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A novel comprehensive method to enhance stability of multi-VSG grids

M. Choopani, S.H. Hosseinain*, B. Vahidi

Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran

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ABSTRACT

This paper introduces a novel approach to enhance the stability of islanded grids with multiple virtual synchronous generators (VSGs) in-operation. The proposed method mainly relies on the concept of "center of inertia" (COI) response of the system. We discuss that an islanded grid with '*n*' connected VSGs, can experience up to '*n-1*' oscillation frequencies due to swing power between VSGs, while the COI-frequency only indicates the major disturbances. The main idea of this method is to control the input power of VSGs to suppress the power fluctuations and reduce oscillations of VSGs relative to COI-frequency. For each VSG, a controller which includes three proportional, integral and derivative terms is used to match the VSG speed with COI-frequency in transient conditions. The state-space analysis shows that these parameters provide a high degree of freedom for adjusting the grid stability-indices to desired values. In addition, the method is able to effectively eliminate the adverse effect of the high impedance of VSGs to achieve desired performances.

1. Introduction

In recent years, the integration of inverter-based renewable energy resources (RESs) into the power system has been constantly growing. Many control methods have been proposed and implemented so far to connect these converters to the grid. These methods depend on the type of RESs, network architecture, and grid requirements [1,2]. The emergence of smart-grids has provided a brilliant prospect for better operation of power grids [3–5]. However, advanced solutions need to be developed to overcome the challenges of this road-map [6–8]. One critical problem facing islanded grids is the desired frequency regulation [9,10] because the traditional control methods do not have the grid-forming ability [11]. Moreover, grids with high penetration of RESs can experience frequency instability due to lack of sufficient inertia [12–14]. To overcome these problems, emulating virtual inertia into the converters has been introduced in the literature to imitate the synchronous generator (SG) operation as a virtual synchronous generator (VSG) [15,16]. The energy storage part of VSGs emulates the kinetic energy of SGs to support the islanded networks to maintain grid frequency in sudden load changes [17–19]. As expected, VSGs will be one of the leading components of the future advanced networks [20,21], Therefore, improving the stability of multi-VSG grids seems to be essential [22]. There are several methods to improve stability of multi- inverter grids that address stability issues in both islanded and grid-connected networks [23–25]. However, research on VSGs is limited to certain cases, mostly grid-connected grids. For example, adding a correction loop to VSG equation to increase damping and improve transient response has been suggested [26]. Method proposed in [27] removes dependency of Q-δ, *P-V* and decouples the control loop of active and reactive power. Another method for decoupling the voltage and damping factor is also developed in [28]. Refs. [29,30] recommend a bang-bang control approach to reduce frequency oscillations via Lyapunov-stability criterion fulfillment, in which inertia of VSG changes in real-time based on sign of angular speed and its derivative. However, as aforementioned, these methods apply to grid-connected VSGs with almost constant frequency.

The desired performance of the islanded grids depends on solving specific issues including voltage control, frequency control, small-signal stability and transient stability. In addition, the proper active and reactive load sharing is one of the principal topics discussed in the papers [31–39]. Various load-sharing approaches have been proposed to improve stability, including output impedance control [31,32], robust droop control [33,34] and using communication [35–39]. These methods are presented for conventional converters, while limited studies have been conducted on load-sharing and stability enhancement of multi-VSG grids. For example, the effect of the output reactance of VSGs on transient load sharing has been studied in [40], but the theoretical analysis is not discussed. Refs. [41,42] have proposed novel methods for oscillation damping of VSGs by introducing virtual reactance at the VSG's output, however, the mathematical analysis of these techniques is limited only to two-VSG systems and is difficult for multi-VSG grids.

Ref. [43] has provided a comprehensive analysis of similarities and

* Corresponding author.
E-mail address: hosseinian@aut.ac.ir (S.H. Hosseinain).

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differences between the two well-known control methods of converters, which are VSG and droop-control method. Also, it has introduced small-signal models and frequency regulation characteristics for both islanded and grid-connected operation. However, it has not provided a method for improving stability, and merely examines the dependence of the frequency regulation parameters on frequency oscillation. Ref. [44] has discussed transient stability of microgrids with multiple VSG units. In fact, it has optimized the stability index that is defined as the virtual rotor angle distance between each VSG with respect to the center of inertia (COI) of the microgrid. Although the proposed index is well-known for the transient stability of the power systems [45,46], using this method to improve transient stability is a novel method in the microgrids and active distribution networks.

The first step in analyzing the stability of multi VSG-grids is the accurate load-sharing study of these networks. Because findings of this research are the basis for improving the sustainability of multi-VSG grids. We will show that active load-sharing between VSGs causes their different speeds in transient conditions, which results in the presence of different electrical frequencies at any point in the network.

The proposed method is based on increasing synchronization and damping of VSGs to the desired level in smart grids through a centralized controller.

The rest of the paper is organized as follows: Section 2 includes the electrical load-sharing equations between VSGs. Section 3 highlights the role of the damping factor on stability of multi-VSG grids, and discusses the concept of oscillating VSGs around COI-frequency of the system. Section 4 introduces the proposed method. Simulation results will be provided in Section 5. Section 6 presents a complete discussion of the effect of latency on the proposed method. Section 7 concludes the paper.

