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Integration of Distributed Energy Resources in Power Systems

Implementation, Operation, and Control

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Chapter 12

Virtual synchronous generators and their applications in microgrids

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CHAPTER OUTLINE

12.1 BASIC CONCEPTS OF VIRTUAL SYNCHRONOUS GENERATORS

The portion of distributed generating (DG) units and renewable energy sources (RESs) in power systems with respect to its total power capacity is increasing rapidly; and a high penetration level is expected for the next two decades. In the conventional centralized power generations, in which the synchronous machine dominates, enormous synchronous generators (SGs) comprise rotating inertia due to their rotating parts. 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 grid stability. These generators are capable of injecting the kinetic energy preserved in their rotating parts to the power grid in the case of disturbances or sudden changes of generation and load power. Moreover, the slow dynamics of the huge generators allows

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the system to dampen the transients after a change or disturbance through oscillations and thereby remain balanced between the power generation and demand within the required timescale.

The growing DG/RES units have either very small or no rotating mass (which is the main source of inertia) and damping property and therefore, the grid dynamic performance and stability is affected by insufficient inertia and damping of DGs/RESs. The most challenging issue with the inverter-based units is to synchronize the inverter with the grid and then to keep it in step with the grid even when disturbances or changes happen [1–3]. A power system with a big portion of inverter-based DGs is prone to instability due to the lack of adequate balancing energy injection within the proper time interval [4]. Instability may happen in the form of frequency variation with high rate, low/high frequency, and out-of-step of one or a group of generators. Voltage rise due to reverse power from photo voltaic (PV) generations, 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 islanded microgrids, can be considered as negative results of these issues.

One solution towards stabilizing such a grid is to provide additional inertia, virtually. A virtual inertia can be established for DGs/RESs using short-term energy storage together with a power electronics inverter/converter and a proper control mechanism. By controlling the output of an inverter, it can emulate the behavior of a real synchronous machine. In this idea, the inverter-based interface of the DG unit is controlled in a way to exhibit a reaction similar to that of a synchronous machine to a change or disturbance. This concept is known as virtual synchronous generator (VSG) [5] or virtual synchronous machine (VISMA) [6]. This design is expected to operate like a synchronous generator, exhibiting the amount of inertia and damping properties, by controlling the amplitude, frequency, and the phase angle of its terminal voltage. Therefore, it can contribute to the regulation of grid voltage and frequency. In addition, synchronizing units, such as phase-locked loops, can be removed [7]. 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 objective of the VSG scheme is to reproduce the dynamic properties of a real 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 [8]. The dynamic properties of a SG provides the possibility of adjusting active and reactive power, dependency of the grid frequency on

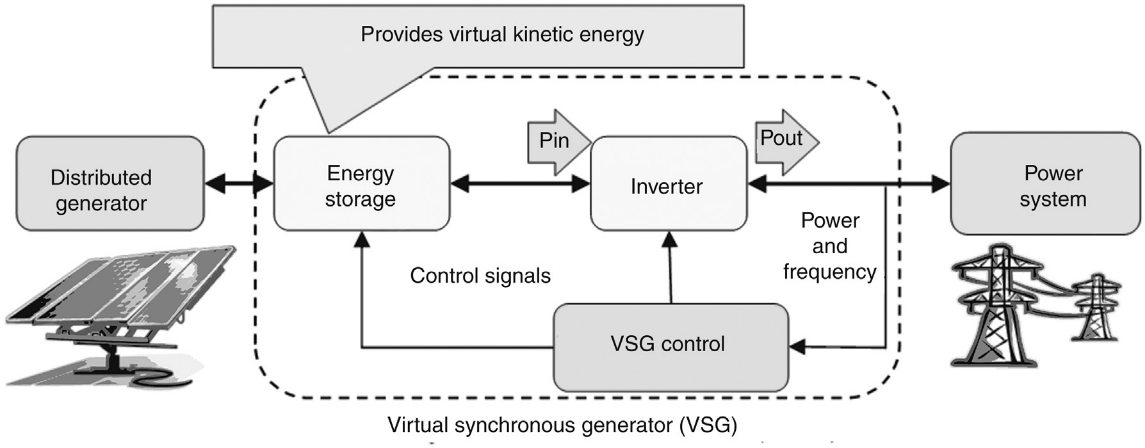


FIGURE 12.1 General structure of VSG.

