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Phase unbalance mitigation by three-phase damping voltage-based droop controllers in microgrids

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ABSTRACT

Microgrids aggregate grid assets in geographically confined areas, allowing them to locally tackle grid issues and capture the value of their aggregated flexibility by bringing intelligence in the grid in a bottom-up approach. For the control of distributed generation units in single-phase islanded microgrids, the voltage-based droop (VBD) control strategy has already been developed. The VBD strategy can also be used in grid-connected microgrids, which makes a transition between both modes possible. Phase unbalance is a significant issue in three-phase microgrids and will become more pressing with increasing penetration of single-phase renewables. Therefore, the effect of several traditional control strategies for three-phase distributed generation units to phase unbalance is discussed. Subsequently, in this paper, a new control strategy is presented which extends the basic VBD control strategy so it can be used as a three-phase controller which at the same time mitigates unbalance in islanded and grid-connected microgrids, i.e., the three-phase damping VBD control. It is concluded that the presented three-phase damping VBD control method mitigates unbalance, allows the DG units to share the unbalanced currents, and is able to operate both in grid-connected and islanded systems.

1. Introduction

Recently, there has been a considerable increase in the amount of distributed generation (DG) units in the electric power system, a large part of which use renewable energy sources. Despite the numerous advantages these small-scale units offer, the current fit-and-forget approach of connecting them to the electrical network is not a sustainable option. The distribution system is increasingly being confronted with congestion and voltage problems, which limits the further penetration of DG. For further increasing the penetration of renewables, these units will need to be fully integrated into the power system. Therefore, a more coordinated approach for integrating DG in the distribution networks is required. Microgrids are designed to provide this coordination by aggregating and controlling generators, loads and storage elements [1]. They are likely to play a key role in the evolution towards the smart grid [2]. In this sense, the smart grid can emerge as a system of integrated smart microgrids [3].

Microgrids can operate both in grid-connected and islanded mode, where the normal operating mode is the grid-connected mode. For islanded low-voltage microgrids, new control methods have been developed, a survey of which is given in [4]. For (extended) islanded microgrids, the droop control concept is most promising to ensure a reliable system operation [5,6]. In a low-voltage microgrid, without significant inertia and with predominantly resistive lines, the P/V and Q/f droop concept is often applied [7]. The droop controller is used to adjust the active power P proportional to the deviation of the voltage V from the set-point. Also, the reactive power Q is adapted according to a deviation of the grid frequency f from the nominal value. The voltage-based droop (VBD) microgrid control of [8] for islanded microgrids is a variant of the P/V droop control that focuses on an optimal integration of renewables in the network and also incorporates a dc-bus controller.

In three-phase grid-connected systems, especially at the low-voltage level, unbalance is a major concern which will likely further increase with higher penetration of single-phase DG units [9]. International standards, such as EN-50160, pose limits for the Voltage Unbalance Factor (VUF). Compensation of unbalance is usually done by installing dedicated unbalance mitigation devices, such as active power filters injecting negative sequence voltages or currents [10]. The power quality of the system can also be improved by adding active power filtering functions in the control strategies of DG units [11].

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Like in grid-connected networks, care should be taken to unbalance in islanded microgrids. Only a low share of the three-phase controllers in islanded microgrids take into account unbalance although these small-scale microgrids are often largely unbalanced. Inverter-based three-phase DG units can provide unbalance suppression [13–16]. Compensation of the negative sequence current of unbalanced loads while focusing on minimal negative sequence currents in the lines is in the scope of [17]. The negative sequence current is shared among the DG units by adjusting the negative sequence output impedance. In [18,19], unbalance compensation is done by reducing the negative sequence voltage. In [20], a communication-based controller is added to the droop controller for improving the voltage quality of a critical load, i.e., compensation of the voltage unbalance and the harmonics. This compensation effort is shared among the DG units according to their rated powers.

In grid-connected networks, more attention has been given to phase unbalance. In [21], unbalance mitigation by DG units is achieved in a grid-connected feeder. The grid-following DG units inject a current which is dependent on the zero and negative sequence voltage. The method is further being extended in the European FP7 project INCREASE[1] for managing renewable energy sources in low voltage (LV) and medium voltage (MV) networks, by the provision of ancillary services including unbalance mitigation and voltage control. This controller is developed for grid connected networks, thus, with grid-following DG units. In this paper, the method of [21] is altered for being used by grid-forming DG units, which can supply an islanded microgrid. These grid-forming DG units are voltage-controlled, hence, inject a voltage which is dependent on the zero and negative sequence current as opposed to grid-following units which are current-controlled.

