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Intelligent Distributed Generation and Storage Units for DC Microgrids—A New Concept on Cooperative Control Without Communications Beyond Droop Control

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***Abstract*—Low voltage dc microgrids have been widely used for supplying critical loads, such as data centers and remote communication stations. Consequently, it is important to ensure redundancy and enough energy capacity in order to support possible increments in load consumption. This is achieved by means of expansion of the energy storage system by adding extra distributed energy storage units. However, using distributed energy storage units adds more challenges in microgrids control, since stored energy should be balanced in order to avoid deep discharge or over-charge in one of the energy storage units. Typically, voltage droop loops are used for interconnecting several different units in parallel to a microgrid. This paper proposes a new decentralized strategy based on fuzzy logic that ensures stored energy balance for a low voltage dc microgrid with distributed battery energy storage systems by modifying the virtual resistances of the droop controllers in accordance with the state of charge of each energy storage unit. Additionally, the virtual resistance is adjusted in order to reduce the voltage deviation at the common dc bus. The units are self-controlled by using local variables only, hence, the microgrid can operate without relying on communication systems. Hardware in the loop results show the feasibility of the proposed method.**

***Index Terms*—Cooperative control, dc microgrids, droop control, fuzzy logic.**

I. Introduction

With the increasing use of renewable energy sources (RES), microgrids appear as a solution for integrating distributed energy resources (DER), loads and energy storage systems (ESS) as controllable entities, which may operate in grid-connected or even islanded mode, either in ac or dc configuration [1]. In fact, during recent years, the interest in studying dc microgrids has increased considerably, since dc microgrids do not have issues associated with synchronization, reactive power flows, harmonic currents, and dc/ac conversion losses, which are inherent in ac microgrids [2].

On the other hand, the intermittent nature of RES, added together with unpredictable load fluctuations, may cause instantaneous power unbalances that affect the operation of the microgrid. Hence, ESS are required to guarantee reliability, security and power stability. In this sense, it is desirable to have two or more distributed ESS for providing redundancy and more energy support [2], [3].

Also, it is very important to coordinate RES and ESS units in order to avoid that the power generated by RES may collapse the system when ESS are full and there is a power unbalance in the microgrid. In this sense, the RES may change their control strategy from maximum power point tracking (MPPT) to a control strategy for regulating the voltage on the dc common bus. Moreover, the most effective way of charging a battery is by means of a two stage procedure which involves two different control loops [4]. Given the above points, the operation of each RES and ESS in the microgrid should be accompanied by a decision-maker strategy in order to switch between controllers.

Apart from that, when a number of ESS exist in a microgrid, a coordination is required to ensure stored energy balance among the units, in order to avoid deep-discharge in one of the energy storage unit and over-charge in the others. Therefore, during the process of charging, it is desirable to prioritize the charge of the unit with the smallest state of charge (SoC), and similarly, during the process of discharging, the unit with the highest SoC should provide more power to the microgrid than the others in order to ensure stored energy balance [5], [6]. In other words, conventional control loops for current sharing at each energy storage unit, may be complemented with stored energy balance control systems.

Commonly, voltage droop control method has been used when, two or more units are connected in parallel to the dc bus through a dc/dc converter, in order to ensure a current sharing feature among the units [3], [7], [8]. Droop method or, in his dc version, virtual impedance ensures equal or proportional fixed current sharing. However, this is not the best solution when the power electronics converters are connected to different prime movers, for instance: photovoltaic systems or wind-turbines,

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and energy storage systems, and particularly distributed battery sets with different SoC.

In [3] a good stored energy balance has been achieved, by adaptively adjusting the virtual resistance (VR) in droop controllers. However, a centralized supervisory control is used, and there is a single point of failure in the system. Additionally, the voltage regulation is not strongly guaranteed. Other authors have proposed algorithms for adjusting the battery current based on a constant coefficient, whenever differences are detected in the SoC among batteries [9]. However, centralized controllers are required and the use of a constant coefficient may cause slow approximation or oscillations around the equilibrium point. Besides, in [9] voltage deviation at the common dc bus is not taken into account. In [10] a strategy for adjusting the droop controller based on the SoC in a distributed ESS has been proposed. However, the strategy proposed in [10] only takes into account the case when the batteries are supplying power to the load. Additionally, in [2] a gain-scheduling control in aggregation with a centralized fuzzy controller has been proposed in order to achieve good voltage regulation and power sharing, as well as stored energy balance in a distributed ESS. The solution proposed in [2] uses the centralized fuzzy controller in order to modify the voltage reference for balancing the stored energy.