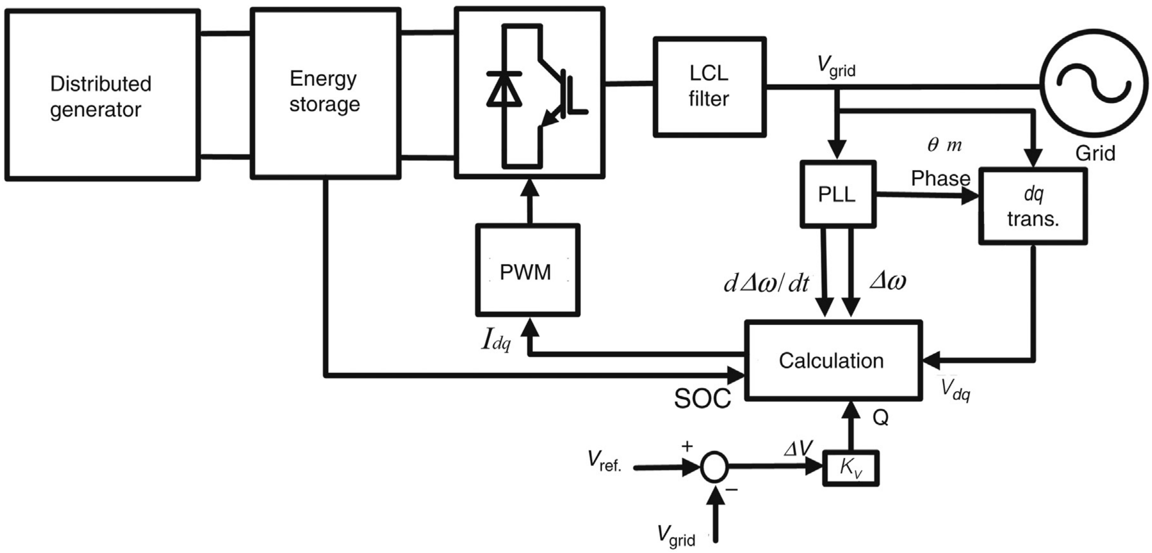
the rotor speed, and highlighting the rotating mass and damping windings effect as well as stable operation with a high parallelism level [9].

The VSG consists of energy storage, inverter, and a control mechanism as shown in Fig. 12.1. In this scheme, the VSG serves as an interface between the direct current (DC) bus and the grid. 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, there is no difference between the electrical appearance of an electromechanical SG and electrical VSG from the grid's point of view [10].

In the VSG control block, generally, a dynamic equation similar to the swing equation of the SGs is embedded that determines the output power based on the rate of the change of frequency and the frequency mismatch with respect to the nominal frequency.

12.2 CONTROL SCHEMES OF VIRTUAL SYNCHRONOUS GENERATORS

The idea of VSG control emerged in October 2007 and, up to now, several groups have developed various designs with the same fundamentals introduced in Section 12.1. The VSG concept and application were introduced in Refs. [11,12]. The same concept under the title of Synchronverter is described in Ref. [13]. The VSYNC project under the sixth European Research Framework program [5,8,11,14–20], the Institute of Electrical Power Eng. (IEPE) at Clausthal University of Technology in Germany [9,10,21,22], the VSG research team at Kawasaki Heavy Industries (KHI) [23], and the Osaka University [4,24–29] in Japan are explained in detail next.