2. Load sharing

In this section, first, the structure of VSGs is introduced briefly, and then the load sharing in multi-VSG grids is investigated.

2.1. Principle of a VSG

Fig. 1 shows the basic diagram of VSG configuration. Although various architectural designs have been proposed for implementation of VSGs in the literature, their central nuclei are the electromechanical swing that is defined as:

$$P_{in}-P_e=\left(2H\frac{d\omega_m}{dt}-D(\omega_m-\omega_g)\right)\omega_m \tag{1}$$

where ω_m represents virtual angular frequency of VSG, ω_g is an electrical grid frequency at the point that a voltage-measuring device is connected. P_e and P_{in} are electrical power and input power of the inverter, respectively. The parameter H emulates inertia constant of a synchronous generator that allows VSG to contribute the fast frequency control of the islanded grid. The parameter D imitates the virtual damping factor that tries to maintain the VSG speed (ω_m) equal to the grid frequency (ω_g). Detailed analysis of coefficient D is introduced in the next section.

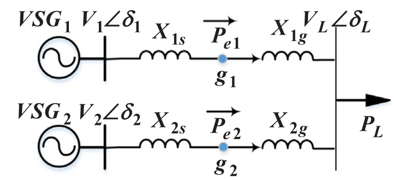

Fig. 2. The two-VSG electrical system.

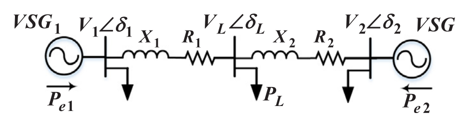

Fig. 3. The two-VSG simulated test system.

2.2. Load sharing between VSGs

The purpose of this part is to study the load-sharing between VSGs in islanded grids. However, for simplicity, a two-VSG loss-less network has been analyzed. Finally, the results are generalized for a multi-VSG grid. In Fig. 2, the electrical output power of i^{th}-VSG is:

$$P_{ei}=\sum_{j=1,\dots,n}^{j\neq i}\frac{V_iV_j}{X_{ij}}\sin(\delta_{ij}) \tag{2}$$

where X_{ij} is the total reactance between i^{th}-VSG and bus j. For the small deviation of $\delta_{ij\Delta}$ due to applying the load of $P_{L\Delta}$, it is:

$$\delta_{ij}=\delta_{ij0}+\delta_{ij\Delta} \tag{3}$$

where subscript *0* denotes the initial conditions. For the small deviation of $\delta_{ij\Delta}$, it is estimated that $sin(\delta_{ij\Delta})\cong\delta_{ij\Delta}$ and $cos(\delta_{ij\Delta})\cong 1$; thus:

$$\sin(\delta_{ij})=sin(\delta_{ij0}+\delta_{ij\Delta})\cong sin(\delta_{ij0})+\delta_{ij\Delta}cos(\delta_{ij0}) \tag{4}$$

As a result, (2) can be rewritten as:

$$P_{ei}=\sum_{j=1,\dots,n}^{j\neq i}\frac{V_iV_j}{X_{ij}}sin(\delta_{ij0})+\sum_{j=1,\dots,n}^{j\neq i}\frac{V_iV_j}{X_{ij}}cos(\delta_{ij0})\delta_{ij\Delta} \tag{5}$$

The first term of (5) indicates the load-flow state before the disturbance and the second term represents the power deviation of i^{th}-VSG, which is defined as follows:

$$P_{ei\Delta}=\sum_{j=1,\dots,n}^{j\neq i}\frac{V_iV_j}{X_{ij}}cos(\delta_{ij0})\delta_{ij\Delta} \tag{6}$$

Moreover, k_{ij} is an important term, which is recognized as a synchronizing torque coefficient that determines the strength of VSG to maintain its synchronism with the grid. It is defined as:

$$k_{ij}=\frac{V_iV_j}{X_{ij}}cos(\delta_{ij0}) \tag{7}$$

By this definition and considering $\delta_{ij\Delta}=\delta_{i\Delta}-\delta_{j\Delta}$, (6) is rewritten as follows:

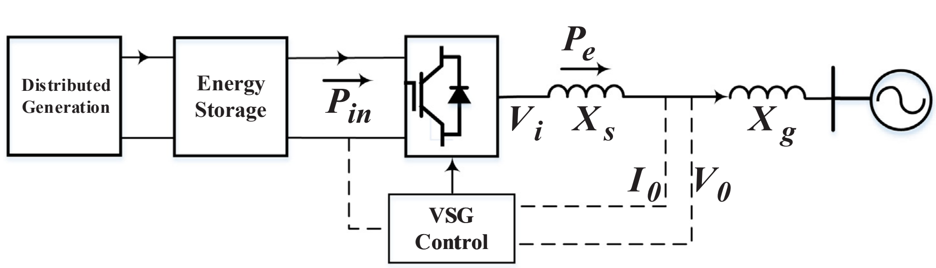

Fig. 1. Basic control structure of a VSG.

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