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Published (to be published) in: *International Journal of Electrical Power & Energy Systems*

(Expected) publication date: 2014

Citation format for published version:

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Virtual synchronous generators: A survey and new perspectives

Hassan Bevrani \(^{a,b,*}\), Toshifumi Ise \(^{b}\), Yushi Miura \(^{b}\)

\(^{a}\) Dept. of Electrical and Computer Eng., University of Kurdistan, PO Box 416, Sanandaj, Iran
\(^{b}\) Dept. of Electrical, Electronic and Information Eng., Osaka University, Osaka, Japan

**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.

**Keywords:** Virtual inertia, Renewable energy, VSG, Frequency control, Voltage control, Microgrid

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
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 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:

\[ P_{VSG} = P_0 + K_i \frac{d\Delta \omega}{dt} + K_P \Delta \omega \]

Here \( \Delta \omega = \omega - \omega_0 \) and \( \omega_0 \) 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.

\[ K_i = \frac{2H P_{g0}}{\omega_0} \] (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

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**Nomenclature**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>DG</td>
<td>distributed generator</td>
</tr>
<tr>
<td>LC</td>
<td>load controller</td>
</tr>
<tr>
<td>LV</td>
<td>low voltage</td>
</tr>
<tr>
<td>MC</td>
<td>microsource controller</td>
</tr>
<tr>
<td>MG</td>
<td>microgrid</td>
</tr>
<tr>
<td>MGCC</td>
<td>microgrid central controller</td>
</tr>
<tr>
<td>MV</td>
<td>medium voltage</td>
</tr>
<tr>
<td>PCC</td>
<td>point of common coupling</td>
</tr>
<tr>
<td>PI</td>
<td>proportional integral</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Locked Loop</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaic</td>
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<tr>
<td>VSG</td>
<td>virtual synchronous generator</td>
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<tr>
<td>RES</td>
<td>renewable energy sources</td>
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<tr>
<td>SG</td>
<td>synchronous generator</td>
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<tr>
<td>SOS</td>
<td>state of charge</td>
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Fig. 1. General structure and concept of the VSG.
occur. Increasing $K_F$ and $K_I$ means that more power will be either injected or absorbed for the same amount of frequency deviation and rate of frequency change, respectively.

In a real synchronous generator, energy consumed by damping term is absorbed by resistance of damping windings. However, in the case of VSG, this power fluctuation should be absorbed by the energy storage device to balance the grid powers. In order to select the storage technology for an VSG application case, the most important parameters are [11]: maximum power of the loads in the considered grid; the power of the controllable generation units; averaged SOC at normal operation; detection time; control delay; and maximum total response time delay.

As mentioned, increasing of $K_I$ provides a higher amount of equivalent inertia for the VSG, however there is a limit. This limit is mainly imposed by inverter capacity and PLL accuracy. The inverter capacity does not have the overload capacity of a synchronous machine. Thus, a high derivative term leads to bigger power overshoots during transients (frequency deviations), and the inverter must sustain an important overload. The accuracy in frequency-tracking depends to the used Phase Locked Loops (PLL). Therefore, the optimal value of derivative term in (1) can be obtained by a tradeoff between the virtual inertia, the inverter overload capacity, and the PLL characteristics.

3. VSG in microgrids

A microgrid (MG) is an interconnection of domestic distributed loads and low voltage distributed energy sources, such as microturbines, wind turbines, PVs, and storage devices. The MGs are placed in the low voltage (LV) and medium voltage (MV) distribution networks. This has important consequences. With numerous DGs connected at the distribution level, there are new challenges, such as system stability, power quality and network operation that must be resolved applying the advanced control techniques at LV/MV levels rather than high voltage levels which is common in conventional power system control [12,13].

3.1. Microgrid structure

The VSG systems can be used as effective control units to compensate the lack of inertia and in result the control of active and reactive power as well as MG voltage and frequency. A simplified MG architecture with VSG units is shown in Fig. 2.