■ **FIGURE 12.2 Structure of VSG developed by VSYNC group.**

12.2.1 VSYNC's VSG Design

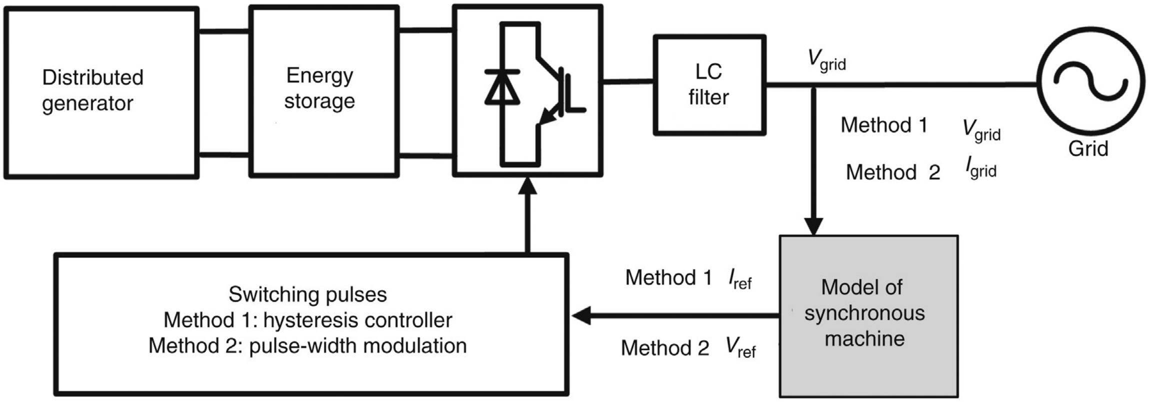
The initial VSG invented by this group with its full control connections is shown in Fig. 12.2. Here, energy storage unit connected to the grid through an inverter and LCL (L(Inductor), C(Capacitor) and L are combined type) filter. The VSG control produces the current reference to be used in the current controller. The phase locked loop (PLL) is used to produce the rate of frequency change ($d\omega/dt$) using the grid terminal voltage Vg. In addition, it provides the phase angle reference for rotating frame for dq control of inverter quantities. The "Calculation" block produces the current reference in dq-coordinates from the measured grid voltage, state of charge (SOC) of the storage device, $\Delta\omega$, $d\Delta\omega/dt$, and voltage reference through the following equations:

$$P = K_{\mathrm{SOC}}\Delta SOC + K_{\mathrm{P}}\Delta\omega + K_I \frac{d\Delta\omega}{dt} \tag{12.1}$$

$$Q = K_{\mathrm{V}}\Delta V \tag{12.2}$$

$$i_{\mathrm{d}} = \frac{v_{\mathrm{d}}P - v_{\mathrm{q}}Q}{(v_{\mathrm{d}} + v_{\mathrm{q}})^2} \tag{12.3}$$

$$i_{\mathrm{q}} = \frac{v_{\mathrm{d}}Q - v_{\mathrm{q}}P}{(v_{\mathrm{d}} + v_{\mathrm{q}})^2} \tag{12.4}$$



■ **FIGURE 12.3 Basic structure of VISMA.**

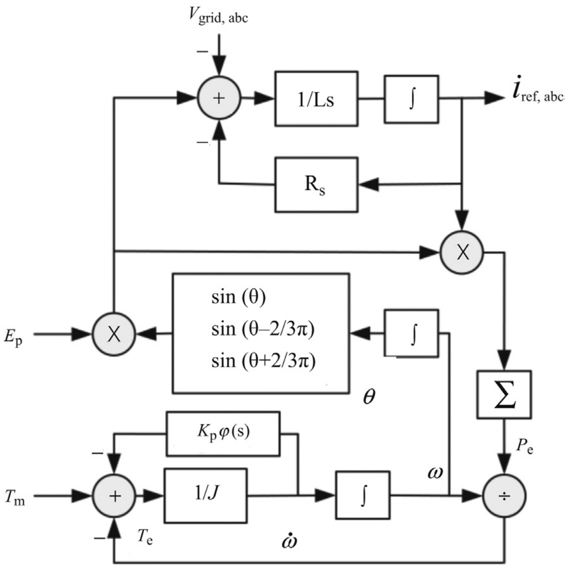
K_{SOC} must be set such that the active power P is equal to the nominal VSG output power, when the SOC deviation (ΔSOC) is at its maximum level. Similarly, the K_V must be chosen such that the VSG produce its maximum reactive power for a specified voltage deviation (eg, 10% [24]).

