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Stability improvement of DC grids involving a large number of parallel solar power optimizers: An active damping approach

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HIGHLIGHTS

- The higher number of power optimizers the lower stability margin of the dc grids.
- Power increase of power optimizers decreases the stability margin of dc grids.
- The proposed active damping approach improves the stability margin of dc grids.
- A high number of power optimizers can be connected to dc grids with proposed method.

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ABSTRACT

This paper aims to address a new challenge associated with parallel operation of a large number of solar power optimizers in dc power grids. It is first shown that as the number of solar power optimizers increases the stability margin of the host dc power grid decreases. Then, to circumvent the stability problem, a novel active damping approach is presented which can improve the stability of dc grids dominated by a large number of solar power optimizers. In this approach, an inner feedback loop is added to the control system of a voltage source dc-dc converter regulating the dc grid voltage. The feedback transfer function is properly tuned to achieve the highest stability margin of dc grid. The presented approach works robustly for any number of solar power optimizers. Different simulation results are provided to confirm the effectiveness of the proposed approach.

1. Introduction

Solar systems are increasingly being connected to power grids to provide clean and renewable energy. However, with the advent of solar systems in power grids new technical challenges have arisen and consequently, need to be addressed. For instance, the authors in [1,2] deal with the maximum power point tracking (MPPT) issue for PV systems. In [3,4], new topologies of power converters are presented for integrating PV systems into the power grid. Another important issue is about configuration of PV panels. PV panels are conventionally configured as strings connected to the grid by a central inverter. In this configuration, any mismatch of PV modules would confine the strings output current to the minimum current of PV modules [5,6]. To overcome this problem, the micro-inverter technology can be used as a promising solution in the sense that it can provide a distributed maximum power point tracking (DMPPT) algorithm [7–9]. This new algorithm enables each module to independently track a maximum power point, ensuring the maximum energy harvesting of PV modules [5,10]. Moreover, this technology allows better data gathering and better protection of power sources [6].

The new technology of solar power optimizer is similar to the microinverter technology. In this new technology, the MPPT operation of each module is provided by a dc-dc converter [10,11]. The installation of power optimizers is easier and more cost-effective than the micro-inverters. Moreover, compared to micro-inverters, the power optimizers are characterized by wider module compatibility, greater scalability and more energy harvesting in shade. Regarding the benefits of the solar power optimizers, they are expected to become an integral part of the future photovoltaic systems. Hence, dc distribution systems are more likely to be replete with a large number of dc-dc low power converters which serve as solar power optimizers. It is noted that some researches have been carried out to tackle the associated challenges of solar power optimizers as [12,13].

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Recently, dynamic interactions of grid-connected converters with different passive and active components and their effects on the stability of power grids have been studied. In ac power grids, it is known that these interactions are the result of grid impedance, fast inner current loops and also the output high-order filter of the inverters. These interactions can lead to resonances among the grid and the inverters [14]. So far, for a single grid-connected inverter, passive [15,16] or active [17,18] damping methods have been presented to prevent these interactions. In [19], instead of reshaping the output admittances of grid-connected inverters, an active damper which can dynamically adjust the grid impedance has been proposed. The above-mentioned resonant behavior has been reported in solar power plants involving multiple inverters as well [20].

The stability of dc power grids has also been investigated considering different issues [21,22]. In [22], authors have studied the stability of a dc microgrid equipped with renewable resources and a voltage source converter having the role of an interlinking converter between ac and dc microgrids. The stability of dc microgrids in presence of Constant Power Loads (CPLs) has been studied in [23] and stabilization strategies are presented. However, the effects of parallel operation of grid-connected converters on the stability of power grids and challenges associated with the presence of a large number of low-power converters (as solar power optimizers) are only adequately addressed in ac systems. Hence, more research are required to investigate the technical challenges of implementing multiple solar power optimizers in dc systems.

Within the context alluded above, the propose of this paper is to study parallel operation of a large number of solar power optimizers and a dc-dc voltage source converter in order to evaluate their effects on the stability of dc power distribution grids. The paper presents an active damping approach to improve the stability of such grids.

This paper is organized as follows: Section 2 presents description and modeling of dc grid components. In Section 3, the model of the whole dc grid is obtained. Then, with the help of this model, the dc grid stability is evaluated considering the number of connected solar power optimizers and their operating point as well as the operation mode of voltage source dc-dc converter. In addition, an active damping approach to improve the dynamic response and stability of the dc grid is proposed. Simulation studies are provided in Section 4, while conclusion remarks are given in Section 5.