In a MG, each feeder has a circuit breaker and a power flow controller commanded by the central controller or energy manager. The circuit breaker is used to disconnect the correspondent feeder (and associated unit) to avoid the impacts of sever disturbances through the MG. The MG is connected to the distribution system by a point of common coupling (PCC) via a static switch (SS in Fig. 2). The static switch is capable to island the MG for maintenance purposes or when faults or contingency occurs [13]. The MG central controller (MGCC) facilitates a high level management of the MG operation by means of technical and economical functions. The microsource controllers (MCs) control the microsources (DGs) and the energy storage systems. Finally, the controllable loads are controlled by load controllers (LCs) [13,14].

The VSGs can be connected between a DC bus/source and an AC bus, anywhere in the MG. These systems are going to be more vital to overcome fluctuations caused in the MG due to integration of large number of DGs with low or no inertia. On the relationship between rating power of the MGs and amount of required VSG power (from all installed VSGs), there is no a particular suggestion in the literature. But, since the VSGs mainly support the primary regulation control level, considering about 5% of total MG power as the required VSG power could be quite effective for the regulation purpose (It is noteworthy that amount of reserve power for secondary regulation purpose in a power grid is about 10–15% of total available power).

Small power systems such as MGs are characterized by very fast changes in the rotating speed of generators after any sudden imbalance between production and demand such as the loss of a large generating unit. Conventional technologies used for power generation are not always capable of responding quickly enough to prevent unacceptably low frequency in such cases, even when...
the available amount of frequency control reserve exceeds the power deviation. It results in relatively frequent use of load-shedding, with subsequent consequences on the economic activity, to restore the power equilibrium and prevent frequency collapse [32]. With an appropriate control strategy, the VSGs equipped with fast-acting storage devices can help MGs to mitigate the frequency excursions caused by generation outages, thus reducing the need for load-shedding.

As the reactive power generated by the DG increases (becomes more capacitive), the operating voltage increases, too. Therefore the local voltage set-point should be reduced to keep the voltage at or near its nominal set-point. Same behavior exists for frequency and active power. In the case of parallel inverters, these control loops, also called \( P - \omega \) and \( Q - V \) droops, use feedbacks from the voltage and frequency of each DG/inverter for sensing the output active and reactive powers to emulate virtual inertias.

Therefore, in power electronic-based MGs, the droop control can be done by adding virtual inertias and controlling the output impedances; and can be useful to control active and reactive power injected to the grid. However, in the later case, the droop control is in face of several challenges that should be solved using advanced control methodologies. A slow transient response, line impedance dependency, and poor active/reactive power regulation are some of these challenges [13].

Usually in a MG, if the reactive power \( Q \) generated by the DGs increases, the local voltage must decrease, and vice versa. Also, there is similar behavior for frequency vs. real power \( P \). These relationships which are formulated in (2) and (3), allow us to establish feedback loops in order to control MG’s real/reactive power and frequency/voltage [13].

\[
\Delta \omega = \omega - \omega_0 = -R_P (P - P_0) \tag{3}
\]

\[
\Delta V = V - V_0 = -R_Q (Q - Q_0) \tag{4}
\]

\( \omega_0, P_0, V, \) and \( Q_0 \) are the nominal values (references) of frequency, active power, voltage and reactive power, respectively.

It is noteworthy that the described droop controls characteristics in (2) and (3) have been obtained for electrical grids with inductive impedance \((X \gg R)\) and great amount of inertia, which is the case in conventional power system with high voltage lines. In a conventional power system, immediately following a power imbalance due to a disturbance, the power is going to be balanced by natural response generators using rotating inertia in the system via the primary frequency control loop [15]. As mentioned, in the MG on the other hand, there is no significant inertia and if an unbalance occurs between the generated power and the absorbed power, the voltages of the power sources change. Therefore in this case, voltage is triggered by the active power changes.

In fact, for medium and low voltage line which the MGs are working with, the impedance is not dominantly inductive \((X \approx R)\). For resistive lines, reactive power \( Q \) mainly depends on \( \delta \) and real power \( P \) depends on voltage \( V \)[16]. This fact suggests different droop controls characteristics, called opposite droops. However, each microgenerator has a reference reactive power to obtain a voltage profile which matches the desirable real power. In low voltage grids, \( Q \) is a function of \( \delta \), which is adjusted with the \( V \) vs. \( P \) droop. It means there is possibility to vary the voltage of generators exchanging the reactive power [13]. So, the conventional droops are still operable in low voltage grids and MGs.