12.2.2 IEPE's VSG topology

This group developed a VSG design and called it VISMA [9,10,21,22]. The basic idea is shown in Fig. 12.3. The initial VISMA denoted as "Method 1" in Fig. 12.3 implements a linear and ideal model of a synchronous machine to produce current reference signals for the hysteresis controller of an inverter [9,22]. The control diagram of this scheme is shown in Fig. 12.4. The grid voltage is measured and, using a SG model, the current reference is produced to trigger the inverter switches through hysteresis controller. E_p and T_m in Fig. 12.4 are the voltage reference resembles the electromotive force of a SG and the virtual mechanical torque resembles the prime mover torque of an SG, respectively. Then the authors added an algorithm to compensate small disturbances and improve the quality of the grid voltage.

In Fig. 12.4, J is the moment of inertia, R_S is the stator resistance, and L_s is the stator inductance, K_d is the mechanical damping factor, $\varphi(s)$ is the phase compensation term with the transfer function of $1/(0.5s + 1)$, ω is the angular velocity, θ is the angle of rotation, T_m and T_e are the mechanical input and electrical torques, respectively.

The phase compensation term ensures that the virtual damping force counteracts any oscillating movement of the rotor in opposite phase. Despite simplifying the excitation winding, the induced electromotive force is given by adjustable amplitude E_P and the rotation angle θ [10].



■ **FIGURE 12.4 Block diagram of the VISMA for method 1.**

12.2.3 KHI's VSG

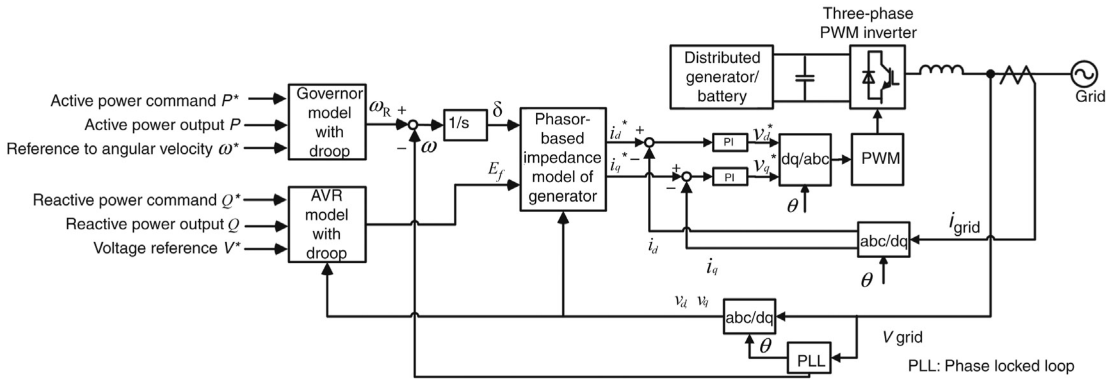
KHI's VSG uses the phasor diagram of a SG to produce current reference [23]. The relation between voltage and current phasors of an SG is algebraic. The complete control diagram is shown in Fig. 12.5. The load angle δ is produced from the governor model that has the active power command, active power feedback signal and the reference angular velocity as inputs and uses a droop controller. The automatic voltage regulator produces the electromotive force E_f, from reactive power command, reactive power feedback signal, the voltage reference, and the voltage feedback signal through a droop controller. The δ, E_f, and grid voltage signals v_d, v_q are used to produce the current reference based on the phasor diagram with the virtual armature resistance and virtual synchronous reactance.

