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On Virtual inertia Application in Power Grid Frequency Control

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(Invited Paper)

Abstract

To achieve a more sustainable supply of electricity, using distributed generators (DGs) utilizing renewable energy sources (RESs) is a promising solution. However, emerging renewable energy based DGs into power grids reduces the total inertia of the system, and hence, the power grid dynamics and performance can be negatively affected. To address these issues, several inverter control methodologies have been recently proposed for the DGs, and some efforts have been done for introducing the concept of virtual inertia and better understanding of dynamic characteristics of power networks in the presence of high penetration of DGs and RESs. The present paper emphasizes some significant points on the importance of inverter-based virtual inertia on the grid frequency regulation, dynamic impacts, and new relevant ideas to improve power grids frequency stability and control performance.

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1. Introduction

The distributed inverter-based power sources are going to become the dominant components in the future power grids. The estimated renewable energy share of global electricity production by the end of 2016 was about 24.5%. Most countries have determined clear plan and target to reach for next few years. For instance, the United Kingdom (UK) and Ireland have set a goal to increase the introduction rate of RESs up to around 40% by 2020, and are planning to export large amounts of wind power from Ireland to the UK [1]. However, integration of numerous

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inverters may create significant challenges in the electric power grid dynamics, mostly due to the reduction of system inertia. As an example, it is predicted that the introduction of a large number of RESs in the UK power grid could reduce the inertial constant to 70% by 2030 [2].

Reducing inertia may significantly magnify the power grid frequency deviation. Frequency deviation is a result of an imbalance between the electrical load demand and the power supplied by connected generators, so it provides a useful index to indicate the generation and load imbalance. A permanent off-normal frequency deviation may affect power system operation, security, reliability and efficiency by damaging equipment, degrading load performance, overloading transmission lines, and triggering the protection devices.

A solution towards stabilizing such a grid is to provide additional inertia, virtually. A virtual inertia can be established for DGs/RESs by using a short term energy storage together with a power inverter/converter and a proper control mechanism. This concept is known as *virtual synchronous generator* (VSG) or *virtual synchronous machine* (VSM). The units will then operate like synchronous generators (SGs), exhibiting amount of inertia and damping properties of conventional synchronous machines. 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 VSG fundamentals and relevant main concepts are well discussed in [3].

Several studies have been done on various types of VSGs, to simulate the dynamic behaviour of an SG, and represent the inertia and damping property from its fundamental swing equation, which not only enables the stand-alone operation of a VSG or parallel operation of multiple VSGs, but also enhances the frequency stability of power grids. Since to enhance the dynamic response, the parameters of the VSG control loops can be easily tuned in the software program, the VSG concept is known as a useful solution for improving the resilience of the electric power networks [4, 5].

The present paper contains the following sections: first the fundamentals and main concepts of VSG control are introduced. Then, the impact of virtual inertia (VSG) on the grid active power and frequency response is analysed. In continuation, an updated frequency control scheme is presented, and finally, the paper is concluded.

Nomenclature

AGC	automatic generation control
DC	demand control
DG	distributed generator
DR	demand response
EC	emergency control
IC	inertia control
LFC	load-frequency control
MG	microgrid
PC	primary control
P-F	power-frequency
PWM	pulse width modulation
RES	renewable energy source
SC	secondary control
SG	synchronous generator
TC	tertiary control
UFLS	under frequency load shedding
VSG	virtual synchronous generator

2. VSG control

The VSG consists of three fundamental components as shown in Fig. 1a: energy source, inverter, and a control mechanism. The VSG serves as an interface between a primary energy source and the grid. In the VSG control

block, generally a dynamic function similar to the swing equation of the SGs is embedded that determines the output power based on the grid measurements and their rate of changes.

