and i_i, are also defined in the figure.

Each battery inverter will provide the following real power P and reactive power Q to the ac bus [41]:

$$P = \frac{VE}{X} \cdot \sin\delta \tag{1}$$

$$Q = \frac{V}{X}(E \cdot \cos\delta - V) \tag{2}$$

where E is the rms amplitude of the inverter output voltage, δ is the power angle, V is the rms amplitude of the ac bus voltage and X is the output reactance.

In practical applications, power angle δ is small. Thus, (1) and (2) can be rewritten as

$$P = \frac{VE}{X} \cdot \delta \tag{3}$$

$$Q = \frac{V}{X}(E - V) \tag{4}$$

Consequently, the real power of each inverter can be controlled by power angle δ and the reactive power can be regulated by means of output voltage E, which justifies the success of the conventional droop method. These equations, where the relationships P–δ and Q–V are decoupled, are valid when the output impedance is mainly inductive, whereas in low voltage grids the line impedance is mainly resistive. However, in this paper, an rms voltage regulation is carried out instead of an instantaneous voltage regulation [4]. In doing so, the filter inductance also becomes part of the output impedance for the droop method. Given the high value of this filter impedance (the per-unit value is generally about 10%), it is possible to consider the output impedance as inductive, regardless of the line impedance.

The line impedance also causes inaccuracy of reactive power control in the conventional droop method. In contrast, the real power control is not affected by line impedance since the steady-state frequency is the same in all points of the grid [42,43]. As this

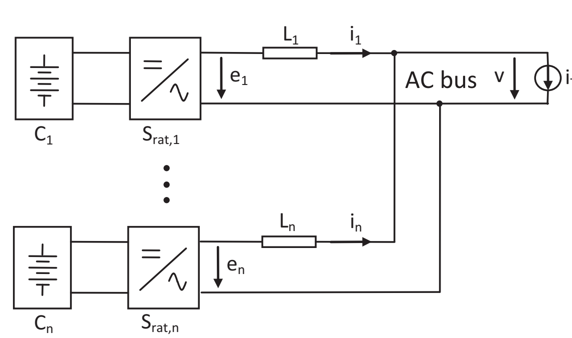

Fig. 2. Battery inverters connected in parallel.