12.2.4 VSG system of Osaka University

The block diagram of this scheme is shown in Fig. 12.6 [24,25]. The well-known swing equation of synchronous generators is used as the heart of the VSG model:

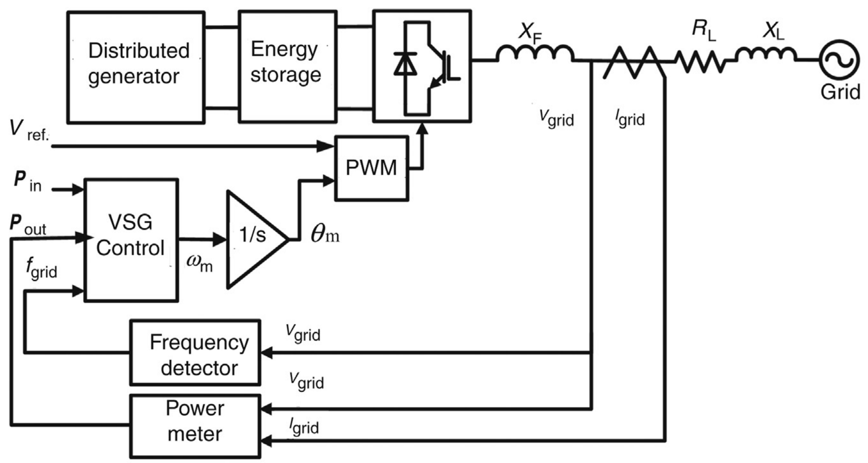
$$P_{out} = P_{in} - J\omega_m \frac{d\omega_m}{dt} - D\Delta\omega \tag{12.5}$$

where P_{in}, P_{out}, J, ω_m, and D are the input power (as same as the prime mover power in a synchronous generator), the output power of the VSG,



■ FIGURE 12.5 The algebraic type VSG introduced by the Kawasaki Heavy Industries.

the moment of inertia of the virtual rotor, the virtual angular velocity of the virtual rotor, and the damping factor, respectively. $\Delta\omega$ is given by $\Delta\omega = \omega_m - \omega_{grid}$, ω_{grid} being the grid frequency or the reference frequency when the grid is not available. Using voltage and current signals measured at the VSG terminals, its output power and frequency are calculated. A governor model shown in Fig. 12.7 is implemented to tune the input power command based on the frequency deviation. The grid frequency is detected by a frequency detector block that can be a PLL. Having the essential parameters, (12.5) is solved by numerical integration. By solving (12.5), the momentary ω_m is calculated and by passing through an integrator, the virtual mechanical phase angle θ_m is produced.



■ FIGURE 12.6 Block diagram of the VSG by the Osaka University.

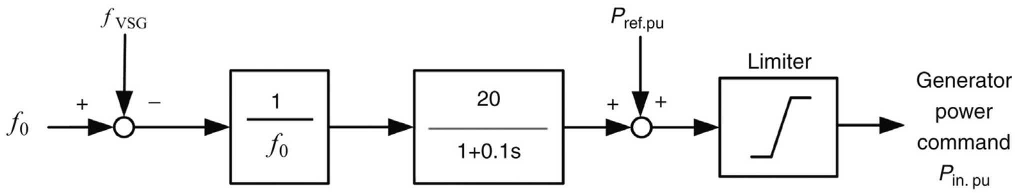


FIGURE 12.7 Governor model for the VSG of Fig. 12.6.

$V_{ref.}$ in Fig. 12.6 is the voltage reference that determines the voltage magnitude at the inverter terminal. Implementing a controller for $V_{ref.}$ results in a regulated voltage and reactive power at the VSG terminal. The phase angle and the voltage magnitude reference are used as the VSG output voltage angle and magnitude commands to generate PWM pulses for the inverter.