Fig. 1b shows a more detailed structure of a VSG controlled inverter [6]. It shows the connection diagram of a three-phase inverter with VSG control. The measured signals are the line-to-line voltages (v_{uv} , v_{vw}) and line currents (i_u , i_w), and v_{pn} represents the voltage of the DC link. The pulse width modulation (PWM) signals (pwm_u , pwm_v , pwm_w) are calculated in the VSG control and then sent to the bridge inverter. The arrows at the measurement points indicate positive directions. In this system, the voltage is measured at the grid side of the transformer. The inductor current is measured/used to prevent overcurrent. Although the value of system current at the source side of the transformer is the difference between the current flowing into the filter capacitor and the inductor current, the current in the small filter capacitor is negligible and can be ignored. The inductor current is then equal to the system current.

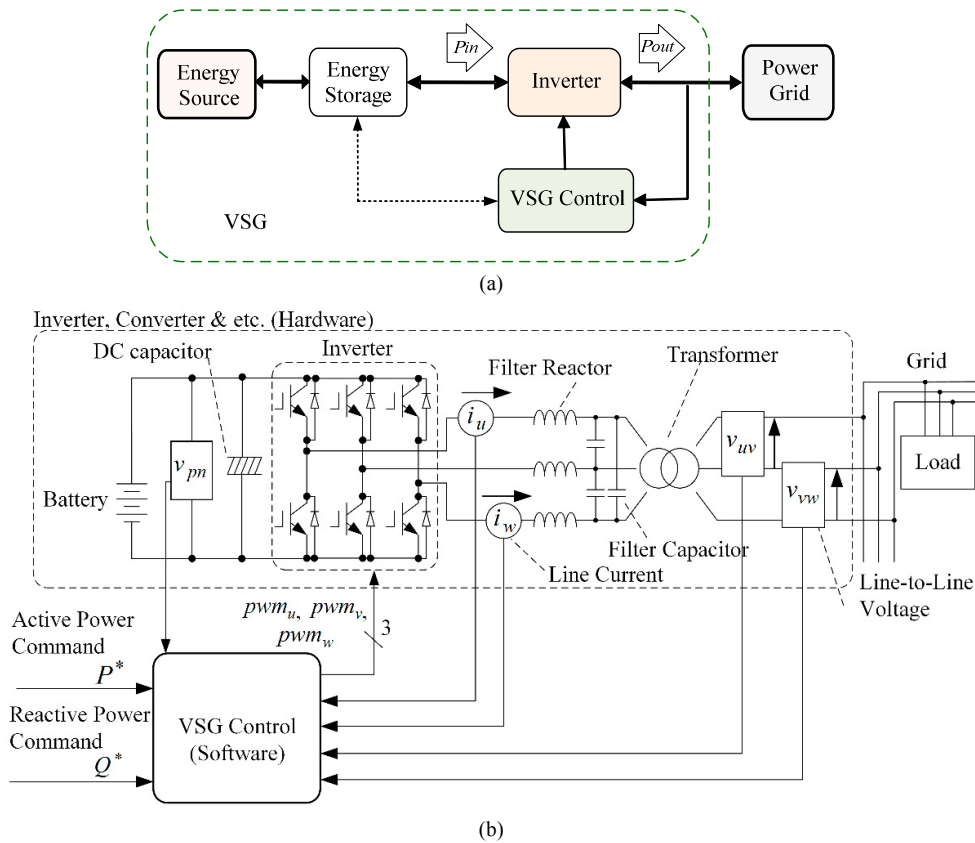


Fig. 1. VSG structure: a) Conceptual structure of the VSG, b) three-phase inverter with VSG control [6]

3. VSG impact analysis on active power and frequency regulation

3.1. Active Power and Inertia

In case of occurring an imbalance between the generated and consumed power (ΔP) in a grid, the kinetic energy (E_k) stored in the rotating mass of a generator is used to compensate this deviation. As the grid frequency is determined by the speed of the SG, this results in a frequency deviation from its nominal value. The amount of produced active power from a SG, say i -th SG, can be described as follows [3]:

$$\Delta P_i = \frac{d}{dt} E_{k,i} = \frac{d}{dt} \frac{J_i \Delta \omega_g^2}{2} = J_i \Delta \omega_g \frac{d\Delta \omega_g}{dt} \quad (1)$$