### 3.2. Microgrid controls and the VSGs role

Control is one of the key enabling technologies for the deployment of a MG system. A MG has a hierarchical control structure with different layers. It requires effective use of advanced control techniques at all levels. As already mentioned, the MGs should be able to operate autonomously but also interact with the main grid. In islanded mode, to cope with the variations, and to response to load disturbances; and performing active power/frequency regulation, and reactive power/voltage regulation, the MGs need to use proper control loops. In this mode, the MG operates according to the available standards, and the existing controls must properly work to supply the required active and reactive powers as well as to provide voltage and frequency stability. A general scheme for operating controls in a MG is shown in Fig. 3.

Similar to the conventional power systems [17], a MG can operate using various control loops. The control loops in MGs can be mainly classified in four control levels: local, secondary, central/emergency, and global controls. The local control deals with initial primary control such as current and voltage control loops in the microsources. The secondary control ensures that the frequency and average voltage deviation of the MG is regulated towards zero after every change in load or supply. It is also responsible for inside ancillary services. The central/emergency control is performed by the MGCC which interfaces between the MG and other MGs as well as higher distribution networks (such as main grid). This control level covers all possible emergency control schemes and special protection plans to maintain the MG stability and availability in the face of contingencies. The emergency controls identify proper preventive and corrective measures that mitigate the effects of critical contingencies. The global control coordinates the MGCC units in an interconnected MGs network. The global control as a centralized control allows the MG operation at an economic optimum and organizes the relation between the MG and distribution network as well as other connected MGs. In contrast to the local control, operating without communication, global control may need communication channels.

During the grid-connected operation, all the DGs and inverters in the MG use the grid electrical signal as reference for voltage and frequency. In this mode, it is not possible to highlight the VSG contribution to the grid inertia, due to system size differences. However, in islanding, the DGs lose that reference. In this case the DGs may use the VSG units, and may coordinate to manage the simultaneously operation using one of effective control techniques such as master/slave control, current/power sharing control, and generalized frequency and voltage droop control techniques [13]. The balance between generation and demand of power is one of the most important requirements of the islanded operation modes. In the grid-connected mode, the MG exchanges power to an interconnected grid to meet the balance, while, in the islanded mode, the MG should meet the balance for the local supply and demand using the decrease in generation or load shedding.

During the islanded mode, if there are local load changes, local DGs will either increase or reduce their production to keep constant the energy balance, as far as possible. In an islanded operation, a MG works autonomously, therefore must have enough local generation to supply demands, at least to meet the sensitive loads. In this mode, the VSG systems may present a significant role to maintain the active and reactive power. Without VSGs, the DG units may trip. That is not a problem in grid-connected operation, because in this situation, the main grid compensates the increases or decreases of the load.

Immediately after islanding, the voltage, phase angle and frequency at each DG in the MG change. For example, the local frequency will decrease if the MG imports power from the main grid in grid-connected operation, but will increase if the MG exports power to the main grid in the grid-connected operation. The duration of islanded operation will depend on the size of storage systems. In this case they are sized to maintain the energy balance of the tested network for few minutes. The VSG control algorithms for islanding and grid-connected modes are different, as the islanded MG has to define its own frequency and voltage.
to maintain operation [18]. When the main grid has returned to normal operation, the frequency and voltage of the micro-grid must be synchronized with and then reconnected to the main grid.

4. Existing VSG topologies and applications

From 2008 up to now, several topologies are introduced for the VSG systems, world wide. The VSYNC project under the 6th European Research Framework program [3,5,8,9,11,18–21,24], the Institute of Electrical Power Eng. (IEPE) at Clausthal University of Technology in Germany [6,7,25,26], the VSG research team at Kawasaki Heavy Industries (KHis) [27], and the ISE Laboratory in Osaka University [28–30] in Japan, can be considered as some of the most active research groups in this area. Most of addressed topologies are designed to provide a dynamic characteristic similar to the described one in (1). In this section, the overall frameworks of some developed VSG structures are explained.