The value of J together with D in (12.5) determines the time constant of the VSG unit. Selecting the proper value of them is a challenging issue without a routine. Mimicking a synchronous machine, J is the inertia emulating characteristic given by $J = 2HS_0/\omega_0^2$, where H is the machine inertia constant, S_0 is the nominal apparent power of the machine, and ω_0 is the system frequency. The parameter H tells that for which period of time the machine is able to supply the nominal load based solely on the energy stored in the rotating mass. The higher H, the bigger the time constant, resulting in a slower response but smaller frequency deviation after a change or disturbance. Although it depends on the machine size and power, for typical synchronous machines H varies between 2 and 10 s.

By (1.5), the initial rate of frequency change ($d\omega/dt$) provides an error signal (with equilibrium of zero). When this signal is zero and frequency matches ω_{grid}, the output power of VSG follows the power command P_{in}. When there is a frequency variation due to a change of disturbance, the error signal will be a nonzero value and causes power oscillations. If the term $D\Delta\omega$ is neglected, power will be exchanged only during the transient state without necessarily returning back the output frequency to the nominal value. In order to cover this issue, a frequency droop part $\Delta\omega$ is added as shown in (12.5). The $D\Delta\omega$ emulates the damper windings effect in a SG, and represents the linear damping. It must be chosen so that the P_{out} to be equal with the nominal power of the VSG when the frequency deviation is at the specified maximum value [14].

Considering only the virtual inertia effect ($J\omega_m d\omega/dt$), increasing the moment of inertia, J 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 [4,30].

In summary, the virtual mass counteracts the frequency drops by injecting/extracting active power and the virtual damper suppresses the oscillation so these features are equally effective to electromechanical synchronous machines. J and D should be fixed so that the VSG exchanges its maximum active power when the maximum specified frequency variation and rate of frequency change occur. The larger J and D means that more power will be either injected or absorbed for the same amount of frequency deviation and rate of frequency change, respectively. However, oppositely, large values of J and D with specific power rating results in a small frequency excursion.

As mentioned, increasing of J provides a higher amount of equivalent inertia for the VSG, however there is a limit. This limit is mainly imposed by the 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 on the performance of the implemented PLL. Therefore, the optimal value of derivative term in (12.5) can be obtained by a tradeoff between the virtual inertia, the inverter overload capacity, and the PLL characteristics.

This group has added reactive power control to have a constant voltage at VSG terminals [26], and evaluated the performance in various voltage sag conditions, and enhanced the voltage sag ride-through capability of the VSG [27]. Oscillation damping approaches have been developed for a DG using the VSG [28,29].

12.3 APPLICATIONS FOR MICROGRIDS

A microgrid is an interconnection of domestic distributed loads and low voltage distributed energy sources, such as microturbines, wind turbines, PVs, and storage devices. The microgrids 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 [31,32].

The VSG systems can be used as effective control units to compensate for the lack of inertia and result in the control of active and reactive power as well as microgrid voltage and frequency. A microgrid with VSG units is shown in Fig. 12.8. The VSGs can be connected between a DC bus/source