The J [kg/m^2] is a moment of inertia and ω_g (rad/s) is the grid frequency. For a power system with n SGs, the total active power can be obtained as follows, where J_{eq} is the equivalent system inertia constant.

$$\Delta P = \sum_{i=1}^n \Delta P_i = \left(\sum_{i=1}^n J_i \right) \Delta \omega_g \frac{d\Delta \omega_g}{dt} = J_{eq} \Delta \omega_g \frac{d\Delta \omega_g}{dt} ; J_{eq} = \sum_{i=1}^n J_i \quad (2)$$

In order to program this behavior into the control of a grid-connected inverter, one must determine the amount of active power that the inverter needs to exchange with the grid as a function of the grid frequency. The amount of power that the inverter can use to compensate frequency deviations also depends on the type of energy source presented in the VSG. In case of DG, possibly converting some forms of renewable energy to electricity, the main purpose of the inverter is to deliver active power to the grid, leaving only a limited amount of inverter power for compensation of frequency deviations (virtual inertia emulation). Depending on the nature of the primary energy source, a part of the energy storage capacity is used to provide a more or less constant active power to the grid, and the remaining part can be used to emulate rotational inertia [3].

The active power balance for a system containing several SGs and VSG units can be expressed by :

$$\begin{aligned} \Delta P &= \Delta P_{sg} + \Delta P_{vsg} \\ &= \sum_i \Delta P_{sg,i} + \sum_j \Delta P_{vsg,j} \\ &= \frac{d}{dt} \left(\sum_i \frac{J_{sg,i} \Delta \omega_g^2}{2} \right) + \frac{d}{dt} \left(\sum_j \frac{J_{vsg,j} \Delta \omega_g^2}{2} \right) \\ &= \sum_i J_{sg,i} \Delta \omega_g \frac{d\Delta \omega_g}{dt} + \sum_j J_{vsg,j} \Delta \omega_g \frac{d\Delta \omega_g}{dt} \\ &= \left(\sum_i J_{sg,i} + \sum_j J_{vsg,j} \right) \Delta \omega_g \frac{d\Delta \omega_g}{dt} \\ &= J_{eq} \Delta \omega_g \frac{d\Delta \omega_g}{dt} \end{aligned} \quad (3)$$

Here, ΔP_{sg} and ΔP_{vsg} are the total active power produced by the SGs and VSGs, respectively. Virtual inertia emulation requires the inverter to store or release an amount of energy depending on the grid frequency's deviation from its nominal value, analogous to the inertia of a SG. As discussed in [7], the maximum virtual inertia is proportional to the nominal power of the VSG converter divided by the maximum rate of frequency change allowed.

3.2. Virtual Inertia and Active Power-Frequency Regulation

In this section, the impact of virtual inertia on the grid active power-frequency (P - F) characteristic is represented using a linearized low-order dynamic model. The power grid including multiple SGs can be considered as an aggregated equivalent SG.

Fig. 2 shows a connection diagram of a VSG in parallel operation of an SG (as the lumped model of the power grid). First, we will focus on the dynamic P-F characteristic representation of the SG. Here, P_g is the output active power, Q_g is the output reactive power, E_{fg} is the electromotive force, x_g is the reactance (to simplify the calculations, the resistance r is neglected), δ_g is set from standard point to E_{fg} , and ω_g and ω_0 denote the rotor

angular velocity and its reference. ω_g and ω_0 are expressed in rad/s, and other variables are expressed in pu. The infinitesimal change of the general swing equation can be represented as (2), where M_g represents a moment of inertia expressed in seconds, and $P_{in,g}$ and $P_{out,g}$ denote the input and output active powers expressed in pu. In this study, small variations are represented using the prefix Δ .