2. Description and modeling of dc grid components

The structure of the dc grid is depicted in Fig. 1(a), where it is connected to the ac grid by a Synchronous Converter (SC) and a Voltage Source Inverter (VSI). The VSI is in current-controlled mode, and it regulates the dc-link voltage. The solar power optimizers are assumed to be flyback dc-dc converters working in current-controlled mode and performing a sub-module MPPT algorithm. The SC which is shown in Fig. 1(b) is a bidirectional dc-dc converter regulating the dc grid voltage. If the load demand exceeds from the total output power of solar power optimizers, the power is imported to the dc grid from the main ac distribution grid. In this condition, the switches *Q2* and *D1* conduct, which is referred to as mode (1) of the SC. If the power generation of PV system exceeds the load demand, the SC exports the excessive power to the main ac grid. In this condition, the two other switches conduct, which is referred to as mode (2) of the SC.

2.1. Small signal modeling of the SC and PV converters

The topology of the SC and PV converters are depicted in Fig. 1 (b) and (c), respectively. For the PV converters, the circuit equations in *on* and *off* states are as:

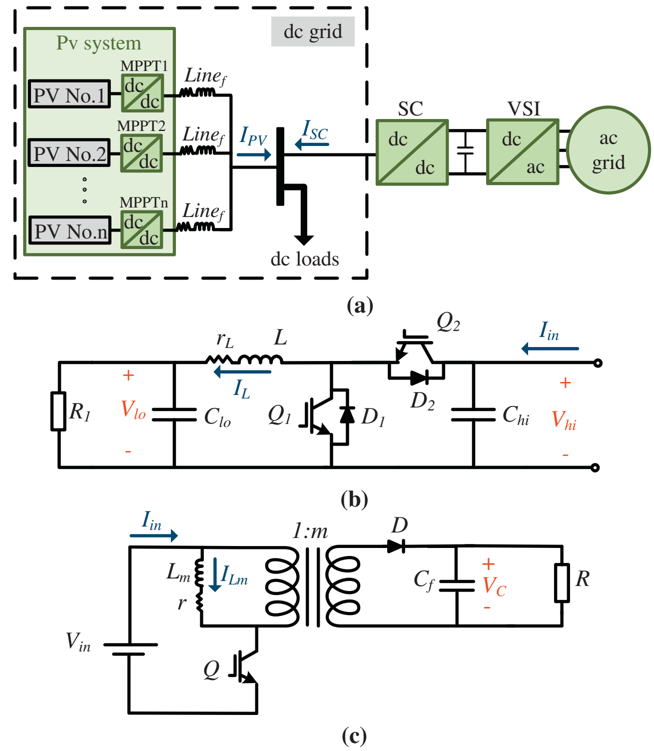

Fig. 1. (a) DC grid equipped with solar power optimizers and SC, (b) topology of SC, and (c) topology of PV converters.

$$State\ on: \begin{cases} V_{Lm} = V_{in} - rI_{Lm} \\ I_{C_f} = -\frac{V_C}{R},\ I_{in} = I_{Lm} \end{cases} \tag{1}$$

$$State\ off: \begin{cases} V_{Lm} = \frac{-V_C}{m} - rI_{Lm} \\ I_{C_f} = \frac{I_{Lm}}{m} - \frac{V_C}{R},\ I_{in} = 0 \end{cases} \tag{2}$$

The circuit equations for the SC in mode (1) are:

$$State\ on: \begin{cases} V_L = V_{hi} - V_{lo} - r_L I_L \\ I_{C_{lo}} = I_L - \frac{V_{lo}}{R_1},\ I_{C_{hi}} = I_{in} - I_L \end{cases} \tag{3}$$

$$State\ off: \begin{cases} V_L = V_{lo} + r_L I_L \\ I_{C_{lo}} = I_L - \frac{V_{lo}}{R_1},\ I_{C_{hi}} = I_{in} \end{cases} \tag{4}$$

The parameters of (1)–(4) are provided in Fig. 1(b) and (c). After perturbing the variables in the above equations and ignoring the second-order terms, the linear models are obtained. Then, these linear models can be used for obtaining transfer functions of the converters as discussed in [24,25].

2.2. Control system of the SC and PV converters

The first step in designing the control system is to obtain a proper transfer function which relates duty cycle ($\widehat{d}$) to the control variables. The SC is responsible for regulating the dc grid voltage. Since the switching algorithm of the SC changes according to its mode of operation (mode (1) or mode (2)), different transfer functions for the SC have to be derived. These transfer functions, as depicted in control systems of the converters in Fig. 2, are $G_{id} = \widehat{i_{out}}/\widehat{d}$ for the PV converters, and $G_{vd} = \widehat{v_{lo}}/\widehat{d}$ for the SC.

Since the transfer functions of the SC in mode (1) and (2) are unequal, different compensators must be designed for the SC. According to [24], stable terminal behavior of the converters