4.1. VSYNC’s VSG topology

The VSYNC research group realized the concept of VSG system as shown in Fig. 4 [3]. Here, the VSG comprises an energy storage unit connected to a DC link and a power inverter with LCL grid filter. The Eigen-frequency of the LCL circuit is positioned approximately halfway between the nominal power frequency and converter switching frequency. A current mode control for grid currents is commonly employed.

Current reference templates \(I_{ref}\) are provided by the PLL circuit. Although, the PLLs are often used to synchronize two periodical processes or to measure frequency, in this structure it can be used to produce the VSG reference current using the grid terminal voltage \(V_g\). Here, the PLL provides a response similar to the SG’s one, and emulates its electro-mechanical characteristics. The PLL output is used to drive the inverter. As described in [3], in addition to the emulation of inertia, the PLL also provides the phase angle reference for rotating frame for \(dq\) control of inverter quantities.

A detailed configuration of an improved version of above VSG is depicted in Fig. 5a. The "reference current" block processes all required information in order to produce the error current signal \(i_{dq}\). \(K_{SOC}\) is must be set such that the active signal \(P\) is equal to the nominal VSG output power, when the SOC deviation (ASOC) is at its maximum level. Similarly, the \(K_v\) must be chosen such that the VSG produce its maximum reactive power for a specified voltage deviation (e.g., 10% [19]).

In other effort related to the VSYNC research group [20], the current of DC bus at the VSG is controlled by collecting some information such as grid frequency and the batteries SOC as a result of monitoring of the energy exchange VSG-battery pack. In the addressed approach the frequency is estimated based on the zero-crossing method, and finally the current set point \(I_{sp}\) is computed from the following equation:

\[
I_{sp} = \frac{P}{V_{battery}}
\]

Fig. 3. A general scheme for MGs control levels.

Fig. 4. VSG structure using PLL to emulate the synchronous generator behavior.
\[ I_p = \frac{K_I \frac{d\Delta \omega}{dt} + K_P \Delta \omega}{V_{dc}} \]  

where \( \frac{d\Delta \omega}{dt} \) is the rate of frequency change, \( K_I \) is a dimensionless factor and \( K_P \) is expressed in kg m\(^2\)/s\(^2\). Eq. (4) can be easily obtained from Eq. (1) after neglecting \( P_0 \).

### 4.2. IEPE’s VSG topology

In [6, 7], based on dynamic of a simplified SG model, a topology which provides the reference current (voltage) from the grid voltage (current) is suggested. The overall VSG scheme is shown in Fig. 6a.

In this structure, the output active/reactive power of the VSG, as well as the amount of inertia and damping effect can be easily set by adjusting the model parameters such as those parameters represent the virtual torque and virtual excitation of a real SG in a power plant. Fig. 6b shows the simplified model of SG to produce the reference current \( (i_{ref,abc}) \) from the grid voltage signals \( (v_{g,abc}) \).

In Fig. 6b, \( J \) is the moment of inertia, \( R_s \) is the stator resistance and \( L_s \) is the stator inductance, \( K_P \) is the mechanical damping factor, \( \varphi(s) \) is the phase compensation term, \( \omega \) is the angular velocity, \( \theta \) is the angle of rotation, \( T_e \) and \( T_m \) are the electrical and mechanical torque. The phase compensation term ensures that the virtual damping force counteracts any oscillating movement of the rotor in opposite phase. Despite of simplifying the excitation winding, the induced electromotive force (EMF) is given by adjustable amplitude \( E_p \) and the rotation angle \( \theta \).

### 4.3. ISE lab’s VSG topology

Fig. 7 shows the block diagram of a VSG system suggested by ISE laboratory in [28]. In this scheme, the well-known swing equation of a SG, given in (6), is realized as the heart of VSG model.

![VSG structure using PLL](image-a.png)  
(a)  

![VSG structure based on current-voltage model of SG](image-b.png)  
(b)  

**Fig. 5.** VSG structure using PLL: (a) detailed framework, (b) reference current block.  

**Fig. 6.** VSG structure based on current-voltage (voltage-current) model of SG: (a) VSG topology, (b) current-voltage model of SG.
Here, $P_m$ is input power (as same as prime mover power in a SG), $P_{out}$ is output power, $J$ is the moment of inertia of the rotor, $\omega$ is the virtual angular velocity of the virtual rotor $(\Delta \omega = \omega - \omega_0)$ and $D$ is the damping factor.

$$P_{in} - P_{out} = J \Delta \omega \frac{d\Delta \omega}{dt} - D \Delta \omega \quad (6)$$

By solving this equation in each control cycle, the momentary frequency $\omega$ is calculated and by passing through an integrator, the virtual mechanical phase angle, $\theta_m$ is produced for generating PWM pulses.