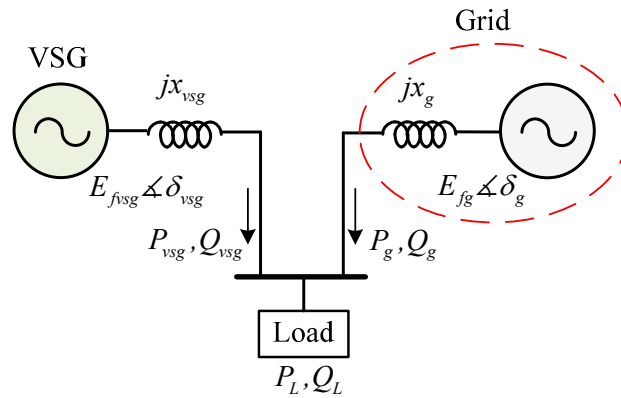


Fig. 2. Block diagram of parallel operation of a VSG and the connected grid

$$\Delta P_{in,g} - \Delta P_{out,g} = M_g (d\Delta\omega_g / dt) \tag{4}$$

Assume $H_{gov,g}(s)$ represents the transfer function of its governor, by rewriting $\Delta P_{out,g}$ as ΔP_g the Laplace transformation of above equation yields:

$$-H_{gov,g}(s)\Delta\omega_g - \Delta P_g = M_g s \Delta\omega_g \tag{5}$$

and

$$G_{P\omega,g}(s) = \frac{\Delta\omega_g}{\Delta P_g} = -\frac{1}{M_g s + H_{gov,g}(s)} \tag{6}$$

Generally, $H_{gov,g}(s)$ can be written most simply as $H_{gov,g}(s) = K_g / (1 + sT_g)$, where K_g with no units indicates the inverse of a droop constant, and T_g in seconds indicates the engine and electrical delays, which certainly exist in actual systems. The result of this expansion is

$$G_{P\omega,g}(s) = -\frac{T_g s + 1}{M_g T_g s^2 + M_g s + K_g} \tag{7}$$

In steady state, $G_{P\omega,g}(s) = \Delta\omega_g / \Delta P_g = -1 / K_g$, which represents a droop characteristic as described in [7]. From these equations, it can be seen that resonance will occur if the load power fluctuates at a frequency close to the natural frequency $(1 / 2\pi(K_g / M_g T_g)^{1/2})$, or if other SGs have similar natural frequencies.

Now, consider the VSG configuration described in Fig. 1. Since a software-based VSG created with software has no need to adopt the delays of an actual governor, thus (6) for VSG can be obtained by setting $T_{vsg} = 0$ as follows:

$$G_{P\omega,vsg}(s) = -\frac{1}{M_{vsg} s + K_{vsg}} \tag{8}$$

$G_{P\omega,vsg}(s)$ has no resonance frequency, and the VSG can avoid unnecessary interference among the other parallel running machines. Virtual realization is a characteristic advantage of VSG control, which cannot be

achieved in actual SGs.

Next, we consider a parallel operation of a virtual inertia source (e.g, VSG) and SG as shown in Fig. 2.

Because the difference between the small variations in δ_{vsg} and δ_g is given by $\Delta\delta_{vsg} - \Delta\delta_g = \omega \int (\Delta\omega_{vsg} - \Delta\omega_g) dt$, the small variations in P_{vsg} and P_g are $\Delta P_{vsg} = P'_{vsg} \Delta\delta_{vsg}$ and $\Delta P_g = P'_g \Delta\delta_g$, respectively. Here, $P'_{vsg} = (E_{f_{vsg0}} V_{g0} / x_{vsg}) \cos \delta_{vsg0}$ and $P'_g = (E_{f_{g0}} V_{g0} / x_g) \cos \delta_{g0}$ are known as synchronization forces, and hereafter, subscript 0 represents the initial value of each parameter. Therefore, from the relationship $\Delta P_{vsg} + \Delta P_g = \Delta P_L$, ΔP_{vsg} and ΔP_g can be obtained as (9).

