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A control strategy for microgrids: Seamless transfer based on a leading inverter with supercapacitor energy storage system

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HIGHLIGHTS

- A microgrid coordinated by a leading inverter with supercapacitor energy storage.
- Minor control changes are required for microgrid transfer to grid.
- Precise control of grid power, with minimum microgrid communication requirements.
- No communication data changes with the microgrid status and number of inverters.
- Implementing the requirements for compliance with grid codes is straightforward.

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ABSTRACT

In the current paper, an improved control strategy designed for synchronizing and transferring autonomous microgrids (MGs) to the grid is presented. The proposed approach is based on an MG leading inverter (MGLI) supplied by a supercapacitor energy storage system, which takes over the MG only during a transitory load and distributes it to the available MG supporting inverters (MGSIs). This paper presents the control systems for both the proposed MGLI and the associated MGSIs, the focus being on the specific issues related to MG synchronization and grid transfer. By means of the proposed solution, the operation of the MG and its transition between autonomous and grid-connected modes require merely the adaptation of the MGLI control system, while the MGSIs operation remain unchanged during all MG states. The comprehensive experimental results, which were carried out on a laboratory-scale MG, have shown that the system is kept stable and with minimum disturbance to the local MG voltage and frequency during the analysed events, namely the scheduled MG transfer to the grid, power-flow control during grid-connection operation, and disconnection from the grid, respectively.

1. Introduction

The European energy policy requirement of increasing the share of renewable energy sources (RES) in terms of end consumption [1] has led, in the course of the last decade, to a massive research and development in related fields. Pursuing a more sustainable integration of RES into the distribution networks, while preserving – or even improving – a system's reliability, power quality, and security of supply [2], changed the conventional concept of *the grid* in order to accommodate new components of the future Smart Grid in the form of microgrids (MGs). Although the MG is considered a building block in smart-grid evolution, there are currently many technological gaps to be filled, although several definitions can be found in the literature for *microgrid* [3]. According to [4], an MG involves an aggregation of distributed energy resources, energy storage systems (ESSs) and flexible loads within a low-voltage distribution system that can operate either islanded or interconnected to the grid.

The change of the grid-related state represents one of the most important features of an MG, but maintaining the system's stability during and after the self-transfer between the two operating modes (i.e. grid-connected and islanded) poses considerable technical challenges. Moreover, ensuring a seamless transition becomes a more difficult task as the number of involved sources increases [5], while traditional synchronization methods are no longer suitable in such cases [6]. Among the three categories of synchronization methods identified in [7] (i.e. active, passive, open-transition), the active synchronization control is of particular interest in this paper, since it provides higher operational flexibility and performance.

Many existing solutions just consider the seamless transfer and synchronization of individual inverters serving a local load [8,9], which represents a simplistic approach [10], and difficult to extrapolate for multi-source MGs [6]. In this case, adopting the usual solution based on

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a dual-mode control method, where the inverter is switched between voltage- and current control to transfer the system from island to grid-connected mode [11–14], may increase the complexity and decrease the reliability of the system [9], as well as causing additional unnecessary transients [8].

Two different MG control approaches are distinguished [15], namely centralized and decentralized. While the fully centralized control relies on a central controller to coordinate the MG units through high-speed communication infrastructures (renowned for reliability issues), the responsibility in a fully decentralized approach for ensuring equal power sharing and voltage-frequency control is distributed to each MG unit, with communication either being unnecessary or having less stringent requirements [16]. Within the latter category, besides agent-based control methods, droop control is the most common method, though this does not guarantee constant voltage and frequency for MGs [17] and it can be used only in islanded operation mode. A centralized control solution widely used in the past, especially for paralleling inverter units in UPS systems [4], is the master-slave method. Although simple control algorithms are required, while it achieves excellent power-sharing performance [18], the expansion of master-slave control to complex microgrids is limited by the need for high-bandwidth communication networks [19]. As reported in [19,20], maintaining system stability in such cases involves time delays of the communication bus in the range of milliseconds, which is difficult to achieve in large-scale MGs. As opposed to master-slave control, the solution proposed in this paper allows much higher communication delays (i.e. hundreds of milliseconds, as proven in Section 3), which also enables the use of cheaper and more reliable low-speed communication networks.