In this paper, an overview of different grid-following three-phase controllers together with their unbalance mitigation aspects are given. The analysis and equations of the different controllers are given in a consistent manner, making it easy to compare the controllers with respect to their unbalance mitigation capabilities. For grid-forming units, used to stabilise an islanded microgrid, unbalance mitigation is a rather new research topic. In literature, a single-phase damping VBD control is developed for stabilising a small balanced islanded microgrid, thus for grid-forming units. Also a three-phase damping control has been developed for grid-following units in unbalanced grid-connected networks. The three-phase damping control strategy is not directly applicable in the VBD controller as it deals with current-controlled DG units and the VBD controller is implemented in voltage-controlled units. This has a large impact on the design of the control loop and also on the choice and implication of the damping resistance R_u as discussed later. Also, unbalance mitigation in islanded microgrids focusses on better power distribution over the three phases of the DG units, on a better unbalance sharing between multiple DG units and either on voltage or current unbalance mitigation in the microgrid lines, dependent on what is more likely to congest the network. In grid-connected networks, unbalance mitigation focusses more on mitigating the unbalance provided by the utility grid, i.e., current unbalance mitigation. Here, by combining and altering the two strategies above, the three-phase damping VBD control for grid-forming units which can be used in both islanded and grid-connected networks is presented. For this means, likewise as for the grid-following controllers, the mathematical equations for the control are given in the same consistent manner.

In Section 2, unbalance is defined and in Section 3, the difference between grid-following and grid-forming units is clarified. In Section 4, a discussion of three-phase grid-following controllers for DG units is given, and the control schemes are transformed into the zero-positive-negative sequence symmetrical components. This allows to present the new control strategy in a coherent manner with previous controllers and discuss the influence of the different strategies on the unbalance of the system. Next, in Section 5, the three-phase damping VBD control is presented. For this means, a consistent discussion of three-phase grid-forming controllers is given, similar as for grid-following controllers. In Section 6, case studies on a simplified microgrid show the effect of this unbalance mitigation control loop. They also compare the system behavior for different values of the virtual damping resistance. In Section 7, a more realistic microgrid is analysed.

2. Voltage and current unbalance

Unbalance is a significant issue in low-voltage distribution feeders. It can be caused, e.g., by single-phase DG units or an asymmetrical impedance of the system. The main cause of unbalance however is the presence of asymmetrical loads. The unbalance can be quantified by means of the unbalance factor (e.g., voltage unbalance factor (VUF)).

In the following, the VUF will be analysed. The percentage voltage unbalance factor (% VUF) equals (EN 50160):

$$\%\mathrm{VUF} = \frac{|\underline{V}_2|}{|\underline{V}_1|}100. \qquad (1)$$

with $|\underline{V}_2|$ and $|\underline{V}_2|$ the amplitude of the negative sequence and positive sequence voltage components respectively. The current unbalance factor (CUF) is defined analogously.

International standards, such as EN-50160, pose limits for the VUF as unbalance may lead to adverse effects, such as additional losses in the electric power system [21]. Negative sequence components lead to negative rotating fields, which are hazardous for rotating machines because they produce a braking torque and additional heating which may lead to a faster thermal aging of the machine. Also, the capacity of the grid assets is reduced as the capacity of the transformers or network lines is based on the maximum current. The power quality of the system can be improved by adding active power filtering functions in the control strategies of DG units [11].

3. Grid-following and grid-forming units

The controllers discussed below can be classified in either grid-following or grid-forming. Most existing control strategies for DG units are grid-following. This means that the inverter of the DG unit determines a reference current dependent on the voltage measured at its terminals. Hence, these units are current-controlled. Because of the lack of a utility grid, at least one grid-forming unit should be present in an islanded microgrid in order to provide for the load changes in the system. A grid-forming controller "forms" the grid voltage, which implies a voltage control strategy and, thus, voltage-controlled DG units. Multiple grid-forming units can be used to share the power changes of the power system. Grid-following units, on the other hand, generally inject their available power not taking into account the load changes.

4. Grid-following controllers for grid-connected unbalanced microgrids

In this paragraph, several control strategies for three-phase grid-following, thus, current-controlled, DG units are analysed. The mathematical formulations of these controllers are included in a coherent manner in order to build up to the three-phase damping control strategy for grid-connected networks, which in turn builds

[1] http://www.project-increase.eu.