$$\begin{cases} \Delta P_{vsg} = \frac{P'_{vsg} P'_g}{P'_{vsg} + P'_g} \frac{\omega_0 (\Delta\omega_{vsg} - \Delta\omega_g)}{s} + \frac{P'_{vsg}}{P'_{vsg} + P'_g} \Delta P_L \\ \Delta P_g = \frac{P'_{vsg} P'_g}{P'_{vsg} + P'_g} \frac{\omega_0 (\Delta\omega_g - \Delta\omega_{vsg})}{s} + \frac{P'_g}{P'_{vsg} + P'_g} \Delta P_L \end{cases} \quad (9)$$

From (6-9), the transfer function from ΔP_L to $\Delta\omega_g$ is calculated as follows:

$$\frac{\Delta\omega_g}{\Delta P_L} = \frac{G_{P\omega,g}(s)}{1 + \left(\frac{1}{P'_g} - \frac{\omega_0}{s} G_{P\omega,g}(s) \right) / \left(\frac{1}{P'_{vsg}} - \frac{\omega_0}{s} G_{P\omega,vsg}(s) \right)} \quad (10)$$

The control block diagrams of (3) and (6) are shown in Fig. 3 [6].

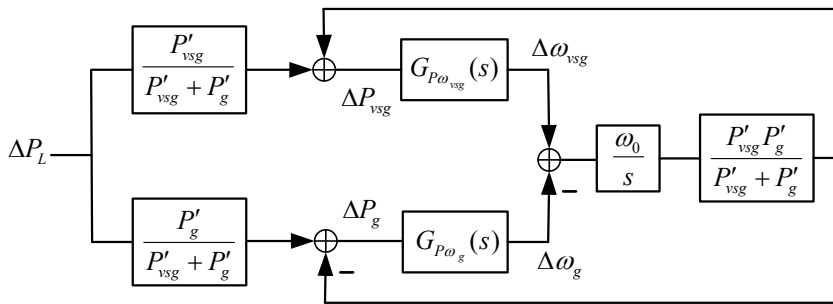


Fig. 3. Block diagram of active power and frequency control for Parallel operation of VSG and grid

It is important that the reactances in the P-F ($P-\omega$) control must be carefully assessed. It can be assumed that, under $P-\omega$ control, the impact of the reactance in the low-frequency band is small. Therefore, constant values are assigned to x_{vsg} in P'_{vsg} and x_g in P'_g in Fig. 3.

4. Frequency control loops: an updated scheme

Depending on the amplitude and duration of frequency deviation, different frequency control loops may be required to maintain power system frequency stability. A conceptual scheme of typical frequency control loops is represented in Fig. 4. The f and P_{tie} are frequency and tie-line power signals. Under normal operation, small frequency deviations can be automatically attenuated by the *primary control*. For larger frequency deviation (off-normal operation), according to the available amount of power reserve, *secondary control* which is known as load-

frequency control (LFC) is responsible to restore system frequency. The LFC is the main component of automatic generation control (AGC). However, for a serious load-generation imbalance associated with rapid frequency changes following a significant fault, the LFC system may be unable to restore frequency. In this situation, another action must be applied using *tertiary control*, standby supplies, or *emergency control* and protection schemes (such as under frequency load shedding-UFLS) as an option to decrease the risk of cascade faults, additional generation events, load/network and separation events.

The demand side may also contribute to frequency control using self-regulating effect of frequency-sensitive loads, such as induction motors and through the action of frequency-sensitive relays which disconnect some loads at the given frequency thresholds. Therefore, the demand response or *demand control* can be considered as a frequency control loop. However, this type of contribution is not always taken into account in the calculation of the overall frequency control response. In a large multi-area power system, all forms of frequency control (primary, secondary, tertiary, demand control and emergency) are usually present.

Demand control is the ability to control and manipulate demand side loads to continuously turn them off/on or change their consumption based on situation and in response to power quality, system security, voltage and frequency, technical and economic constraints, applied by grid operators. The main difference of load shedding and demand response in the grid frequency control, is in the continuous demand side participation, that can be realized based on smart or innovative methods. Load shedding is applied in off-normal and emergency condition, while DR control is working in normal operation. Demand response has the potential to decrease the generation side contribution in frequency control that consequently reduces CO2 emission, energy consumption and the required amount of reserves and hence the system operational costs.

