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Grid-forming VSC control in four-wire systems with unbalanced nonlinear loads

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ABSTRACT

A grid-forming voltage source converter (VSC) is responsible to hold voltage and frequency in autonomous operation of isolated systems. In the presence of unbalanced loads, a fourth leg is added to provide current path for neutral currents. In this paper, a novel control scheme for a four-leg VSC feeding unbalanced linear and nonlinear loads is proposed. The control is based on two control blocks. A main control commands the switching sequence to the three-phase VSC ensuring balanced three-phase voltage at the output; and an independent control to the fourth leg drives neutral currents that might appear. The proposed control is noninvasive in the sense that both control blocks are independently implemented, avoiding the use of complex modulation techniques such as 3D-SVPWM. Moreover, the main control is deployed in *dqo* reference frame, which guarantees zero steady-state error, fast transient response during system disturbances and mitigation of harmonics when nonlinear loads are present. Simulations and experimental results are presented to verify the performance of the proposed control strategy.

1. Introduction

Isolated microgrids can be defined as a cluster of distributed generation, energy storage devices and loads connected through a relatively small grid, usually at medium or low voltage levels. Storage devices and distributed generation, such as photovoltaic arrays, fuel cells and wind turbines are customarily connected to the microgrid through power electronic interfaces that include DC/AC converters [1,2]. These converters can be operated in two modes: grid-feeding mode and grid-forming mode. In grid-feeding mode, the converter supplies a given active and reactive power set points. Active power set point is subject to power availability from the primary resource (wind, sun, etc.), while reactive power is predefined either locally or through a central control [3]. In grid-forming mode, the converter seeks to control a predefined frequency and voltage, for which it is usually connected to a storage system. Nowadays, the preferred converter topology, at least for the grid-forming role, is the IGBT-based voltage source converter (VSC) type [4,5].

Fig. 1 shows a common configuration in real microgrid applications [6,7], where there is a VSC which is responsible to hold voltage and frequency during isolated operation, substituting the main grid functions. Distributed generation (DG) represents the set of grid-feeding generation (i.e. PV, combined heat and power, wind, biomass) that only injects active and reactive power without taking any responsibility in improving the power quality of the grid (unbalances, stability, harmonics, flickers, etc.). These DGs can be seen as intermittent balanced and unbalanced negative loads as they can include single-phase PV generation. The connected loads can include linear and nonlinear type as well as three-phase and single-phase loads (i.e. electric vehicles). In this context, significant unbalances and harmonics can be found and must be duly considered by the grid-forming VSC to hold frequency and voltage at the point of interconnection (POI), regardless the type of load connected, and the disturbances caused by DGs during an isolated operation.

The first approaches to overcome unbalances were based on reactive power compensators (variants of Steinmetz circuit). Those approaches minimize or, under certain circumstances, eliminate unbalances by means of additional costly equipment such as active filters [8,9], dynamic voltage restorers [10] or STATCOMs [11]. Other schemes deal with unbalances by trying to firmly hold a three-phase balanced voltage everywhere, regardless the type of loads. However, some of these methods are limited to unbalances with only negative-sequence component, neglecting the possible

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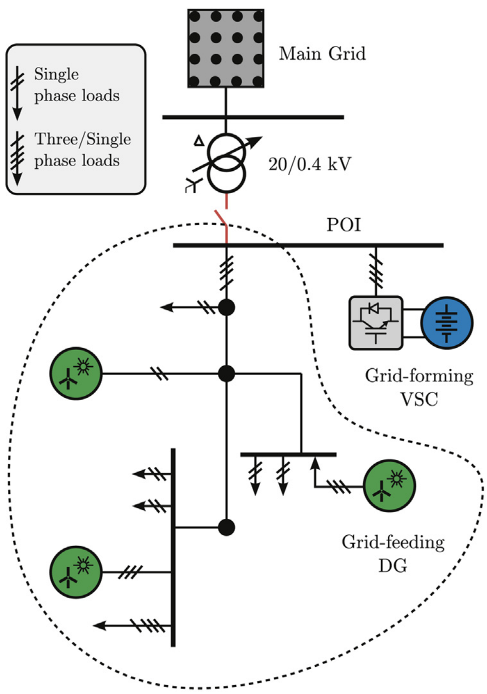

Fig. 1. Common microgrid topology with one grid-forming VSC responsible to hold frequency and voltage during isolated operation.

presence of a zero-sequence component circulating through a neutral phase [12–14].

