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Virtual synchronous generators: A survey and new perspectives

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ABSTRACT

In comparison of the conventional bulk power plants, in which the synchronous machines dominate, the distributed generator (DG) units have either very small or no rotating mass and damping property. With growing the penetration level of DGs, the impact of low inertia and damping effect on the grid stability and dynamic performance increases. A solution towards stability improvement of such a grid is to provide virtual inertia by virtual synchronous generators (VSGs) that can be established by using short term energy storage together with a power inverter and a proper control mechanism.

The present paper reviews the fundamentals and main concept of VSGs, and their role to support the power grid control. Then, a VSG-based frequency control scheme is addressed, and the paper is focused on the poetical role of VSGs in the grid frequency regulation task. The most important VSG topologies with a survey on the recent works/achievements are presented. Finally, the relevant key issues, main technical challenges, further research needs and new perspectives are emphasized.

1. Introduction

The capacity of installed inverter-based distributed generators (DGs) in power system is growing rapidly; and a high penetration level is targeted for the next two decades. For example only in Japan, 14.3 GW photovoltaic (PV) electric energy is planned to be connected to the grid by 2020, and it will be increased to 53 GW by 2030. In European countries, USA, China, and India significant targets are also considered for using the DGs and renewable energy sources (RESs) in their power systems up to next two decades.

Compared to the conventional bulk power plants, in which the synchronous machine dominate, the DG/RES units have either very small or no rotating mass (which is the main source of inertia) and damping property. The intrinsic kinetic energy (rotor inertia) and damping property (due to mechanical friction and electrical losses in stator, field and damper windings) of the bulk synchronous generators play a significant role in the grid stability.

With growing the penetration level of DGs/RESs, the impact of low inertia and damping effect on the grid dynamic performance and stability increases. Voltage rise due to reverse power from PV generations [1], excessive supply of electricity in the grid due to full generation by the DGs/RESs, power fluctuations due to variable nature of RESs, and degradation of frequency regulation (especially in the islanded microgrids [2], can be considered as some negative results of mentioned issue.

A solution towards stabilizing such a grid is to provide additional inertia, virtually. A virtual inertia can be established for DGs/RESs by using short term energy storage together with a power electronics inverter/converter and a proper control mechanism. This concept is known as *virtual synchronous generator* (VSG) [3] or *virtual synchronous machine* (VISMA) [4]. The units will then operate like a synchronous generator, exhibiting amount of inertia and damping properties of conventional synchronous machines for short time intervals (in this work, the notation of "VSG" is used for the mentioned concept). As a result, the virtual inertia concept may provide a basis for maintaining a large share of DGs/RESs in future grids without compromising system stability.

The present paper contains the following topics: first the fundamentals and main concepts are introduced. Then, the role of VSGs in microgrids control is explained. In continuation, the most important VSG topologies with a review on the previous works and achievements are presented. The application areas for the VSGs, particularly in the grid frequency control, are mentioned. A frequency control scheme is addressed, and finally, the main technical challenges and further research needs are addressed and the paper is concluded.

2. Fundamentals and concepts

The idea of the VSG is initially based on reproducing the dynamic properties of a real synchronous generator (SG) for the power electronics-based DG/RES units, in order to inherit the advantages of a SG in stability enhancement. The principle of the VSG can be applied either to a single DG, or to a group of DGs. The first

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Nomenclature

CHP	combined heat and power	PI	proportional integral
DG	distributed generator	PLL	Phase Locked Loop
LC	load controller	PV	photovoltaic
LV	low voltage	VSG	virtual synchronous generator
MC	microsource controller	RES	renewable energy sources
MG	microgrid	SG	synchronous generator
MGCC	microgrid central controller	SOS	state of charge
MV	medium voltage		
PCC	point of common coupling		

application may be more appropriate to individual owners of DGs, whereas the second application is more economical and easier to control from the network operator point of view [5]. The dynamic properties of a SG provides the possibility of adjusting active and reactive power, dependency of the grid frequency on the rotor speed, and highlighting the rotating mass and damping windings effect as well as stable operation with a high parallelism level [6].