In this paper, a decentralized and modular strategy based on fuzzy logic is proposed for achieving good stored energy balance among several ESS. In particular, one of the main advantages of fuzzy logic controllers is that they can manage different control objectives simultaneously [11]. Therefore, the proposed fuzzy system adjusts the VR of the droop controllers in accordance with the SoC at each ESS. Meanwhile, the fuzzy inference system is able to adjusts the VR in accordance to the common dc bus voltage, in order to reduce the voltage deviation. Fuzzy logic control has been lately proposed for energy management of ESS in microgrids thanks to its simplicity in summarizing complex algorithms [5]. However, in [5] just a single battery is analyzed.

This paper is organized as follows. In Section II the configuration and operation of the microgrid under isolated operation mode is described. Section III shows the design and operations of the proposed fuzzy controllers. Section IV presents the results under different operation modes. The proposed method is tested in a low voltage microgrid under islanded operation. Hardware in the loop by using a dSPACE 1006 and the controldesk shows the effectiveness of the proposed method and its advantages in comparison to conventional methods. Finally, Section V presents conclusions and perspectives for future works.

II. Configuration and Operation of the DC Microgrid

The dc microgrid under study is composed by two RES [PV panels, and wind turbine generator (WTG)], dc loads, and two banks of valve regulated lead-acid (VRLA) batteries, as shown in Fig. 1. The microgrid is basically formed around $48V_{dc}$ common bus, these kinds of low voltage microgrids have been widely used for residential applications and for

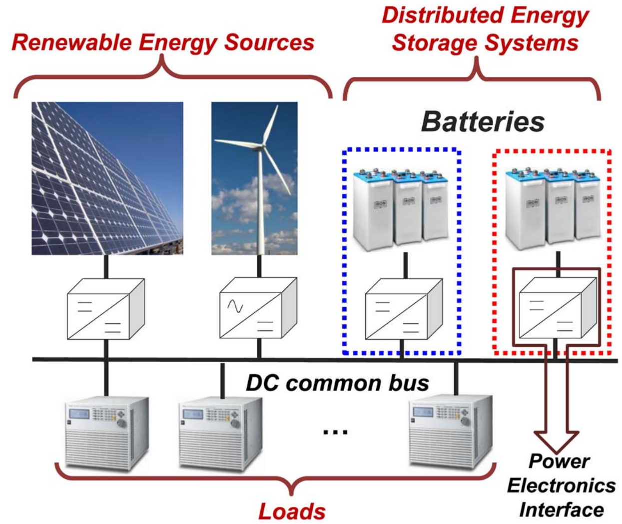

Fig. 1. DC microgrid configuration.

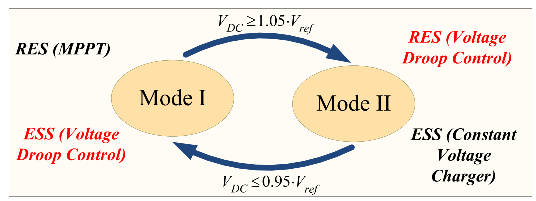

Fig. 2. Transition diagram between operation modes.

supplying energy to computer equipment in communication networks [12]–[14]. In particular, the microgrid will be analyzed under islanded operation mode since this mode is crucial for remote applications, and the interaction of batteries with RES plays an important role [15].

When the microgrid operates in islanded mode it is easy to identify two different operation modes based on the kind of distributed energy resource responsible of the dc common bus regulation (see Fig. 2). To be more precise, the dc common bus voltage can be regulated by distributed ESS (mode *I*) or by distributed RES (mode *II*).

Apart from that, the control strategy that governs each energy storage unit, changes in accordance to the SoC of the battery and the balance between the power generated by the RES and the power consumption. In the case of the RES, the control strategy changes in accordance to the voltage in the common dc bus in the same way that changes the operation mode of the microgrid [3], [16]. As a consequence, each DER, including batteries and RES, requires at least two inner control loops in order to operate under the two different operation modes and control states [3]. Fig. 3 shows a complete diagram of the microgrid with conventional inner control loops (fixed virtual resistance at the voltage droop controllers). In Fig. 3 it is also possible to see the block diagrams for the inner control loops used in the batteries converters (voltage droop control and constant voltage charger). Likewise, Fig. 3 shows the block diagrams for the inner control loops used at each RES converter (MPPT and voltage droop control). Fig. 4 shows the equivalent circuit under each operation mode, which will be explained in detail in this section.