As shown in Fig. 7, the output power and grid frequency are calculated in the power/frequency meter block. The grid frequency is known to compute $\Delta \omega_m$ (the virtual angular velocity deviation of the virtual rotor) based on swing Eq. (6) by the VSG control block, and then the obtained $\theta_m$ (virtual mechanical phase angle) is supplied to the inverter through the PWM unit as a phase command.

### 4.4. KHI’s VSG topology

The KHI uses an algebraic type model to establish the VSG [27]. In this model, in order to guarantee a desirable operation under all types of load (specifically unbalanced and nonlinear loads), a current feedback loop to produce the current reference according to the phasor diagram of a SG is used. Furthermore, two loops for compensating of angular velocity and line voltage deviations are also considered. The block diagram of the proposed VSG by the KHI is shown in Fig. 8.

In this figure, $\Delta P = P - P_0$ and $\Delta \omega = \omega - \omega_0$, $P$ is the grid power active and power reactive deviations, respectively, $P_0$ is the nominal angular velocity (frequency) of the grid. The $\omega_0$ and $\omega$ are angular velocity of virtual rotor and estimated by the PLL, respectively.

### 4.5. VSG applications

Over the last three years, several applications have been suggested for the introduced VSG topologies (described in previous section) in the power system. In [3], the VSG is used to improve the rotor angle stability. Although, the performed simulation shows that the VSG improves the damping, but the magnitude of the excursion is not improved. The authors suggested that the magnitude of the excursion can be reduced by applying reactive power.

The VSGs can contribute to voltage compensation during a short circuit in order to reduce voltage dip (like rotating machines inject reactive power to the system during a fault). Laboratory scale results and field demonstration was planed at two sites located in the Netherlands and in Romania [22]. Thus, it is expected that the VSG also can prevent the electricity grid blackouts due to voltage instability and can retain safety in fault situations.

Several research works have considered the application of the VSGs in active/reactive control, and hunting reduction control [27,29,30]. Frequency control is also known as an important control problem which can be effectively addressed by the VSGs [31–35]. Next section is focused on the frequency control issue using virtual inertia provided by the VSGs.

### 5. VSG-based frequency control

In system dynamic point of view, the SGs, due to their high inertia provide a long time constant; such that the rotor speed and thus the grid frequency cannot alter suddenly while the load changes. Hence the dynamic frequency stability will be enhanced by the total rotating mass.

In future, a significant share of DGs in the electric power grids is expected. This increases the total system generation power, while does not contribute to system rotational inertia. Because most of DGs do not present rotational inertia, or due to using interfaced switching converters, there is no direct connection between their rotational speeds with the system frequency.

In these grids the natural power exchange of the DGs with the grid has less influence on the system frequency performance. This results in larger frequency variations due to changes in generation/load power, such that the existing conventional frequency control loops may lose their effectiveness to provide a desirable performance and to maintain the system stability.

As already mentioned, in these grids, the VSGs may provide a solution, by adding virtual inertia to the DGs. The purpose of using VSG in frequency control is to take advantage of the short response time of storage devices to improve the frequency response
Performances of the power systems. Frequency control in a power system with the SVG unit can be done via a fast active power exchange between energy store and grid. In this way the overall system may contain amount of inertia that still is proportional to the total generation power, resulting in the same amount of frequency fluctuations as in the current power system. The goal of VSG control is to emulate an energy source with rotational inertia. First, it is needed to review the relationship between the active power and inertia for a conventional SG.