A major challenge arising from an MG's operational autonomy relates to the dramatic reduction of a system's inertia once the level of power-electronics-based generation increases, which leads to stability issues, mainly in the frequency-control process [21]. To address the issue, a popular solution today consists of enhancing the inverters with virtual inertia, which aims to mimic the behaviour of conventional synchronous generators in transitory regimes. Various techniques are proposed in relevant literature for controlling the inverters following the concepts of inertia emulation and virtual synchronous generator (VSG) [22–24]. For this purpose, the proposed system uses the VSG approach to control the MG during autonomous operation, but since this case has been presented in detail in [25], discussion on the matter will be limited in the current paper.

The grid-connected operation implies the MG behaving as a current source at the point of common coupling (PCC) with the grid, delivering or absorbing power to or from the grid. In order to maintain the synchronization of the MG sources with the grid voltage, two main solutions are available, with one based on conventional phase-locked-loop (PLL) technology and the other offering self-synchronization by means of control methods developed around the concept of a synchronous generator [26,27]. Regardless of the approach used to control the power injected to the grid, one major challenge consists of maintaining optimal power sharing among the MG units, it not being possible to address the issue by similar control mechanisms used in autonomous operation mode (e.g. droop control).

Inspired by conventional power systems, a three-level structure is typically adopted to organize the MG's voltage control and frequency control processes, namely primary, secondary and tertiary [28,29]. From the perspective of the system's stability and power quality, the first two levels are of interest, while the latter may be used to optimize the power flow in the MG in line with an economic strategy. Depending on the MG operating regime (i.e. autonomous or grid-connected), the primary and secondary controls act slightly differently. Whereas in autonomous mode the successive deployment of the two processes ensures the control of MG voltage and frequency [30], during grid-connection operation their role is no longer the same, because the grid determines the MG frequency and, according to the line's impedance, only limited control can be achieved over the voltage. Moreover, due to the requirement to control the amount of power transferred through the PCC, as previously mentioned, the MG control strategy must be automatically modified immediately after the MG is transferred to the grid. For this purpose, a common solution involves adapting the same control mechanism that in islanded mode provided MG voltage- and frequency-control, to perform power-flow control in grid-connected mode. In order to achieve equal power sharing, the MG units supporting the power exchange with the grid are coordinated by means of a communication infrastructure, which can be implemented either in a centralized manner [6,10,29,31], or using a distributed approach where the information is passed by means of neighbour agents [5]. The bandwidth represents one important limiting factor when designing the communication infrastructure, with a trade-off between the amounts of transferred data and transitory response usually being required [10]. Most solutions use low-bandwidth communication networks to achieve MG secondary voltage- and frequency-control when operating autonomously, and power-flow control through the PCC in grid-connected mode. The data packet is typically sized for two signals (i.e. voltage and frequency) [31], but there are methods requiring additional signals for controlling the MG in the two states [6,29,32,33], both of which increase the complexity of the systems and reduce control reliability. However, achieving precise and fast control of grid power in the case of distributed control techniques becomes more difficult, since each inverter must receive from the MGCC, through the communication network, the power reference calculated according to the MG power production, to local consumption, and to the scheduled grid power reference [16]. As detailed in the following sections, the proposed solution solves this problem by placing a leading inverter in the PCC, which provides a fast control of grid power and ensures power sharing among MG units by using a low-speed communication network.

The major contributions of the proposed control solution can be summarised as follows:

- The control solution is designed to ensure fast control during MG switching and operation to grid, while keeping the required control and communication to a minimum.
- A leading inverter coordinates the MG transition and operation to grid, while the other MG units do not change their operating status.
- The transmitted data package from the leading inverter to the other supporting inverters remains unchanged regardless of the MG operating state, while its complexity does not vary with the number of inverters. Plug-and-play operation is thus easily achieved.
- The proposed control method facilitates compliance with the grid codes.

After the Introduction, the paper is organized as follows: Section 2 presents the MG targeted configuration and the proposed control, and a stability analysis of the studied system is described in Section 3, while Section 4 provides experimental validations using a complex laboratory MG, and the paper's main conclusions are summarized in Section 5.

2. MG configuration and control

The targeted MG structure, presented in Fig. 1, includes resources such as distributed generation (DG) units and energy storage systems (ESSs) of differing capacities (i.e. short- and long-term). An MG-leading inverter (MGLI) based on a supercapacitor ESS (SC-ESS) represents the primary control unit and has two main purposes within the MG, namely to create the voltage reference during autonomous operation and to control the power transfer to the grid while in grid-connected mode. While the autonomous operation mode of the proposed MG was introduced in [25], this paper goes further and shows how the MGLI can be enhanced to also accomplish the seamless transfer of the MG between the two states (i.e. island and grid-connected). The MG units are interconnected through a low-bandwidth communication line, which in