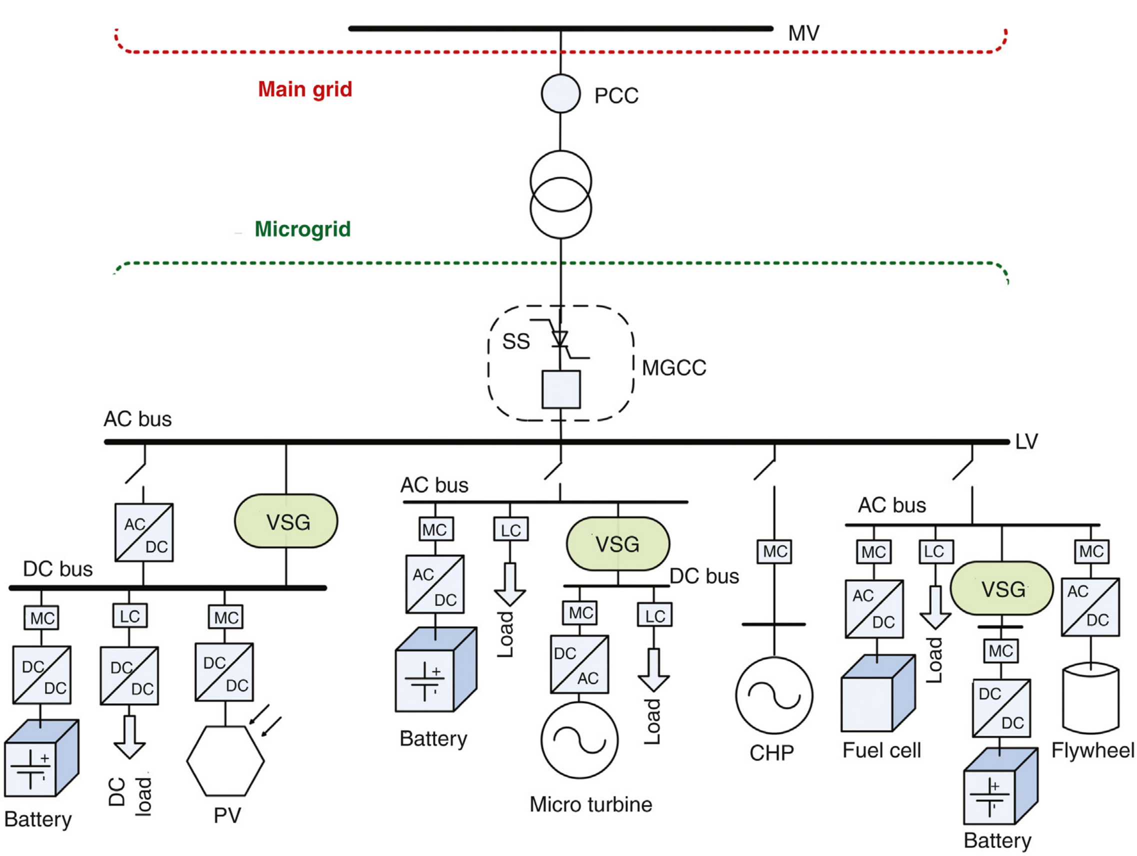


FIGURE 12.8 A structure of a microgrid with multi VSG units.

and an AC bus, anywhere in the microgrid. These systems are going to be more vital to overcome fluctuations caused in the microgrid due to integration of large number of DGs with low or no inertia [31]. Some loads can be also locally controllable using the load controllers. The load controllers are usually used for demand side management.

In microgrids with small power capacity, a change or disturbance in the system (such as a temporary imbalance between production and demand after loss of a large generating unit) results in a high rate variation in the rotating speed of generators. 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 [31]. 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 [33]. With an appropriate control strategy, the VSGs equipped with fast-acting storage devices can help microgrids to mitigate the frequency excursions caused by generation outages, thus reducing the need for load shedding [31].

During the grid connected operation, all the DGs and inverters in the microgrid use the signals of grid voltage and frequency 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 simultaneous operation using one effective control techniques such as master/slave control, current/power sharing control, and generalized frequency and voltage droop control techniques [32]. The balance between generation and demand of power is an important requirement of the islanded operation modes. In the grid-connected mode, the microgrid exchanges power to an interconnected grid to meet the balance, while, in the islanded mode, the microgrid should meet the balance for the local supply and demand using the decrease in generation or load shedding [31].

During the islanded mode, if there are local load changes, local DGs will either increase or reduce their production to keep the energy balance constant as far as possible. In an islanded operation, a microgrid 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 [31].

Immediately after islanding, the voltage, phase angle, and frequency at each DG in the microgrid change. For example, the local frequency will decrease if the microgrid imports power from the main grid in a grid-connected operation, but will increase if the microgrid exports power to the main grid in the grid-connected operation [31]. 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 network for few minutes. The VSG control algorithms for islanding and grid-connected modes are different, as the islanded microgrid has to define its own frequency and voltage to maintain operation [16]. When the main grid has returned to normal operation, the frequency and voltage of the microgrid must be synchronized with and then reconnected to the main grid.

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