5.1. Active power compensation and Inertia

In case of occurring an imbalance between the generated and consumed power ($\Delta P$) in a conventional grid, the kinetic energy ($E_k$) stored in the rotating mass of a generator is used to compensate for this deviation. As the grid frequency is determined by the speed of the SG, this results in a frequency deviation from its nominal value [8]. The amount of produced active power from a SG, say $i$-th SG, can be described as follows:

$$\Delta P_i = \frac{d}{dt} E_{k,i}$$

(7)

The kinetic energy stored in the rotor of a SG, having a moment of inertia $J$ [kg/m²] and rotating at grid frequency $\omega_g$ (rad/s) is given by:

$$E_{k,i} = \frac{J_i \Delta \omega_i^2}{2}$$

(8)

Therefore,

$$\Delta P_i = J_i \Delta \omega_i \frac{d \Delta \omega_i}{dt}$$

(9)

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.

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

$$J_{eq} = \sum_{i=1}^{n} J_i$$

(10)

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 present in the VSG. In case of DG, possibly converting some forms of renewable energy to electricity, the main purpose of the inverter will be 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 will be used to provide a more or less constant active power to the grid, and the remaining part can be used to emulate rotational inertia [33].

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

$$\Delta P = \Delta P_{SG} + \Delta P_{VSG}$$

$$= \sum_{i=1}^{n} \Delta P_{SG,i} + \sum_{j=1}^{m} \Delta P_{VSG,j}$$

$$= \sum_{i=1}^{n} J_i \Delta \omega_i \frac{d \Delta \omega_i}{dt} + \sum_{j=1}^{m} J_{v,j} \Delta \omega_g \frac{d \Delta \omega_g}{dt}$$

(11)

and, comparing (4) and (6) gives:

$$J_{eq} = \sum_{i=1}^{n} J_{SG,i} + \sum_{j=1}^{m} J_{VSG,j}$$

(12)

Here, $\Delta P_{SG}$ and $\Delta P_{VSG}$ are the total active power produced by the SGs and VSGs, respectively.

Virtual inertia emulation requires the inverter to be able 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 can be seen from (9), the maximum virtual inertia is proportional to the nominal power of the VSG converter divided by the maximum rate of frequency change allowed. Depending on the application case and desired nominal power of the VSG, the best type of electrical storage should be determined [23]. It can be shown that the smallest possible size of VSG storage is proportional to the product of virtual inertia emulated and the maximum frequency deviation allowed [34].

In a MG, the active power response to a frequency deviation is governed by both power-frequency droop and inertia constant, imposed by the mechanical part (e.g. micro-hydro turbine). This action has the advantage of increasing the system damping [35] and thus the faster stabilizing of frequency. Similar idea is also studied for many kinds of DGs [36–39], such as for the wind
turbines. Using the kinetic ESS (blade and machine inertia) to participate in primary frequency control is addressed in [39]. Frequency regulation impacts are defined to be those impacts that occur on the basis of a few seconds to minutes. Therefore, when comparing different wind integration studies, it is important to adopt a clear definition of the time scales involved [40].

Integrating energy storage systems (ESSs) or energy capacitor systems (ECSs) into the wind energy system to diminish the wind power impact on power system frequency has been addressed in several reported works [40–43]. In [40–43], different ESSs by means of an electric double-layer capacitor and superconducting magnetic energy storage and energy saving are proposed for wind power leveling. The impact of wind generation on the operation and development of the UK electricity systems is described in [44]. Impacts of wind power components and variations on power system frequency control are described in [40,45–47].

The technology to filter out the power fluctuations (in result frequency deviation) by wind turbine generators for the increasing amount of wind power penetration is growing. The new generation of variable-speed, large wind turbine generators with high moments of inertia from their long turbine blades can filter power fluctuations in the wind farms.

Some preliminary studies showed that the kinetic energy stored in the rotating mass of a wind turbine can be used to support primary frequency control for a short period of time [39]. The capability of providing a short-term active power support of a wind farm to improve the primary frequency control performance is discussed in [36]. To support primary frequency control for a longer period, some techniques such as using a combination of wind and fuel cell energies are suggested [48].

5.2. Frequency control framework

Over the last few years, the main contributions to frequency control in a DG-based MG are the energy storage units, which compensate the difference between the DGs production and the loads power demand [2]. It has been shown that fast-operating storage devices such as lithium-ion batteries or advanced flywheels can provide frequency control services more effectively than conventional resources, at lower life-cycle cost and reduced CO₂ emissions [31].

