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A control strategy for enhancing the Fault Ride-Through capability of a microgrid during balanced and unbalanced grid voltage sags

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ABSTRACT

In order to widely integrate high power microgrids within the distribution networks, they should possess Fault Ride-Through (FRT) capabilities, as well as provide ancillary services during abnormal grid operation. This paper proposes a new control strategy for improving the ability of a microgrid to ride through balanced and unbalanced grid voltage sags. The microgrid consists of several inverter-interfaced Distributed Energy Resources (DERs), powered by Wind Turbine Generators (WTGs), each combined with a Supercapacitor Energy Storage System (SCESS). During balanced and unbalanced grid voltage sags, the proposed control strategy maintains the microgrid grid-connected, while provides the local loads with a high quality voltage profile. The developed control method is complemented by properly sized controlled series inductances, placed at the point of common coupling (PCC) with the main grid. Under fault conditions, the DERs operate collectively in order to support the voltage within the microgrid, by injecting additional reactive power, without the necessity of any physical communication among them. During unbalanced grid voltage conditions, the DERs are controlled to compensate the unwanted negative and zero sequence voltage components. Thus, the microgrid loads are supplied with a set of balanced three-phase voltages. The proposed control strategy is verified by detailed simulation results.

1. Introduction

The increasing penetration of renewable energy resources in the distribution networks, has contributed to an upcoming decentralized approach of the power grid, where clusters of Distributed Energy Resources (DERs), loads and Energy Storage Systems (ESSs) form entities, called microgrids. The microgrids should be able to operate either connected with the main electrical grid or isolated in island mode, in case of grid unavailability [1–3]. In both grid-connected and islanded operation, the voltage within the microgrid should always comply with the limits imposed by the EN 50160 Standard [4].

The current technical literature in the framework of microgrids addresses several issues, such as the detection of the grid presence [5,6], the synchronization and reconnection to the main grid [7–10] and the control of the DERs for optimal operation and energy management in microgrids [11–15]. During islanded operation the DERs share the power generation in order to fulfill the load demand. The active and reactive power sharing of the load can be performed either by using physical communication among the DERs, or "wirelessly" by using local voltage and frequency measurements as communication parameters (Droop-based methods). The high R/X ratios encountered in low voltage distribution lines require the introduction of a virtual impedance, to assure the proper sharing of the active and reactive power among the DERs and the elimination of circulating currents [16,17]. Moreover, the coordination of a microgrid with an ESS is considered necessary for several reasons [18]. The most important include the reinforcement of the dynamic behavior [19], the contribution to the seamless transition from grid-connected to island mode [20] and the improvement of the operation during faults or transient conditions [21,22]. Finally, several protection techniques and fault clearing methods for islanded microgrids have been proposed in the available literature [23,24].

In case of faults or voltage disturbances at the host grid, the up to date technical studies imply the immediate transition from grid-connected to autonomous operation mode [25]. Microgrids are neither required to provide ancillary services, nor possess FRT capabilities.

However, with the increasing power capacity of microgrids, they are possible to supply a significant amount of power to the electric power system, when operating in grid connected mode [26,27]. Disconnecting such a microgrid during grid disturbances,

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might lead to power network instabilities [28]. Thus, new grid operating codes referring to the requirements of grid-connected microgrids need to be developed. In [29], some considerations on grid code requirements for the interconnection and operation of microgrids have been described. Among the proposed requirements, the abovementioned study proposes that a microgrid should possess FRT capabilities and provide ancillary services, during grid faults. According to the proposed requirements, a grid-connected microgrid should ride through balanced and unbalanced voltage sags, defined by an FRT voltage profile. This voltage profile is similar to those described in the FRT requirements for wind parks. Disconnection and transition to island mode of operation is allowed only in case of persistent grid faults.

In order to meet the proposed FRT requirements, dedicated topologies and control schemes for the individual DERs need to be developed. A power quality compensator for microgrids is presented in [30]. The proposed compensator is formed by two power converters; one connected in series and a shunt one, in order to compensate balanced and unbalanced grid voltage sags. The compensator provides a set of balanced three-phase voltages at sensitive loads, connected between the two converters. In [31], by using a back-to-back power converter system, the microgrid is isolated from the main grid during frequency or voltage disturbances. In [32], the use of an additional power converter, connected in parallel with the main converter, is proposed in order to provide extra reactive power support, during severe grid voltage sags. In all previous cases, additional converters are employed, in order to reinforce the FRT capability of a microgrid. However, the use of extra power converters increases the total cost, the losses and the complexity of the control structures.