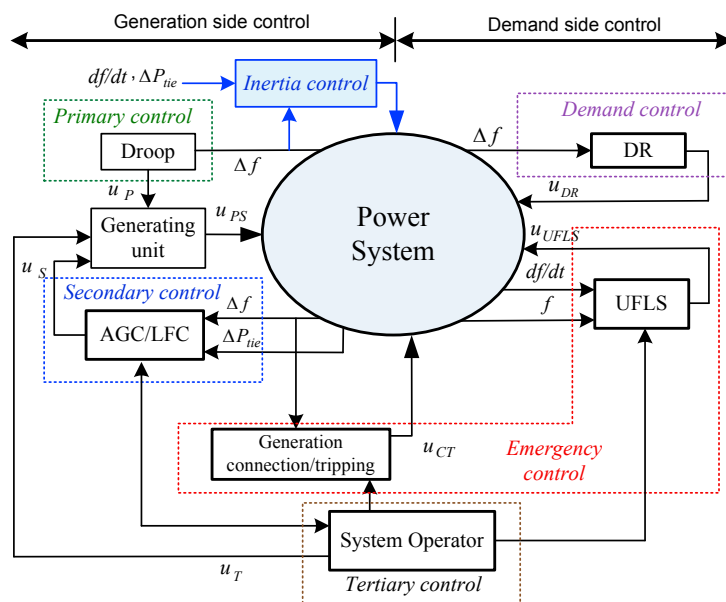


Fig. 4. Frequency control loops

Considering the operation time, the RESs and MGs are expected to support the grid frequency control in the primary frequency control level of power grids. By injecting active power by the VSG, RESs/MGs or HVDC sources in the timescale of hundreds of milliseconds up to a few seconds after a severe load/generation disturbance, they can support the conventional production assets during the activation of their primary reserve. Therefore, the previous five control loops can be updated by adding a new control loop called *inertia control* as shown in Fig. 4.

Fig. 5 shows the contribution of virtual inertia-based power and the powers from the other grid frequency control loops (in timescale of second up to minutes), following a disturbance, to support the power system frequency control. As it can be seen the inertia control (IC) can effectively support the other synchronous generators assets during the activation of their primary reserve.

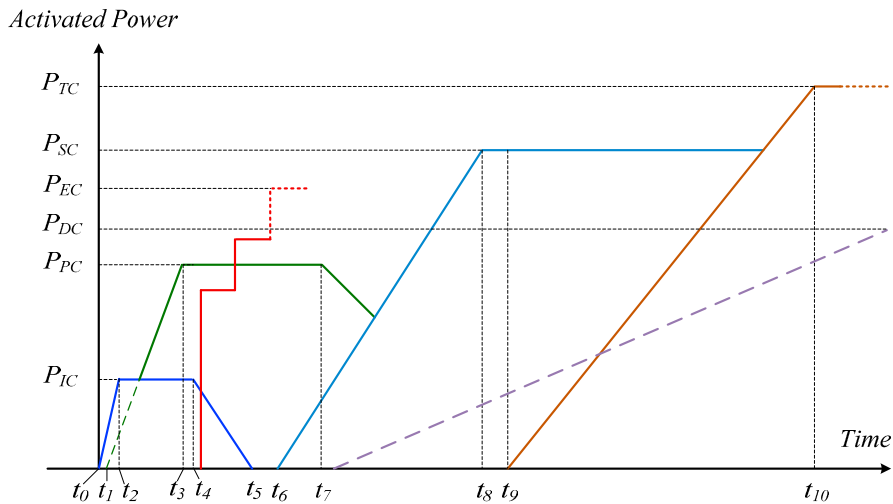


Fig. 5. Activation of frequency control loops following a disturbance at t_0

5. Conclusion

In this paper, the dynamics of the frequency deviations caused by parallel operation of the grid and VSG are analysed, and the stabilization effects provided by VSGs are confirmed. This was verified by conducting a theoretical analysis. Then the overall frequency control scheme in a power grid has been updated by adding inertia control loop.

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