Concerning the VSG concept, the DG units could also actively participate to MG frequency control, either in primary or secondary levels; however their power reserve is a concern in the case of RESs. In frequency control point of view, using multi VSGs with even the same structure but different parameters may provide a better dynamic performance [25]. In this case, the dynamic parameters of the spread installed VSGs must be adjusted in coordination with each other.

In a VSG unit, in addition to the main control algorithm for calculating the active and reactive power that to be exchanged between the inverter and the grid in order to achieve the control goal, e.g. grid frequency regulation; two other control loops exist to operate in a lower control level [33]: (i) a control loop for determining the inverter output voltage which to be applied in order to achieve the active and reactive power exchange between the inverter, the energy storage units and the grid as demanded by the main VSG control. (ii) a control loop to control of the DC–DC converters interfacing the energy storage units to the DC bus of the VSG. This work is mainly focused on the main VSG control issue.

A general VSG control framework is shown in Fig. 9. For a frequency variation and rate of frequency change larger that a specified limit, the VSG algorithm computes the required inertia J to be added to the system and initiates the power transfer (ΔP_{VSG}) between the grid and the storage. According to (1), the amount of VSG power for the required inertia can be estimated as follows (here, K_r = K_f):

\[ ΔP_{VSG} = K_f \frac{dΔx}{dt} + K_pΔx \] (13)

Finally, reference current I_{ref} to activate the PWM units can be calculated based on the existing relationship function between the transferred power from inverter and command current signal, i.e., I_{ref} = (ΔP_{VSG}). This function can be obtained from (13) by considering the relationship between reference current signal and the transferred power from DC bus, similar to the equation given by (5).

In summary, as shown in Fig. 9, following a disturbance, the required virtual rotational inertia should be immediately calculated by the VSG algorithm, and next the VSG is activated in order to verify its frequency stabilizing properties. In an effective control framework, the VSG algorithm must adaptively made a trade of between amount of damping and inertia properties requirement.

Starting time of power injection by the VSG and duration time of power delivery is very important to get a desirable dynamic performance. As the frequency deviation, and the rate of frequency change exceed from the specified thresholds (e.g., 0.5 Hz and 1 Hz/s), the dynamic reserve must be deployed by the VSG as fast as possible (e.g., within 1 s, [31]) before load shedding relays start the operation. The amount of dynamic reserve should be sized so that the frequency nadir (ω_{min}) can remain above a predetermined value.

6. Technical challenges and further research need

Using significant number of VSGs into power systems adds new technical challenges. As the electric industry seeks to reliably integrate large amounts of DGs/RESs into the power system in regulated environment, considerable effort will be needed to accommodate and effectively manage the installed VSG units. A key aspect is how to handle changes in topology caused by penetration of numerous VSGs as new control devices in the network and how to make the power grid robust and able to take advantage of the potential flexibility of distributed VSGs. Here, some important challenges and a scope for further research are briefly explained.

6.1. Improvement of computing techniques and measurement technologies

The ability of VSG to respond to the fast grid frequency changes depends of pre-existing knowledge on the network operation and real-time frequency measurements. Most critical for the VSG algorithm quality are the frequency estimation block and the state of charge estimation. Any improvement in VSG control methods needs a better frequency calculation and/or improved filtering and sensing modules on the VSG hardware platform [20]. The efforts to design more flexible and effective VSGs are directed at developing computing techniques and monitoring/measurement technologies to achieve optimal performance. Advanced computational methods for predicting grid situation, and improved measuring technologies, are opening up new ways of controlling the power system via VSG units.

As mentioned, the accuracy in frequency-tracking depends to the used PLL and this issue directly affects the VSG performance. Develop a more precise alternative for the PLL to be important. But, in this case the delay imposed by the filters and existing measurement channels should be carefully noticed. The delay, specifically in the ADC and DAC channels [24], is an important reason for degrading of the VSG performance and even inaccuracies in the
simulation environments. A relatively large time constant may make a delay in the starting time. As already explained the starting time of power injection by the VSG as well as the duration time of power delivery is very important to get a desirable dynamic performance.