This paper proposes a new control strategy for enhancing the FRT capability of a microgrid, powered by full-converter WTGs. The primary objective is to maintain the microgrid in grid-connected mode during balanced and unbalanced grid voltage sags, according to specific FRT requirements. Thus, after the fault clearance, it is able to immediately supply active and reactive power to the main grid, in order to prevent power system instabilities. Moreover, it maintains a high quality voltage profile within the microgrid, throughout the entire fault duration. During abnormal grid voltage conditions, each individual DER is controlled to provide additional voltage support, by injecting reactive power, without the necessity of using an additional power converter. In particular, under unbalanced grid voltage sags, the DERs are properly controlled to maintain a set of balanced voltages within the microgrid, by eliminating the unwanted negative and zero sequence voltage components. An important feature of the developed control strategy is the absence of physical communication among the DERs or other parts of the microgrid. It is integrated in each DER (as part of the primary control of the microgrid) and is based only local voltage and current measurements, presenting a fast response. The application of the proposed FRT control method is more valuable when the power generated by the DERs is larger than the aggregated power of the loads and the microgrid exports a relatively large amount of power to the main grid. The proposed control strategy is complemented by properly sized inductances inserted in series at the Point of Common Coupling (PCC) with the main grid. Through these inductances, decoupling between the main grid voltage and the microgrid voltage is enhanced and the latter can be effectively regulated through reactive power injection.

During severe voltage sags, due to the decreased grid voltage and the engagement of the inductances at the PCC, the ability to transfer active power to the main grid is limited. Taking this into account, a simple, yet effective control strategy for the active power supplied by the DERs, is proposed. The developed control strategy introduces an upper limit to the active power exchanged between the microgrid and the main grid, which is also used to accurately determine the size of the series inductances. To handle the abrupt active power imbalances created during the fault, a SCESS is integrated in each DER. In this way the FRT capability of the WTGs themselves is also achieved. Finally, analytical expressions for the optimal sizing of the series inductance and the supercapacitor are proposed in this paper.

In summary, the innovative parts of this study are: (1) the FRT of the microgrid is achieved through the inverters of the DERs, without requiring any additional converter, as is the case in previous research works. Instead, properly sized and controllable series inductances are proposed at the PCC with the main grid, (2) successful FRT is achieved both at the level of each individual DER and at level of the microgrid as a unity, through the cooperative action of all microgrid DERs, (3) acceptable voltage quality is ensured within the microgrid during balanced or unbalanced grid faults and (4) immediate injection of active and reactive power to the main grid after its recovery is achieved. It should be mentioned that this paper focuses on an FRT method of a microgrid, while operating connected to the main grid. The proposed FRT control philosophy can be easily superimposed to any method for controlling the microgrid in island or grid-connected mode, some of which have been referenced here, while many others can be found in the technical literature.

The rest of the paper is structured as follows: In Section 2, the examined microgrid topology is presented. In Section 3, the proposed power and control subsystems are presented in detail. Finally, in order to verify the effectiveness of the proposed control strategy, a detailed simulation model has been developed in PSIM software and the results are demonstrated in Section 4. Throughout the text, the innovative parts of this study are thoroughly analyzed, while already known control methods are properly referenced.

2. Microgrid topology

Fig. 1 shows a single-line layout of the low voltage four-wire microgrid and the main grid, studied in this paper. The microgrid is formed by two DERs, feeding several loads. An interconnection switch (S1) placed at the PCC, is used to control the transition from grid-connected to island mode and vice versa. Each DER utilizes a WTG as primary power source, driven by a synchronous generator with external excitation. The back-to-back power converter system is composed by the Machine Side Converter (MSC) and the Grid Side Converter (GSC), connected to each other through a DC-link. Each DER integrates a SCESS connected in parallel with the DC-link capacitor, having as main objective to maintain a constant DC voltage level, during fault conditions.

Key element of the developed FRT method is the use of properly sized series inductances at the PCC, as shown in Fig. 1. The inductances provide decoupling between the grid voltage and the microgrid voltage, with additional reduction of the currents required to compensate the voltage sag. During normal grid conditions, these inductances are bypassed by thyristors to prevent the increase of power losses and voltage drops.

In grid-connected mode, under normal operating conditions, switch S1 is closed. When a fault occurs in the main grid, it will reduce the voltage at the PCC below a threshold level, triggering the activation of the proposed FRT control method. The duration of this operating mode is determined by the adopted FRT curve [27]. This duration in combination with the nominal power of the DERs, determines the size of the SCESSs. In case the fault insists and the grid voltage does not recover within the specific time frame, switch S1 opens and the microgrid switches to islanded mode of operation. In this mode, one of the control methods described in the literature [11–15] could be applied for controlling the DERs.

The proposed FRT control method is independent of the size of the microgrid, provided that the appropriate series inductances are inserted at the PCC and the DERs integrate properly controlled SCESSs.