The VSG consists of energy storage, inverter, and a control mechanism as shown in Fig. 1. The VSG is usually located between a DC bus/source/DG and the grid. The VSG shows the DC source to the grid as a SG in view point of inertia and damping property. Actually, the virtual inertia is emulated in the system by controlling the active power through the inverter in inverse proportion of the rotor speed. Aside from higher frequency noise due to switching of inverter's power transistors [7], there is no difference between the electrical appearance of an electromechanical SG and electrical VSG, from the grid point of view.

Since the VSG should be able to inject or absorb power, the nominal state of charge (SOC) of the energy storage in the VSG should be operated at about 50% of its nominal capacity in a stationary situation. The VSG operation states can be defined based on the SOC situation according to the specified lower and upper limits (e.g., 20% and 80% of maximum charge [8]). When the SOC is between about these limits, the VSG is working in its active (VSG) mode, when the energy in the system excesses, the VSG is working on the virtual load mode. The limits can be determined based on the used energy storage technology.

The output power of a VSG unit can be simply described as follows:

$$P_{VSG} = P_0 + K_I \frac{d\Delta\omega}{dt} + K_P \Delta\omega \quad (1)$$

Here $\Delta\omega = \omega - \omega_0$ and ω_0 is the nominal frequency of the grid. First term (P_0) denotes the primary power that should be transferred to the inverter. Second term indicates that power will be generated or absorbed by the VSG according to the positive or the negative initial rate of frequency change $(\frac{d\Delta\omega}{dt})$. K_I is the inertia emulating characteristic and can be represented by (2); where, P_{g0} is the nominal apparent power of the generator and H shows amount of inertia.

$$K_I = \frac{2HP_{g0}}{\omega_0} \quad (2)$$

Since, actually the initial rate of frequency change just provide an error signal (with equilibrium of zero), power will be exchanged only during the transient state without necessarily returning back the frequency of the grid to the nominal value. In order to cover this issue, a frequency droop part should be added as shown in the third term of (1). The K_P emulates the damper windings effect in a SG, and represents the linear damping. It must be chosen so that the P_{VSG} to be equal with the nominal power of the VSG when the frequency deviation is at the specified maximum value [9].

Actually, the grid frequency and rotational speed drop can be reduced by increasing the virtual mass but the synchronous units may tend to pole wheel oscillation [9]. Considering just virtual inertia (K_I) reduces the maximum deviation of the rotor speed following a disturbance; however the natural frequency and the damping ratio of the system may be decreased [10].

In summary, the virtual mass counteracts grid frequency drops and the virtual damper suppresses grid oscillation so these features are equally effective to electromechanical synchronous machines. The K_P and K_I are negative constant gains and should be fixed so that the VSG exchanges its maximum active power when the maximum specified frequency variation and rate of frequency change

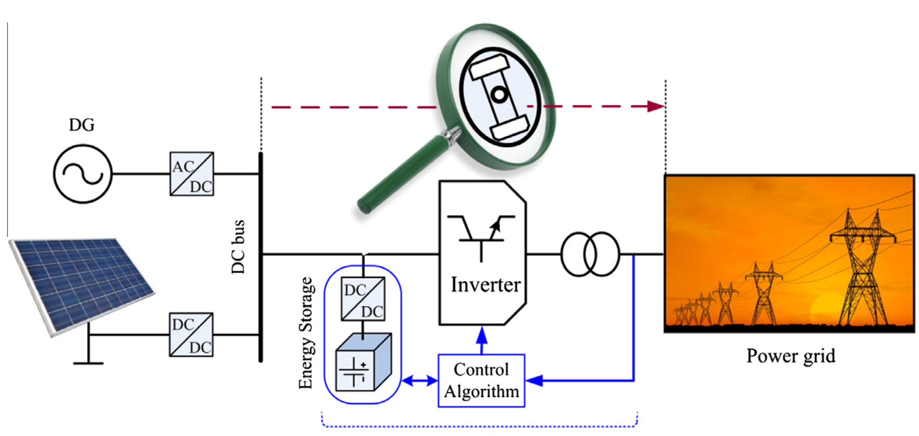

Fig. 1. General structure and concept of the VSG.