Design of more accurate and sensitive grid frequency change and rate of frequency change detectors requires extensive research to incorporate signal processing, adaptive strategies, pattern recognition and intelligent features. Advanced computing algorithm and fast hardware measurement devices are also needed to realize optimal/adaptive VSG schemes for modern power grids.

6.2. Improvement of modeling and analysis tools

A complete understanding of reliability considerations via effective modeling/aggregation techniques is vital to identify a variety of ways that power grids can accommodate the large-scale integration of the VSGs in future. A more complete dynamic frequency response model is needed in order to VSG analysis and synthesis in a grid with a high degree of DG/RES penetration. A proper dynamic modeling and aggregation of the VSG units, for performance and stability studies, is a key issue to understand the dynamic impact of VSGs and simulate their functions in new environment.

6.3. Develop effective intelligent and robust VSG control algorithms

Additional flexibility may be required from various VSGs so the system operator can continue to balance supply and demand on the modern power grids. The contribution of VSGs in frequency regulation task refers to the ability of these units to regulate their power output, by an appropriate control action. More effective practical algorithms and control methodologies are needed to do this issue, effectively. Further studies are needed to coordinate the timing and the size of the kinetic energy discharge with the characteristics of conventional SGs.

6.4. Coordination between VSGs and SGs, and revising of existing standards

In case of supporting frequency system, an important feature of VSG units is the possibility of their fast active power injection. Following a power imbalance, the active power generated by VSGs quickly changes to recover the system frequency following a disturbance. As this increased/decreased power can last just for a few seconds, conventional SGs should eventually take charge of the huge changed demand by shifting their generation to compensate power imbalance. But the fast power injection by VSGs may slow down to a certain extent the response of conventional SGs. To avoid this undesirable effect, coordination between VSGs and conventional SGs in the grid frequency control is needed.

Standards related to overall reliable performance of the power system as instituted by technical committees, reliability entities, regulatory bodies and organizations ensure the integrity of the whole power system is maintained for credible contingencies and operating conditions. There exist some principles to be taken into account in the future standards development on MG system in the presence of DGs/RESs and VSG units. Standards should be comprehensive, transparent and explicit to avoid misinterpretation. Interconnection procedures and standards should be enhanced to address frequency regulation, real power control, and inertia response and must be applied in a consistent manner to all DG technologies.

The reliability-focused equipment standards must be also further developed to facilitate the reliable integration of additional VSGs into the power grid. From a grid system reliability perspective, a set of interconnection procedures and standards are required which applies equally to all generation resources interconnecting to the grid including VSG units. Further work is required to standardize basic requirements in these interconnection procedures and standards, such as the ability of the VSGs owner to provide inertial-response.

To allow for increased penetration of VSGs, a change in regulation reserve policy may be required. In this direction, in addition to deregulation policies, the amount and location of VSG units, operation technology, and the size and characteristics of the grid must be considered as important technical aspects. Moreover, the updating of existing frequency control levels concerning economic assessment/analysis the frequency regulation prices and other issues; and quantification of reserve margin due to increasing VSGs penetration are some important research needs.

7. Conclusion

With growing the penetration level of DGs, the impact of low inertia and damping effect on the grid stability and dynamic frequency performance increases. A solution towards stability improvement of such grids is to provide virtual inertia by VSGs that can be established by using short term energy storage together with a power inverter and a proper control mechanism. In this paper, the most important issues on the VSG concept with the past achievements in this literature are briefly reviewed. The main VSG design frameworks and topologies are described.

It is shown that the virtual inertia can be considered as an effective solution to support the primary frequency control and compensate the fast frequency changes. By injecting active power by the VSGs 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. The VSGs can effectively support the other SGs assets during the activation of their primary reserve. During the frequency drop, the VSG unit behaves as a virtual inertia from the system dynamics point of view.

In this paper, an overview of the key issues in the integration of VSGs in the microgrids and power grids, and their application areas that are of most interest today is also presented. Finally, the need for further research on more flexible and effective VSGs, and some other related areas is emphasized. Some important topics for further research are mentioned as: improvement of computing techniques and measurement technologies, improvement of modeling and analysis tools, development of effective and robust VSG control algorithms, coordination between VSGs and SGs, and revising of existing standards.

Acknowledgements

This work is supported by the ISE Laboratory at Osaka University in Japan.

References