In the most general unbalanced case, the neutral phase must be taken into account, for which two different topologies have been mainly proposed. The first is a split DC link, where the neutral phase is connected to the middle point of the DC link through an inductor filter. This alternative has proved to be unstable in case of large unbalances, unless huge capacitors are used to achieve equal voltage sharing between the split capacitors. Thus, this topology may be infeasible for real implementation on DC-AC voltage converters [15]. The second topology consists of adding a fourth leg to the conventional three-leg VSC, commonly known as four-leg VSC (4LVSC), so that the neutral current can be directly and independently driven through this additional leg. Available control techniques for this configuration can be classified in three groups, depending on the reference frame they use: *abc* frame, $\alpha\beta o$ frame, and *dqo* frame. A survey of advantages and disadvantages arising from the use of each reference frame is presented in [16]. Although there is no absolute consensus of what reference frame is the best for VSC control applications, the *dqo* reference frame excels in the following points: (1) simple control structure, (2) zero error in steady-state and fast transient responses, and (3) fixed switching frequency. Therefore, it is chosen as a reference frame to develop the main control in this paper.

All the techniques that exploit *dqo* reference frame use 3D-SVPWM (Three-dimensional Space Vector Pulse Width Modulation) as an interface between the control's output and the switching sequence for the 4LVSC [17–24]. Such a modulation method, however, exhibits high computational cost, and it is difficult to implement even when using a fast DSP control platform [25,26]. Moreover, those techniques also suffer from any of the following shortcomings: communication infrastructure required [19], control capability limited to only linear loads [17] or resistive loads [18], which can be extended to inductive and capacitive components with certain modifications [18,22], the coupling between voltage/current inner control loops is neglected [22].

The control proposed in this paper overcomes the aforementioned issues by using simple PWM (Pulse Width Modulation) for both the three-phase VSC (main control) and the fourth leg. Furthermore, taking advantage of the *dqo*-frame features described above, the main control loop is devoted to deal with both linear and nonlinear loads, whereas the independent control of the fourth leg uses a PR controller to drive neutral currents. In brief, the main features and contributions of this work can be summarized in the following points:

- Use of simple PWM for both the main control and the fourth leg control of the VSC.
- Truly independent control of the fourth leg, allowing a noninvasive implementation.
- Main control deployed in *dqo* reference frame, hence achieving zero steady-state error and fast transient response during system disturbances.
- Valid for all type of loads.
- No communication infrastructure required.

The rest of the paper is outlined as follows: Section 2 introduces the VSC control in *dqo* reference frame by using symmetrical decomposition. Section 3 presents a novel 4LVSC control consisting of a main control for the three-phase VSC and an independent control applied to the fourth leg. The results and discussion are presented in Section 4. Finally, the conclusions are drawn in Section 5.

2. VSC control based on symmetrical components

In an isolated microgrid, VSCs must set the reference for voltage and frequency. This makes it to work as a voltage source from the point of view of the rest of the microgrid. For this purpose, a capacitor bank is attached between the inductor and the POI where the voltage has to be controlled, as shown in Fig. 2(a).

A cascaded control strategy where one controller takes care of the capacitor voltage, while generating references to another controller in charge of the inductor currents, is the most common approach [5]. In Fig. 2(b), these controllers are highlighted as *voltage control loop* and *current control loop*, respectively. The controllers could be formulated in *dq* frame where the typical coupling between *d* and *q* components can be eliminated using the decoupling terms indicated in the same figure. Using proportional-integral controllers (PI), good transient performance and almost null steady-state error can be achieved.

The control of an isolated VSC in *dq* reference frame, based on symmetrical decomposition, is shown in Fig. 2(a) [27,28]. Three-phase voltage and current measurements are transformed into *dq* reference frame for each symmetrical component (positive, negative and homopolar). Then, a control based on two inner control loops is deployed for each of the symmetrical component control blocks. The aims of this control is to set a frequency and a three phase voltage at the POI. For that, $v_{pd}^{\star}$ reference value sets the output voltage while the others ($v_{pq}^{\star}$, $v_{nd}^{\star}$, $v_{nq}^{\star}$, $v_{hd}^{\star}$, $v_{hq}^{\star}$) are set to zero to ensure a balanced output voltage. The outputs of each symmetrical component control blocks are transformed to *abc* reference frame and then added together resulting in the duty signal that goes to the simple PWM which commands the switching sequence for the VSC. However, this control neither works with nonlinear loads nor includes the control of the fourth leg, and therefore cannot cope with unbalanced loads with neutral current component.